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Accelerating renewable heat: Overcoming barriers to shared-loop ground source heat pump systems in the United Kingdom

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ABSTRACT

Heat decarbonisation is needed rapidly and at scale to reach net-zero carbon emissions by 2050. Shared-loop ground source heat pumps (GSHPs) are an under-researched technology with potential to deliver clean heat at scale. These involve the installation of connected GSHPs for a group of homes, a whole street or apartment building, with shared use of deep boreholes, coupled with individual heat pumps installed in each property. However, a range of socioeconomic, political and technical barriers inhibit their mass deployment and there is a research gap surrounding potential policy, governance and financial support mechanisms to help overcome these. This study investigates the advantages and challenges associated with this technology, and reviews measures which could accelerate uptake. Analysis draws on 58 interviews with policymakers, industry stakeholders, users and non-users in the UK. Advantages include neighbourhood scale-deployment, with the potential to decommission local gas grids. Compared with air-source heat pumps, shared-loop GSHPs are more compact, less noisy, and more efficient, with lower running costs. However, they share many barriers associated with all heat pumps, and have higher up-front costs. A range of policy options are discussed which address the need for investor confidence, skills and training, information provision, and other incentives. Overall, carefully designed policy and financial support mechanisms could accelerate mass deployment of shared-loop GSHP technology, helping to reduce reliance on fossil fuels, boost energy security and reduce carbon emissions.

1. Introduction

Decarbonising heat in buildings is one of the most challenging activities for mitigating greenhouse gas emissions in response to climate change. Accounting for approximately 50 % of final energy consumption globally [1], heating and cooling systems typically have long lifetimes, and the replacement rate of building stock is low [2]. In many countries, the majority source of energy for heating is provided by fossil fuels, and there is an urgent need to electrify heating systems, or shift to zero-carbon fuels.

There is growing consensus that heat pumps represent the most promising technology for decarbonising heating around the world, and various modelled pathways to net-zero involve their rapid and widespread rollout in the next few decades [3,4]. While the share of heat pumps in buildings in Scandinavia, Japan and Australasia is relatively high [5], penetration of heat pumps remains low in much of western and southern Europe, and North America [6]. Different markets favour different heat pump technologies. In Australia and New Zealand, air-to-air systems are commonplace, whereas in Germany and Poland air-to-

water systems are preferred [5]. Heat pumps are increasingly used in District Heating Networks (DHNs) in Scandinavia [7]. The need for expensive drilling works and additional space for ground- and water-source heat pumps means that, despite their greater efficiency, they accounted for less than 10 % of European sales in 2022, with air source heat pumps dominating the market [5].

In response to Russia's invasion of Ukraine and the associated energy price crisis, heat pump deployment has accelerated in some parts of Europe. In France and the USA, more heat pumps than fossil fuel boilers were installed for the first time in 2022, while the rate of uptake in Poland and Czechia doubled over 12 months [5]. In the UK and Netherlands however, where more than 85 % of buildings use natural gas for heating, uptake remains low, hampered by high installation costs and the relatively high unit price of electricity compared with fossil fuels [8,9].

This paper focuses on the UK, where heat pump deployment lags behind European neighbours at 412 systems per 100,000 population (mostly ASHPs), compared with a European average of 3086 per 100,000 [10]. Currently, less than 400,000 HPs are operational [11,12],

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whereas fossil fuelled boilers number roughly 26 million [11]. The UK's government advisors, the Climate Change Committee, forecast a need for 8 million domestic installations by 2035 [4]. There are several barriers to widespread deployment in the UK. Compared with other countries in northern Europe, the UK's building stock is relatively old, with low thermal efficiencies, and are serviced by an extensive gas grid [6]. Only 2 % of homes are connected to DHNs [13], and decision-making with regards to installing new heating systems is therefore highly decentralised [14]. To date, heat pump subsidies have done little to accelerate uptake (Table 2), and there is a need for more research and policy attention on alternative approaches to increasing the deployment of heat pumps in the UK.

This article investigates one novel solution: shared-loop GSHP systems. These involve the installation of connected GSHPs for a group of homes, a whole street or apartment building, with shared use of deep boreholes, coupled with individual HPs installed in each property (Fig. 1). The hope is that shared-loop systems will both reduce capital costs, and enable new business models to be developed, which together will offer a more economically favourable, low-carbon heating option. This idea is investigated here in the context of the residential sector, but could equally apply to the commercial sector.

Currently, in the UK, the capital costs of both typical, individual ASHPs and GSHPs are unfavourable compared with gas boilers (Table 1). Capital costs for individual GSHP systems typically exceed ASHPs due to the cost of drilling, trenching and other construction work. GSHP systems absorb energy from the ground using either an array of buried horizontal collector pipes (1–2 m deep) or vertical boreholes (100–300 m deep). Several analyses claim that GSHP running costs can be lower than ASHPs because the temperature of their heat source – the ground – remains more consistent over the year (approximately 10 °C in the UK), whereas air temperatures fluctuate more widely, and can be negative in winter [16–18]. However, there is limited empirical evidence from installations in the UK to support this claim.

The idea of using heat pumps as part of a low-temperature district heating network has been explored in the ‘fifth generation’ district heating (and cooling) network literature (e.g. 21,22). If neighbourhood-scale, shared-loop GSHPs were developed they could offer similar benefits to district heat networks (DHNs), for example, in enabling local gas grids to be decommissioned. However, compared with high temperature DHNs, shared-loop GSHPs would suffer fewer energy losses. This is due to using lower operating temperatures and a non-centralised heating source (multiple boreholes as opposed to a central boiler). However, there are also downsides, such as needing larger pipe sizes to transmit sufficient energy at lower temperatures [22]. Depending on the

Table 1

Average upfront costs for gas boiler, ASHP and GSHP systems [19,20]. Upfront capital costs include equipment and installation which varies depending on size and type of heat pump or boiler used and type of property.

	Gas Boiler (90 % efficient)	ASHP (CoP 3)	GSHP (CoP 4)
Upfront capital cost	£1500–4600	£7000–13,000	£10,000 - 21,000

approach to deployment, they may also offer householders choice with respect to when they connect to shared loop infrastructure, and electricity supplier. Because GSHPs are more efficient than ASHPs, particularly in winter, with the efficiency gap widening the colder it gets, their use requires less investment in additional electricity supply, transmission and distribution to meet normal heating requirements. In addition, because peak electricity demands during particularly cold spells will be lower, investment in peak capacity will be lower, as will the chance of demanding more than the grid can supply.

The extant market for shared-loop GSHPs is small. By the end of 2020, the UK had installed roughly 2500 systems, primarily in social housing or in newly built clusters of ‘off-grid’ homes. These dwellings benefit from having a single decision-maker (housing association or developer), meaning that systems can be installed at the street or neighbourhood-scale [23,24]. However, from a technical perspective, it is estimated that around 80 % of the UK housing stock is suitable for this technology [25].

Whilst there has been some research into the techno-economic viability of fifth generation DHNs, [21,25–27], there remains a research gap on the shared-loop GSHP concept both in the UK and internationally, especially surrounding the broader socioeconomic, technical and political challenges associated with widespread deployment [23]. There is also a need to specify the necessary policies, governance arrangements, and financial support mechanisms that could help accelerate deployment [15]. This study addresses this gap by responding to three inter-related research questions:

1. What are the main barriers and challenges in the implementation of shared-loop GSHP systems?
2. What policies, governance arrangements and financial support mechanisms are necessary to enable and accelerate implementation of shared-loop GSHP systems?
3. What are the prevailing public attitudes towards shared-loop GSHP systems and potential financial support mechanisms?

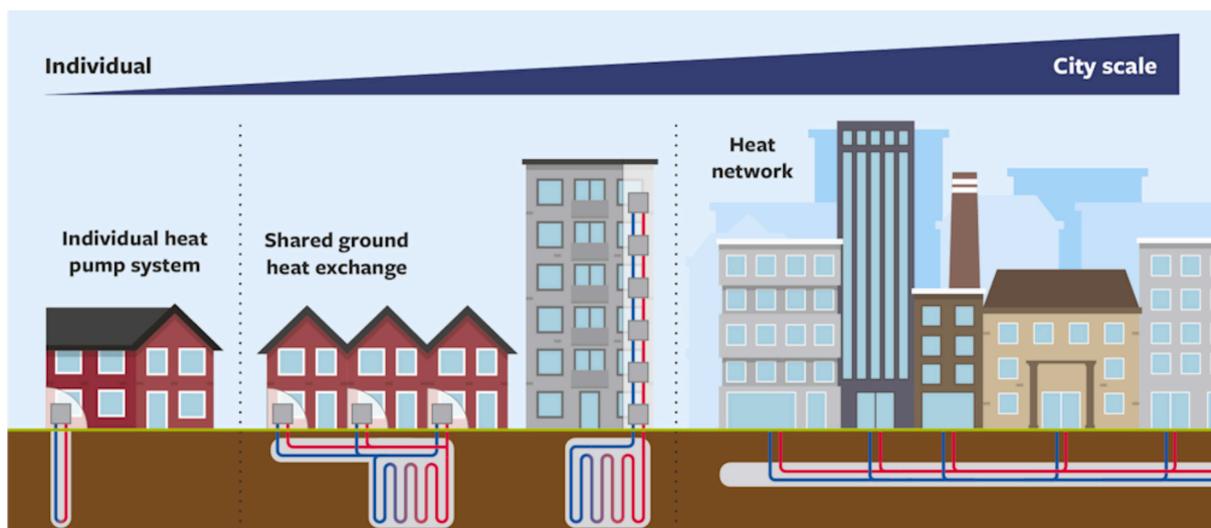


Fig. 1. An illustration of ground source heat pumps at different scales [15].

Addressing these questions, this paper draws on new empirical data from several sources. Interviews were conducted in 2022 with 19 expert practitioners and policymakers. Additionally, interviews, questionnaires and in-home observations were conducted with 17 users of shared-loop GSHPs as part of a major demonstration project. Lastly, 22 householders without HPs were interviewed. While the focus of this study is on the UK, shared-loop GSHPs have potential to accelerate the decarbonisation of heating and cooling internationally. The barriers and solutions discussed in this article have direct implications for energy and climate policymakers around the world.

2. Challenges and context for shared-loop GHSP systems

2.1. Barriers to adoption of traditional heat pumps

There is a growing academic literature focused on the economic, technical, social and policy barriers to the diffusion of traditional ASHPs and GSHPs. Although there has been substantially less written about shared-loop GSHPs, some of these barriers are likely to be shared.

One barrier to the adoption of HPs in general is the incumbency of the UK gas grid, and the popularity of gas for heating amongst UK householders. Gas boilers are a familiar, convenient and easy-to-use technology with quick response times. User satisfaction is high [28], and around 50 % of the UK population think gas does not contribute to climate change [29,30]. A government survey found that registered gas engineers are the most trusted source of information for heating system decisions [31]. These intermediaries typically recommend gas appliances over heat pump alternatives.

Other major barriers to HP deployment include their high upfront capital costs, need for a low temperature heat distribution system, a hot water tank (HWT), and the fact that often fabric insulation is advised by installers to optimise performance [32]. These often increase the costs of system installation significantly beyond the ‘ticket price’ of the HP appliance. Palmer and Cooper [33] estimate that over half of UK homes no longer have a HWT, due to combi-boiler systems being installed. While these barriers concern all HPs, ASHPs face additional obstacles associated with the need for an outdoor unit, which can generate concerns about noise and aesthetic appearance. These can be significant issues in certain locations, such as dense urban neighbourhoods or Conservation Areas.

On the supply side, there are also barriers to deployment including lack of acceptance and awareness of technology by systems designers and users [34,35]. Limited availability of experienced and skilled workers with the technical knowledge to design and install systems is also an issue [36]. Finally, awareness of HP technology in the UK is low. Research by Williams et al. [37] showed that only 42 % of individuals had heard of GSHPs or ASHPs.

2.2. Shared-loop GSHP business models

Currently there is no established business model for shared-loop GSHP systems, however, the two main front runners from the literature are either ‘split ownership’ or ‘Heating as a Service’ models.

The split ownership model involves dividing system assets between different investors. Shared ground loop arrays are funded, installed, owned and maintained by an entity such as a utility company, local authority, housing association or pension fund, to which the end-user pays a standing charge [15]. Under this model, ground-asset investors take on the costs and risks, typically expecting to recuperate infrastructure investments via long-term repayment schedules (20–40 years). The long lifespan of the ground arrays and this ‘patient capital’ can help to reduce the standing charge to levels comparable with those paid for gas and electricity. Besides the economies of scale of shared ground loop systems compared with individual GHSP installations, there is also potential for cost reductions due to learning, product innovation, and deployment-at-scale. Howard and Crook [25] estimate this could reduce

shared loop system installation costs by 40 %, and appliance costs by 50 % over the next 20 years.

The end user would then just pay for the heat pump unit, its electricity use (up to 45 % less than an ASHP) and the monthly standing charge [38]. This model would also allow for separate independent billing and electricity supplier switching. It also has the advantage of reducing the barriers to replacing gas boilers with HPs, as the infrastructure is already in place. This is important as when a boiler breaks down, householders require rapid solutions and often base their decisions on the quickest or most convenient option as opposed to the lowest carbon or even cheapest option in some cases [2].

Another innovative business model gaining increasing attention is Heat as a Service (HaaS). While definitions vary [39], the core principle is that consumers pay for a guaranteed set temperature level or number of ‘warm hours’ with a set amount of flexibility that providers can utilise (e.g. $20 \pm 2^\circ\text{C}$) [29]. Energy suppliers who provide this service can then utilise advanced smart controls linked to ‘time of use’ tariffs, where energy prices vary over the course of the day, and HWTs to remotely heat homes to the required level cost-effectively [40]. They can also use the asset to sell ancillary services which could reduce the net electricity cost for a home by around 14 % [41]. Additionally, providers may seek to install fabric efficiency measures, and may benefit from economies of scale if doing so across a range of similar or proximal dwellings. However, several challenges must be overcome for the model to be widely adopted, including resistance from householders to sign-up to long-term contracts [42], and regulatory barriers created by sustained efforts to encourage consumers to switch suppliers [29].

2.3. District heating network comparisons

Shared-loop GSHPs have much in common with district heating networks (DHNs). The key difference is that DHNs typically distribute heat directly to dwellings using large-centrally located boilers, whereas shared-loop systems involve installing individual units in each home [43]. DHNs are widespread in Scandinavia, but in the UK only serve 2 % of housing, where they tend to use fossil-fuels to supply high-temperature heat and involve relatively higher losses than more modern, low-temperature systems using heat pumps [2].

For DHNs to be cost effective and technically efficient, they require high uptake amongst local communities [21]. The major costs are borne upfront, involving groundworks. When households are able to opt-out, this raises costs for other users and creates uncertainty for investors. Even where already installed, the ongoing viability of DHNs can be uncertain. Research has found that in some parts of Finland and Sweden, some users have disconnected and installed their own HPs in response to high DHN prices and the falling cost of HP installations [44]. For both DHNs and shared-loop GSHPs, the challenge is to balance consumer needs (competitive pricing, flexibility and options) while creating investor-confidence [45].

Accompanying the trend towards more decentralised energy systems and partly driven by growing awareness of the need to decarbonise heating, interest in DHNs is growing [46]. New actors, including local authorities, regional energy agencies, social housing providers or community organisations are becoming actively involved with installing and owning assets [47]. Schmidt et al. [48] argue that where assets are owned by local authorities or energy cooperatives, DHN connections are likely to be higher.

2.4. UK policy context

The UK government's approach to heat decarbonisation is set out in its Heat & Buildings Strategy [49]. Heat pumps feature centrally, and the government has set a target for installing 600,000 per year by 2028. To support roll-out, the government launched the Boiler Upgrade Scheme [50], initially awarding homeowners and small businesses £5000 towards upfront costs of ASHPs, and £6000 for GSHPs. The grant available

for both technologies was subsequently increased to £7500.

The UK government wants to reduce HP installation costs by 25–50 % before 2025 and make them no more expensive to purchase and operate than a gas boiler by 2030 [49]. This will involve reversing a long-standing trend by successive governments to levy the costs of energy decarbonisation more heavily onto electricity bills compared to gas. This has contributed to electricity prices being 3–5 times more expensive than gas, discouraging electricity use for heating [24,51]. Some progress has been made towards addressing HP versus gas price difference. In 2022, Value-Added Tax (VAT) was cut on HP installation and purchase costs [52].

Table 2 identifies several financial support mechanisms in the UK which have helped to boost the uptake of HPs and shared-loop GSHP projects. However, many have been short term, subject to frequent change (e.g. RHI), or insufficiently attractive to both potential customers and installers to drive widespread adoption [53].

2.5. Current trials and research gap

Although there are around 2500 known shared-loop GSHP schemes in the UK [24], these are primarily in social housing or in newly built ‘off-grid’ homes. Few trials have focussed on streets made up of privately owned (or rented) properties connected to the gas grid. One example is ‘Heat the Streets’: a £6.2 million European Regional Development Fund (ERDF) scheme in Stithians, Cornwall, which is providing connected borehole infrastructure for 500 homes [43]. Feasibility studies in London, Leeds, and Devon and have also been funded under the ‘Heat Pump Ready Programme’ [60]. However, all such projects have so far relied on public funding to make them financially viable and there remains a need for research into what policy, governance, financial and regulatory instruments are needed to help support more sustainable, widespread deployment. The next section discusses the methodological approach taken to address this research gap.

Table 2

Recent and current UK policies for low carbon heat.

Policy / financial incentive	Years active	Details	Outcome (approximate installations)	Comments in relation to shared-loop GSHP systems
Low Carbon Buildings Programme grants	2006–2011 (UK)	Upfront grant for microgeneration technologies. Paid an average grant of £900 for ASHPs and £1200 for GSHPs installed in homes [54].	19,000 microgeneration systems installed, including 1500 ASHPs and 1500 GSHPs [54].	Upfront grant too small to make shared-loop GSHP systems viable.
Renewable Heat Premium Payments (RHPP)	2011–2014 (UK)	Offered small grants including £850 for ASHPs and £1250 for GSHPs installed in off-gas grid homes [55].	5900 ASHPs and 2230 GSHPs / WSHPs installed through the scheme [55].	Upfront grant too small to make shared-loop GSHP systems viable and only available in off-gas grid properties.
Renewable Heat Incentive	2014–2022 (UK)	Paid fixed tariff with quarterly payments over 7-years (domestic) and 20-years (non-domestic) [53]. In 2021, tariffs valued at 21 p/kWh for a GSHP and 11p/kWh for an ASHP [20]. ‘Assignment of rights’ amendment in 2018 allowed third parties receive payments in return for financing installation [56].	58,000 ASHPs and 12,250 GSHPs installed in homes up to July 2021: around 22 % of target [56].	Social landlords benefitted from assignment of rights, and ability to access more generous non-domestic scheme (due to classification as DH). Scheme helped deliver 30 % growth in shared loop systems [25].
Green Homes Grant	2020–2021 (England)	Government funded two thirds of the cost of home improvements up to £5000 including ASHP/GSHPs and heating controls. Low-income households could receive 100 % of costs up to £10,000 [57].	3924 ASHPs, 955 hybrid heat pumps and 29 GSHPs installed up to December 2021, well short of targets [58].	Six month scheme. Uncertainty and confusion experienced by manufacturing and installers.
Boiler Upgrade Scheme grants	2022–2025 (England & Wales)	£450 million government funding available for households and small businesses to receive £7500 towards HPs [50]. Installations must replace existing fossil fuel or direct electric heating systems. Heat pump installations will require a minimum CoP of 2.8. Funding limited to 90,000 installations.	May 2022 to June 2023: 12,426 ASHPs; 334 GSHPs; 10 shared-loop GSHPs [50].	Shared-loop GSHP systems supported but only up to a total system capacity of 45 kWh (around 10 properties), funding £6000 per property for a GSHP system.
Social Housing Decarbonisation Fund	2021–2023 (UK)	£800 m fund from the government helping tackle fuel poverty and carbon emissions in social housing [59]. Supported measures include energy efficiency as well as renewable heating systems.	March 2022 to May 2023: 135 ASHPs (average cost £12,700); 128 GSHPs (average cost £23,600) [59].	Shared-loop GSHP recognised as an eligible technology after fabric efficiency measures have been installed, but low take up in year one.

3. Methodology

3.1. Research design and approach

Considering the lack of research undertaken on shared-loop GSHP systems in the UK, this research adopts an exploratory approach, drawing primarily on 58 semi-structured interviews with three distinct groups, conducted between 2020 and 2022. Interview guides for each group are detailed in Appendix A.

The first group ($n = 19$) includes industry professionals, policy experts, civil servants and other stakeholders with expertise in the shared-loop GSHP sector. These are referred to below as *practitioners*. Appendix B includes a list of their roles and organisations. Interviews focused on the political, financial, social and technical barriers associated with shared-loop GSHP systems, and potential solutions. Questions were trialled and refined using pilot interviews, and shared in advance with participants to allow them to prepare [61].

The second group ($n = 17$) consists of householders in 17 separate dwellings with a GSHP installed as part of a shared ground-loop system. Interviews and questionnaires were conducted in their homes, focusing on experiences of installation, comfort, control and costs. The third group comprises 22 householders (occupying 10 dwellings) without a HP installed, and interviews with this group focused on attitudes towards shared-loop GSHP systems as a potential solution for reducing reliance on fossil fuels for heating. This group was shown two short videos explaining a) how a GSHP worked, and b) how a shared-loop GSHP system would be implemented along a street. Gathering data from more than one adult in the same household was a time-efficient way of increasing the range of views included in the study.

3.2. Participant recruitment

Industry professionals, senior policy experts and other key

practitioners across government and the third sector were recruited for interview if they had a good degree of knowledge or experience with the small number of shared-loop GSHP projects already implemented in the UK. Participants were sampled purposefully using a key informant sampling strategy [62]. Key practitioners and organisations were first identified through a review of academic and grey literature including company websites, government policy documents, independent reports, professional networks, webinars and the “Heat Pump Ready Collaboration Platform” provided by BEIS [60]. This generated a list of 75 potential interviewees from a wide variety of professional backgrounds. These individuals were then contacted via email and followed up after a week if no response was received. From the initial list, 25 people accepted the invitation for interview, however, this was narrowed down to 15 based on the most relevant organisations, position seniority and years of expertise in the field. To get a broad range of professional voices, participants were also purposefully chosen to elicit potential heterogeneous viewpoints [63,64]. Therefore, following the 15 interviews four additional participants were interviewed as a result of snowball sampling. At this point, theoretical saturation was reached, where similar recurring opinions and themes emerged and the richness of the data was sufficiently robust to allow analysis to be undertaken [65].

Users of shared-loop GSHP systems were recruited as part of Energy Superhub Oxford (ESO), a national energy demonstration project running from 2019 to 2023 [24]. A total of 57 GSHP systems were installed in social housing properties in a suburb of Oxford, UK from August 2020 to March 2021, and research participants were recruited during the installation phase. Multiple interviews and questionnaires were conducted over the course of the project to monitor changing experiences over time.

The third group - householders without GSHP systems - were recruited through personal and professional networks, and included a mix of homeowners and private renters, varying age ranges, gender splits and cultural backgrounds. Participant details for groups 1 to 3 are included in [Appendix B](#).

3.3. Data analysis

To familiarise and make sense of data, interviews were first transcribed verbatim and thoroughly read twice before manually coding using thematic content analysis with no specific theoretical perspective or predetermined framework [66,67]. This grounded approach was adopted due to the under-researched nature and relative novelty of the study phenomenon. First, text was highlighted where there were obvious comparisons, contradictions and repetitions between and within the three main interview groups [68]. Fragments of text were then extracted from the transcription and labelled with a descriptive code based on whether they related to the research objectives, themes from the literature review, were repeated, or surprised the researcher [66,69]. This method allowed both top-down deductive themes to be generated from a priori knowledge of the academic literature as well as new inductive bottom-up themes to emerge [70]. These steps were then repeated and re-coded in a second cycle.

4. Results and discussion

This section presents and discusses key themes, barriers and novel findings which emerged from an in-depth analysis of the data. Results are presented in four sub-sections: ‘Policy, governance and regulation’ (4.1), ‘Finance and business models’ (4.2), ‘Technical and practical considerations’ (4.3) and ‘Public attitudes and social acceptance’ (4.4). Most insights into research questions 1 and 2 come from sub-sections 4.1–4.3, with 4.4 focused on research question 3. Interview data - including policy proposals made by expert participants - are presented and compared with evidence from existing literature, or with findings from other stakeholder groups. Given the variety of barriers and

solutions, results and discussion sections are combined to allow the reader to more easily navigate this wide-ranging topic. The section finishes with a summary of key findings, research limitations and suggestions for future work.

4.1. Policy, governance and regulation

4.1.1. National direction and uncertainty

Several expert practitioners highlighted the negative impact of uncertainty surrounding different potential solutions for heat decarbonisation in the UK. One participant from a social housing provider said:

“Housing associations and businesses need more certainty and a stronger government position that heat electrification is the way forward.” (P11).

Members of the public were also aware of the uncertainty surrounding national heat strategy, and four participants from Group 3 believed that they would be receiving hydrogen soon instead of natural gas. This led them to dismiss the value of shared-loop GSHPs. One participant from Group 3 said:

“It all sounds wonderful, but what about when hydrogen comes along to my street?” (M05).

This echoes Lowes et al.’s [71] findings, showing the power of incumbents in lobbying and steering peoples’ perceptions positively towards ‘green gas’ or hydrogen as a symbiotic substitute instead of heat electrification. This issue could negatively affect shared-loop GSHP deployment, and there is a need for central government to explain to industry and the wider public that cheap green hydrogen networks is unlikely to be supplied to domestic properties in the near or medium-term future (except perhaps where close to heavy industrial clusters). This is further supported by the Government’s own literature, which proposes to trial a single hydrogen town by 2030 [72].

Six expert practitioners explained that the proposed Future Homes Standard (FHS) could help encourage shared-loop GSHP deployment, especially in new-builds. At the time of interview, the draft standard proposed to prohibit fossil-fuelled heating in new homes from 2025 [73]. Four practitioners thought this should go further to also ban direct electric heating systems:

“Developers will choose the easiest and cheapest thing. It used to be gas boilers. It’s now direct electric heaters...and they are just absolutely the worst thing for the grid.” (P04).

Extending the FHS to restrict the use of direct electric heating would encourage uptake of HPs and benefit users due to lower running costs.

4.1.2. Enabling installation of boreholes and trenches

The need for planning permission to dig boreholes or trenches creates administrative burdens, additional costs and delays for installers. Two Directors of heat pump manufacturers called for GSHP developers to be granted the same powers to dig in streets as given to gas, water and telecoms companies. National legislation is not the only lever here, however. Local authorities could grant shared-loop developers these rights at a local level, and link these with other planned utility works to minimise cost and disruption. They could also choose to simplify and fast-track planning permissions specifically for these low carbon heating solutions.

4.1.3. Compulsory connection and regulation

Expert participants highlighted that a key barrier to private sector investors were concerns over insufficient numbers of properties connecting to new shared-loop GSHP systems. Seven practitioners said that regulation would be required to overcome this barrier, and several pointed to proposals for Heat Network Zones [74], which would mandate residents to connect within a certain timeframe (e.g. 10 years)

or whenever their boiler breaks down (whichever comes first). To allay concerns over consumer choice, this could be applied only where shared-loop GSHPs have been identified as the lowest-cost, lowest-carbon option for a street through Local Area Energy Planning (LAEP) (see section 4.1.4).

Without such a mandate, three practitioners suggested that investors could be reassured by the use of a 'Tenant Service Charge', which commits occupants to minimum payments linked to their overall tenancy agreement. Such an approach would need to be supported by landlords, accompanied by efforts to promote the benefits of the systems, including through highlighting the benefits of time-of-use electricity tariffs to reduce running costs. Other incentives suggested by Group 3 participants could include developers enhancing the local area with new benches, planting, or bins or by upgrading local schools or community centres.

The number of committed homes required to give investor confidence depends on risk tolerance, installation costs and projected heat demand within a given street, and there is a need for further research to determine the threshold conditions for investment to be secured.

4.1.4. The role of local authorities and local area energy planning

Five practitioners explained how some local authorities – having declared climate emergencies - were going beyond the National Planning Policy Framework to leverage local planning powers to accelerate low carbon heating. In London for example, shared-loop GSHP projects are being supported to address carbon reduction targets which exceed national requirements [75]. However, a Principal Energy Officer from a County Council (P16) raised concerns that if they increased standards for new development, developers and investors would go elsewhere and housing targets (and linked government funding) would be put at risk.

Several practitioners cited the potential benefits of Local Area Energy Planning (LAEP), which they said could help to reduce uncertainty for a range of stakeholders by strategically mapping areas suitable for different zero-carbon heating plans, including a) future hydrogen grid-supply, b) ASHPs (streets with outdoor space and enough grid headroom), and c) DHNs (dense urban streets). It was suggested that LAEP could also be used to plan shared-loop GSHPs, for instance in semi-dense streets with limited outdoor space and grid constraints. Having identified areas for shared-loop GSHP systems, local authorities could tender for concession contracts to procure groundworks:

“We could run it as a concession contract in a similar way to electric vehicle chargers. We give permission to the charging company or energy utility to dig up the street...but they would have to bid for it so then it would come at no cost to us.” (P15).

For investors, LAEP can give confidence that other heat decarbonisation technologies will not undercut them and create stranded assets [44]. For members of the public (Groups 2 and 3), local authorities were considered critical actors, as they are more trusted than energy utilities or developers [76]. They also have wider motivations and values beyond the maximisation of profit such as the comfort and welfare of their citizens, local air pollution standards, carbon reduction targets and reducing fuel poverty levels amongst others [23,48]. Participants from all three groups expressed support for local authorities to implement, own and operate schemes themselves, and some expert practitioners highlighted the opportunity to raise 'patient finance' through the National Infrastructure bank, recouping costs through long-term standing charges.

“This is something the local council could deliver. I've seen them advertise a group solar panel buying scheme, so if they promoted it and endorsed it I would be more inclined to join.” (F06).

However, others explained how austerity and budget cuts have significantly eroded the resources, technical knowledge and competencies of local authorities' in-house teams to help support this ambition

[77], and that capabilities varied between local councils:

“Some councils have got one graduate Climate Emergency Officer, whereas some have an energy and sustainability team of 30. You've got a massive disparity in aspiration and ability to deliver.” (P06).

Overall, there was consensus that Local Authorities are crucial for helping to accelerate the deployment of shared-loop GHSP systems, acting as planners, regulators, coordinators, investors and trusted information brokers. However, more power, funding and resources are required to equip them with the capacity to be effective in these varied roles.

4.2. Finance and business models

4.2.1. Electricity levies, HP tariffs and carbon taxes

One barrier that overlapped finance and policy categories was the unfavourable ratio between electricity and gas unit prices. Several practitioners mentioned that if environmental and social levies placed on electricity were removed, this could lead to a tipping point for the affordability of shared-loop GSHPs.

“The price of electricity is artificially high, because of the scale of the environmental and social levies and because of the current mechanism which ties the wholesale price of electricity to the wholesale price of gas...if both of those were fixed, heat pump operation would now be the cheapest form of heat.” (P08).

Currently HPs need to be between 300 and 400 % efficient to compete with gas prices [78]. Two options proposed were (1) incrementally moving levies from electricity onto gas; or (2) putting them into general taxation. Five practitioners suggested that a carbon tax on fossil fuelled heating sources would have similar benefits.

Another policy proposed by several practitioners was to offer lower cost HP electricity tariffs to individual homes or entire streets that join a shared-loop GSHP scheme. Interviews with members of the public (both with and without HPs) indicated positive attitudes towards adopting time of use (TOU) tariffs when more widely available in tandem with a new shared-loop GSHP system.

“If I was told, it's gonna cost you more between four and seven. Yeah, I'd put it on first thing in the morning, or after seven exactly.” (C01).

Lastly, while several practitioners were excited about the possibilities of HaaS business models to help catalyse shared-loop GSHP deployment, our sample of householders looked upon such proposals negatively.

“It would be interesting to be able to offer heat within the rent and a fair usage policy. A bit like a mobile phone contract. That would rely on us being able to optimise renewable assets such as solar PV, battery and time of use tariffs and control those assets to achieve levels of comfort for the lowest costs.... and we would get an understanding of how the tenant was interacting with the property and those assets.” (P10).

“I would rather do the work myself and then pay for exactly what I use. Because surely if they're doing this 'Heat as a Service', there's a middleman to make money. I like to be in full control and know exactly what's going on.” (M04).

4.2.2. Meso-scale policy funding gap

Seven practitioners highlighted how financial incentives for renewable heat were largely targeted at individual householders, or at the city-scale. There is a need for specific meso-scale funding to incentivise shared-loop GSHP systems.

“Shared-loop arrays fall in a bit of a grey policy funding area, sort of between individual heat pump policy and heat network policy.” (P13).

“Shared ground-loop schemes are street-level so do not fall into the criteria for either households or heat networks. If the government is serious about going down this route there needs to be specific funding available.” (P09).

All interviewees discussing funding highlighted the need for longer term certainty: it is essential that schemes are in place for at least 5 years to de-risk investment [56].

4.2.3. Building loans, passports, and tax rebates

A financial barrier mentioned by five practitioners and six members of the public was concern over the length of time required to repay high upfront costs. Some residents said they were likely to move home within 10 years, and some older residents felt they would unlikely reap the benefits of the shared-loop GSHP system within their lifetime:

“The new system would have to be cheaper for us. If it costs too much we will not see the benefits at our age. We wouldn't take out a loan at our age.” (M07).

These findings concur with Sperling and Arler [79] and Carlsson and Johansson-Stenman [80] who found similar results with other high-cost renewable energy systems. One solution to this barrier mentioned by three practitioners was having loans and finance attached to buildings rather than a person. This could work in a similar way to Property Assessed Clean Energy (PACE) loans in the USA [81] or long term service charge agreements which are attached to the deeds of a home [38]. This financial mechanism involves passing financial commitments onto the next homeowner who continues to pay off the system.

“It's quite simple. It will be relatively easy to scale up and would help with some of the credit issues you currently get.” (P17).

Building passports were also suggested to keep track of these loans as well as all renewable energy and low carbon heating measures installed at a property. These can benefit householders by lowering energy bills, increasing a property's value or acting as a selling point when advertising properties for rent. Studies in Wales [82] and the US [83] found that HPs retrofitted into older homes increased price between 4 % and 7 %. Several householders we interviewed were supportive of proposals for more transparent information on heat pumps when buying and renting properties. Building passports can also support future policies. For instance, energy companies and government agencies could use these to assess whether a home is eligible for a cheaper HP tariff (section 4.2.1). They could also be used in tandem with Energy Performance Certificates (EPC) – the use of which is required when selling or renting properties in the UK - as a regulatory compliance tool if future legislation comes in mandating that homes are a certain EPC rating or need to have a HP (or shared-loop GSHP system) installed before a home can be sold or rented by a landlord [84].

Lastly, six practitioners suggested that rebates on property sales tax and local taxes could be used to incentivise share-loop GSHP systems. Similar proposals have been discussed for energy efficiency measures in general [56], and would need to be implemented fairly to ensure that those who cannot afford to make the change are not penalised.

4.3. Technical and practical considerations

4.3.1. Dwelling disruption

One benefit of GSHPs, compared with ASHPs, is that no external unit is required. Space requirements and local noise pollution can present barriers to ASHP deployment in urban areas, or in high-rise apartment buildings. Shared loop GSHPs avoid both issues, and boreholes can be

covered with grass or soil.

Nonetheless, the installation of shared-loop GSHPs inevitably involves disruption to dwellings, from drilling to installation and plumbing works. Seven practitioners cited this barrier, and four further mentioned the indoor space requirement needed for a HWT was a concern given that many tanks were removed alongside the widespread uptake of combination boilers in the UK. This is a challenge for any HP technologies, not just shared-loop GSHP systems. However, government research has estimated that 11 million homes (40 %) retain adequate space for a HWT [85]. Uncertainty, however, remains in what this space is now being used for and whether it could be easily converted back for HWT storage. Further concerns included the need for larger or additional radiators and insulation needed in some thermally inefficient properties.

One solution being explored is to couple GSHPs with heat batteries and phase-change materials so less internal space is required.

“In houses where space is a premium...phase change materials and heat batteries will help, but it's still going to be bigger than your gas boiler.” (P02).

At the start of the ESO project, concerns were raised when roughly a third of tenants said they did not want the new system. However, through sensitive and persistent communications, installers were able to enrol *all* householders in the targeted properties, and when interviewed 6–12 months after installation, tenants had few complaints about the external drilling or internal installation works.

“They were all done within two days. The electricals in one day. They did a great job.” (B09).

“They were polite, courteous, hard-working and safety conscious.” (D01).

This is a surprising finding, given policymakers' fear of implementing any measure that will heavily disrupt consumers and require invasive interventions [71].

4.3.2. Lack of trained and qualified professionals

In the UK, a lack of trained and qualified designers, installers, drillers and suppliers of shared-looped GSHP systems is currently a major barrier to deployment. This skills gap was identified by eight practitioners, including a senior civil servant and trade body leader:

“The training of the installers, we've seen that as well. It's a big problem - there is a severe lack of them. Also how you police the quality of the installs...that's also a problem.” (P12).

“There is currently a limited number of designers who are capable of doing these designs properly. So that's a challenge. I've seen some really bad designs for shared arrays as a result, lots of people insist you need central pumping on and things like that...which you don't.” (P07).

Training provision is needed, including conversion courses for some of the 130,000 existing gas engineers who will need re-skilling so they are not excluded from the clean-heat transition [11]. The UK government has recently made available a grant for specialist HP training providers [86], but there is a need for a national training and testing centre, similar to those demonstrated in Switzerland and Sweden [87].

4.4. Public attitudes and social acceptance

4.4.1. Upfront costs

Concern over upfront costs was a consistent finding from interviews with practitioners and householders. While householders favoured environmentally-friendly heating systems, cost was the principal

barrier. This is similar to the retrofit findings of Gram-Hanssen [88] who found monetary savings are normally the primary motivator over the environment, and more broadly, the endowment effect [89], which posits that if a new system costs the same, people are more hesitant to change.

“I care a lot about the environment but if it's going to cost me a fortune I just simply won't be able to afford it. So day to day running costs have to be cheaper for me to consider it.” (M10).

However, our sample of householders indicated that they would be willing to pay more for a shared-loop GSHP than a gas boiler if they knew the system would last longer and cost less to run.

“If this new system lasts twice as long, I would be more inclined to pay a bit more...probably about £2000 more.” (F02).

For those who had recently joined a shared-loop GSHP scheme, lower running costs and a warmer, more comfortable home were also key drivers to high levels of end-user satisfaction ($n = 14$). Beyond installing efficient systems, reducing running costs for shared-loop GSHPs, can be achieved through the rebalancing of electricity levies or capitalising on flexible TOU tariffs (section 4.2.1).

4.4.2. Awareness, trust, and standards

Awareness of the technology is currently low amongst politicians, local authorities and the public in general. This issue was raised by seven practitioners and was evident in householder interviews. Overcoming this barrier requires information campaigns, home visits and social media marketing to raise awareness of the benefits of the technology, and to counter myths and negative discourse which can circulate in both conventional and social media [71].

In raising awareness, many householders expressed the desire to see evidence of effective shared-loop systems installed elsewhere, and to hear testimonies of neighbours, friends of family members. This aligns with Heiskanen et al. [90] and Berry et al. [91] who found effective learning resulted from seeing new technologies installed by neighbours via ‘open homes’ events in Finland, Australia and the UK. This highlights the need for community-based social marketing and interpersonal relationships in building trust in new energy systems [92]. The public also trusted a shared-loop GSHP scheme more if it was backed by a local authority or the government rather than an energy provider:

“I'd want it to be a public local authority running it. I just don't trust power companies not to try and rip me off. They need to be accountable and it be run not for profit.” (M04).

The need for trusted and reliable installers was also highlighted by householders, confirming the need for targeted skills-based policies (discussed in section 4.3.2).

4.4.3. User experience and controls

Social housing tenants receiving GSHPs were overwhelmingly satisfied with their new heating and hot water systems, especially compared with their previous direct-electric storage heaters (Fig. 2).

Tenants reported lower running costs and increased comfort. Whereas before installation, 72 % tenants *strongly agreed* with the statement ‘my heating system is expensive to run’, only one tenant (4 %) said this when referring to their GSHP. Prior to receiving GSHPs, a majority of tenants relied on plug-in heaters (57 %) and heavy clothes and blankets (73 %) to keep warm. After installation, these figures reduced to 8 % and 25 % respectively.

However, interviews and in-home observations revealed some confusion around HP controls, and including a reluctance to adjust heating schedules to accommodate lower flow temperatures, or avoid peak pricing. Although tenants received clear information (and were generally satisfied with installation and commissioning processes), the

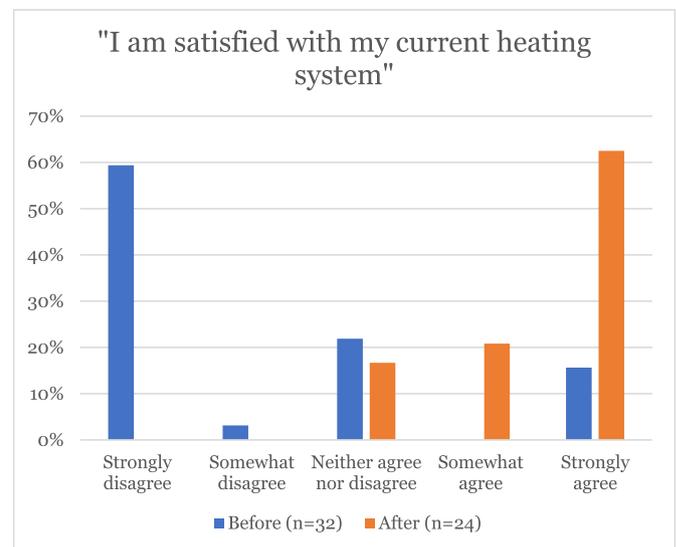


Fig. 2. Survey responses from social housing tenants before and after installation of shared-loop GSHP systems.

new suggested routines went against their instinct for ‘on/off’ control behaviours.

“Well, obviously I try to turn down the heating at night, but it's just constant...I can't see the point of that.” (B01).

To ensure users are competent with controls, it is recommended developers and installers are required to provide clear system information including hard copies, face-to-face demonstrations on commission, and clear routes for accessing further assistance.

4.5. Summary of key findings

Some of the findings about barriers to adoption and public concerns apply to any heat pump system, and are not specific to shared-loop GSHP. These include practitioners' uncertainty about the government's decarbonisation of heat strategy (4.1.1), the relative cost of gas and electricity (4.2.1), the high upfront cost of HP (4.4.1), householder desire to see evidence of systems installed elsewhere and to hear trusted testimonies (4.4.2), lack of trust in installers and inadequate training (4.4.2), need for appropriate controls and support in adapting to a new way of heating (4.4.3), disruption of installation and internal dwelling space needed, particularly for hot water storage (4.3.1). Potential ways to overcome these challenges have already been set out in detail in the paper, and are not repeated here.

Important additional barriers to adoption of shared-loop GSHP relate to the planning, installation, ownership and connection to shared-loop infrastructure (4.1.2, 4.1.3), building confidence in this new system (4.1.4), lack of policy at the meso-scale (4.2.2), and the need for specific training and skills for these systems (4.3.2). The solutions suggested, based on practitioner interviews, householder perspectives and learning from the literature, range from detailed proposals around making installation of heat networks easier, to higher level calls for attention to be paid, and policy developed for, the meso-scale contribution to the net zero transition. Local Authorities are identified as a key enabler of successful shared-loop GSHP project, with roles as planners, regulators, coordinators, investors and trusted information brokers. Some of the debates about whether and how households are required to connect to GSHP infrastructure, business models, and which areas would be best suited to this form of heat provision, can be informed by experience from earlier generations of DHNs and current exploration of fifth generation DHNs. The number of barriers which are unique to shared-loop GSHP (as

opposed to any HP or low-temperature DHN) is relatively small - but this does not necessarily mean they are unimportant.

While this paper has largely focused on barriers, it is important to remember that shared-loop GSHPs have several advantages over other low-carbon options. For example, they are cheaper to run than ASHPs and do not require external units, a particular advantage in dense urban areas or apartment blocks where space is limited, or where there are aesthetic concerns. In terms of performance, the evidence showed that the Oxford tenants who experienced this system were generally very satisfied with it.

4.6. Limitations

This study is investigating a heating system which is currently installed in a very small number of homes in the UK: few householders have experience of living with shared-loop GSHP, most people are unfamiliar with this technology and the practitioner community is modest in size. While the research design has sought to overcome these limitations, for a new, emerging system where many technical, economic, business model and governance questions remain, findings are necessarily tentative. Investigating prevailing public attitudes to an unfamiliar heating system is inherently challenging, as for any other emerging technology, system or service. To overcome this, participants without experience of shared-loop GSHP were shown material about the system prior to being asked their views, but this time-intensive method limited the number of households engaged.

This research has primarily focused on shared-loop GSHP systems themselves. It does not provide detailed comparison with alternative low-carbon heating systems - whether individual GSHPs, ASHPs, hydrogen or biomass.

4.7. Future research

This research builds on an emerging but limited literature surrounding novel shared-loop GSHP systems [15,23,25]. There is a need for further research, including field demonstrations in diverse building and occupancy types; lifecycle cost analysis of shared-loop GSHP schemes versus other heat decarbonisation options; threshold conditions for investment, and policy trials and evaluation. At this stage, a representative survey of public opinion on these systems would be premature, but more exploratory, qualitative research should be undertaken, particularly with those living in homes most suitable for shared-loop GSHP, i.e. blocks of flats and dense urban neighbourhoods with little outdoor space.

5. Conclusions

Shared-loop GSHP systems have the potential to accelerate heat decarbonisation in the UK and elsewhere. By sharing ground loop arrays and installing infrastructure on a 'street-by-street' basis, upfront costs should be reduced through economies of scale compared to traditional GSHP systems. They are more efficient than ASHP systems, and therefore put less strain on the grid, especially during winter cold-snaps. Despite these advantages, various political, financial, social and technical barriers inhibit deployment. These have been discussed through an in-depth qualitative thematic analysis of 58 interviews with policymakers, industry stakeholders, and householders with and without GSHP installations. Interviews with expert practitioners explored a range of potential policy, governance, regulation and financial support mechanisms.

Despite the publication of strategies and national target-setting, heat decarbonisation policy in the UK remains uncertain. There is a need for clarification on the use of hydrogen for domestic heating, and a clear plan for the phase out of fossil fuel boilers. Greater use of Local Area Energy Planning could help identify areas or streets suitable for shared-loop GSHP technology (where preferable to ASHPs or DHNs), which

could also encourage investment. More boldly, policy could mandate connections to shared loop systems once installed, giving certainty to developers.

This research has highlighted the pivotal role for local authorities in encouraging and enabling shared-loop GSHP deployment. They are (largely) seen as trusted intermediaries by local communities, and are ideally placed to coordinate industry stakeholders, lead on LAEP, and many have already committed to ambitious climate targets. Councils can also implement projects themselves by leveraging funding via the National Infrastructure Bank; choose to fast-track developer permissions to install necessary groundworks; and provide advice, support and encouragement to deploy schemes amongst its residents and housing developers. However, UK local authorities are hampered by under-funding, and capacities are variable. In return for funding and resources, statutory requirements could be imposed on local authorities and local distribution networks to ensure shared-loop GSHP targets and carbon budgets are achieved.

Given the high upfront cost of shared-loop GSHP systems, innovative financial support mechanisms are essential to enable deployment until the market matures to cost parity. Special HP electricity tariffs could be implemented at a hyper-local level to help overcome the 'artificially' high electricity-to-gas price differentials barrier mentioned by a majority of practitioner interviewees. Other popular financial support mechanisms included subsidies and grants for groundworks and installation, carbon taxes, tax rebates and long-term loans which are attached to buildings and supported by 'passports'.

There is a need to raise awareness of the benefits of shared-loop GSHPs (and HPs more generally), to increase social acceptability of the technology. Regulated installation and commissioning processes and follow-on support are also essential in ensuring end-users can use new controls effectively, including capitalising on TOU tariffs. Together, these recommendations should build trust, awareness and confidence in the new technology, encouraging other installations naturally through the word-of-mouth of family and friends.

There is a need to address skills shortages which also hinder deployment. A government-backed HP training and testing centre is recommended to help fill a severe knowledge and skills gap within the sector, supported by relevant qualifications, standards and company accreditations. Grants could help re-skill thousands of trusted fossil-fuelled boiler engineers to install new shared-loop GSHPs could work in tandem with support for manufacturers investing in this new technology. Combined, this would help expand the small unestablished market barrier and limit monopoly risks that worried several practitioner and household participants.

Finally, a surprising finding from this study was the disparity between practitioners and the public surrounding disruption. Most practitioners considered this a major barrier to mass deployment, however, most householders (with and without HPs) accepted disruption like any other essential infrastructure works. The development of heat batteries and phase-change materials within shared-loop GSHP systems may help address the issue of limited dwelling space.

Although this study has focused on the UK, the analysis, discussion and associated recommendations are applicable to other countries with extensive incumbent natural gas infrastructures, liberalised energy markets and decarbonisation commitments. This research fills a key research gap by identifying a variety of socioeconomic, political and technical barriers, and by discussing policy, governance, regulation and financial support mechanism which may help overcome these. Implementation of the technology can support national priorities including reduced local air pollution and fuel poverty levels as well as increased national energy security (by being less dependent on volatile foreign gas imports). Accelerated deployment of shared-loop GSHP technology could therefore have a significant net-positive impact on the UKs energy security and climate goals.

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CRedit authorship contribution statement

Christopher Brown: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sam Hampton:** Writing – review & editing, Writing – original draft, Supervision, Project

administration, Methodology, Data curation. **Tina Fawcett:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Appendix A. Interview guides

A.1. Interview guide for practitioners

General questions / Warm-up

1. What is your role and background in relation to ground source heat pumps? How long have you worked in the industry?
2. What are your general thoughts and opinions on shared-loop GSHPs?
3. Do you think a 'split ownership' model would work? Why / why not?
4. What other business models do you think could work? Subscription models, Heat as a Service etc.

Policy barriers / Changes

5. In your opinion, what do you think are the main policy barriers in successfully implementing shared-loop GSHPs? Or planning barriers? Or building regulation barriers?
6. What policy changes would you recommend to overcome these? At national level? At local authority level?

Financial barriers / Changes

7. In your opinion, what are the main financial barriers to successfully implementing shared-loop GSHPs?
8. What financial incentives, mechanisms or support packages would you suggest to overcome these?

Social barriers / Changes

9. In your opinion, what are the main public acceptance barriers or issues to successful implementation?
10. What would you suggest to overcome these?

Technical barriers / Changes

11. In your opinion, what are the main technical challenges to successful implementation? Or practical barriers?
12. What would you suggest to overcome these?

Final questions / Close

13. Who should have overall responsibility (Governance, coordination and delivery) or shared-loop GSHPs? Why? (Government, local authorities, utility companies etc.)
14. What is needed to help support them deliver this?
15. Who should own and maintain the shared ground loop array?
16. Is there anything else you would like to add, or do you have any final comments?

A.2. Interview Guide: Public with shared-loop GSHPs installed

Using your heating system

1. How do you use your system? Switcher unit, TRVs. Have you set a schedule? What times does it come on?
2. Please could you describe your heating and hot water system to me?
3. Where does the heat come from?
4. Had you heard of heat pumps before this installation?
5. How does your use of the heating and hot water system fit in with your routines?
6. What are the most significant changes from the previous system?
7. Has COVID-19 led to any changes in your usage of your heating and hot water system?
8. How does your new system compare with your previous one?

9. What do you like about using the system?
10. What frustrates you about using the system?
11. Do you feel as though you are 'used to' your new system?
12. Is there anything you would change about the system?
13. Have you noticed any difference in your energy bills since you had the new system installed?

Installation

14. Before installation, were you reluctant or enthusiastic about having a new system installed?
15. What were your experiences of the installation process?
16. What do you think are the main reasons the housing association decided to change your heating system? (has anybody mentioned the environmental benefits?)
17. Do you have any feedback for the organisation who installed your new system?

Future

18. You haven't yet been through a whole winter with the new heating and hot water system. How are you thinking about that prospect?
 - a. Do you have concerns about its ability to keep you warm?
 - b. Do you have concerns over the running costs?
19. Have you received any information about switching your energy supplier?
 - a. (If so) could you explain what the alternative would be and how it works?
 - b. Are you considering moving to Octopus, the recommended supplier?

Community interactions

20. Have you spoken to anybody about your new heating and hot water system (neighbours, family, friends)? What sort of things have you discussed?
21. Would you say you were part of a community? If so, how would you describe that? (local neighbourhood, online, sports, even a local pub).
22. Who would you ask for if you needed help with your energy bill, or energy system?

Climate change

23. On a scale of 1 to 10, how concerned are you about climate change? Have you ever spoken to anybody about it? (if so, who with, and what did you talk about?)
 - a. why are you concerned? (prompts about impacts on self / children / grandchildren / vulnerable communities / natural world...)
 - b. Carbon emissions come from the things we do, like using energy, travel, food, the things we buy. In order to cut down on your own carbon footprint, how willing would you be to: (depending on answers above, ask them to explain their answers)
 - i. Change transport habits
 - ii. Change diet
 - iii. Change use of energy in the home
 - iv. Buy fewer, or more sustainable products

A.3. Interview Guide: Public without shared-loop GSHPs installed

Explain the concept of how a heat pump works and how a shared-loop GSHP works using the following videos:

<https://www.youtube.com/watch?v=ejuM7SjQEyE>

https://www.youtube.com/watch?v=PL_90zDOW7o

1. What are your thoughts and opinions on shared-loop ground source heat pumps?
2. What would encourage you to have a heat pump installed as part shared-loop GSHP scheme?
3. What would discourage you or prevent you from joining a shared-loop GSHP scheme?
4. Do you think a 'split ownership' model would work?

(Where you (the householder) purchases the heat pump and connects to network once your boiler needs replacing – you would then have full ownership and control over the heat pump i.e. independent billing, can change electricity provider, pay only for the electricity you use for heating and hot water...)

...but have to pay an annual connection fee to use the shared ground loop (this connection fee will help a separate utility entity recuperate the initial upfront costs to install and maintain the shared ground loop).

Why / why not?

5. What other financial arrangements would work for you?
6. How much would you be willing to pay to replace your boiler with a heat pump? The same? Slightly more? Slightly less? – why?
7. Would you need any financial help to fund a heat pump? What funds would you use?
8. Would you be willing to collaborate with neighbours across your street to let a utility / local Council know the street is interested in getting a shared-loop GSHP installed?
9. How much disruption would you be willing to put up with? With the installation of the heat pump in your home? And the installation of the shared ground loop array outside your home?
10. Who would you trust to install and own the shared ground loop array? (Utility company, local authority, other? – why?)
11. Is there anything else you would like to add, or do you have any final comments?

Appendix B. Details of participants

Table B1

Practitioners interviewed and their associated position and role description (Group 1).

Code	Position	Organisation	Organisation / role description
P01	Chief Executive Officer (CEO)	Heat pump manufacturer and supplier	Specialists in the design, manufacture and installation of ground source heat pumps and the ownership of associated underground infrastructure.
P02	Managing Director	Heat pump manufacturer and supplier	Programme manages ground source heat pump projects with shared ground loop arrays.
P03	Senior Associate	Regulatory Assistance Project (RAP)	Independent, global Non-Governmental Organisation (NGO) advancing policy innovation and thought leadership within the energy community. Based in the European team supporting national and EU level heat decarbonisation policy and goals for carbon reduction, renewable energy deployment and consumer protection.
P04	Research Associate	University of Leeds	University researcher in heat decarbonisation policy, drawing together the latest research and insights on energy storage in shallow geothermal energy systems.
P05	Senior Project Manager	Regen	Not-for-profit centre of energy expertise and market insight whose mission is to transform the world's energy systems for a zero-carbon future.
P06	Senior Manager	North-West Net Zero Hub (and Energy Manager for a Local Authority)	Supporting communities to install and own renewable energy projects.
P07	Chief Technical Officer (CTO) and Chairman	Ground Source Heat Pump Consultancy	Experts in ground source heat pump system designs and installations.
P08	Senior Manager	Heat Pump Federation	Lobbies government for long term policy supporting the electrification of heating and cooling.
P09	Senior Manager	Ground Source Heat Pump Association	Supports the implementation of ground source heat pump systems across the UK.
P10	Director of Net Zero	Housing Association	One of the largest housing associations in the North of England providing around 36,000 homes to rent. They also build and manage homes for sale through the Shared Ownership scheme as well as provide retirement living and Housing with Care.
P11	Assistant Director Environment & Sustainability	Housing Provider	Social housing provider managing around 34,500 homes in England for over 76,000 customers, including affordable properties for general rent, shared ownership and sale.
P12	Senior Manager	Department for Business, Energy and Industrial Strategy (BEIS)	Responsible for coordinating the UK Government's £2.5 billion energy innovation portfolio, including the Heat Pump Ready Programme.
P13	Senior Policy Advisor	Department for Business, Energy and Industrial Strategy (BEIS)	Electrification of heat policy lead, responsible for leading government's work to remove barriers to the deployment of 600,000 heat pumps a year by 2028.
P14	Head of Environment & Climate Emergency	Local Authority (County Council)	Leads a large multi-disciplined team with responsibility for renewable energy, energy management, affordable warmth, corporate sustainability and sustainable transport.
P15	Sustainability & Climate Change Manager	Local Authority (London Borough Council)	Responsible for renewable energy, energy management and heat decarbonisation across the Borough.
P16	Principal Energy Officer	Local Authority (County Council)	Responsible for delivering renewable energy and heat management projects in Council owned domestic and non-domestic buildings.
P17	Senior Analyst	Climate Change Committee	Senior analyst for heat decarbonisation in the buildings team.
P18	Senior Policy Advisor	Nesta	Senior Advisor in the Energy & Sustainability Team, designing and implementing interventions in energy and sustainability projects across government, industry, and non-governmental organisations.
P19	Senior Manager	National House Building Council (NHBC)	Raising the construction standards of new homes in the United Kingdom and providing consumer protection for homebuyers through its 10-year Buildmark warranty.

Table B2

Participants with shared-loop GSHP systems installed (Group 2).

Code	Number of people in home	Gender	Ownership status	Type of home	Existing heating system
B01	1	Male	Social housing tenant	Apartment	Electric storage heater
B03	1	Male	Social housing tenant	Apartment	Electric storage heater
B04	1	Male	Social housing tenant	Apartment	Electric storage heater
B05	2	Female, Male	Social housing tenant	Apartment	Electric storage heater
B07	1	Male	Social housing tenant	Apartment	Electric storage heater
B08	1	Male	Social housing tenant	Apartment	Electric storage heater
B09	1	Male	Social housing tenant	Apartment	Electric storage heater
B10	1	Female	Social housing tenant	Apartment	Electric storage heater
B12	1	Female	Social housing tenant	Apartment	Electric storage heater
B15	1	Male	Social housing tenant	Apartment	Electric storage heater
B18	1	Male	Social housing tenant	Apartment	Electric storage heater
C01	1	Male	Social housing tenant	Apartment	Electric storage heater
C05	1	Male	Social housing tenant	Apartment	Electric storage heater
D01	1	Male	Social housing tenant	Apartment	Electric storage heater
D03	1	Male	Social housing tenant	Apartment	Electric storage heater
D04	1	Female	Social housing tenant	Apartment	Electric storage heater
D05	1	Male	Social housing tenant	Apartment	Electric storage heater
D06	1	Male	Social housing tenant	Apartment	Electric storage heater

Table B3
Participants without shared-loop GSHP systems installed (Group 3).

Code	Number of people in home	Gender	Ownership status	Type of home	Existing heating system
F01	1	Female	Rented	Semi-detached	Gas
M01, F02	2	Male, Female	Home Owners	Detached	Gas
M02, F03	2	Male, Female	Home Owners	Semi-detached	Gas
M03, F04	2	Male, Female	Home Owners	Terraced	Gas
M04	1	Male	Rented	Terraced	Gas
M05, M06	2	2× Male	Home Owners	Detached	Gas
M07, F05	2	Male, Female	Home Owners	Detached	Gas
F06, F07	2	2× Female	Rented	Semi-detached	Gas
M08, F08	2	Male, Female	Home Owners	Terraced	Gas
F09, F10, M09, M10, M11, M12	6	2 x Female, 4× Male	Rented	Terraced	Gas

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