Unlocking the potential for thermal energy storage in the UK

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The candidate confirms that the work submitted is his/her/their own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

Rapid and deep energy system decarbonisation is essential to a safe future. Thermal energy storage may hold the key to significant carbon reduction of the heating, cooling and electricity sectors, but the UK remains largely locked in to a fossil-fuel based heating regime. Global urbanisation trends mean cities are crucial to the net-zero transition. This thesis provides a sociotechnical analysis of current and future thermal storage deployment, recognising that fundamental change is complex and involves individuals and companies, supply chains, infrastructures, markets, policy and regulation, norms and traditions. I explore this through the overarching research question: How can cities unlock the potential for thermal energy storage to support the UK's net-zero transition?

The work is presented through three empirical chapters. A pilot study used a survey, thematic analysis, and pre-existing sociotechnical frameworks to explore the current state of UK thermal storage deployment and how sociotechnical characteristics are shaping current and future deployment prospects. A case study of a particular storage approach known as geoexchange analyses the results of interviews with geoexchange practitioners using sociotechnical frameworks, and proposes a new critical success factors framework. Finally, a comparative case study of two UK cities explores the specific role of local authorities to use powers at their disposal within a common planning framework to support the deployment of urban shared ground heat exchange in residential and mixed-use developments. Based on this study, a framework for local policy, support and enforcement activities is proposed.

Applied contributions are provided through new knowledge on sociotechnical factors shaping the prospects for TES to support the net-zero transition, the first sociotechnical analysis of UK geoexchange deployment, and policy and practice proposals to support city-based shared ground heat exchange. Theory is advanced through application, testing and development of several existing frameworks for understanding sociotechnical change. Based on empirical evidence, two novel frameworks are proposed to support deployment of geoexchange and shared ground heat exchange.

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List of acronyms and abbreviations

100% RES	100% Renewable Energy Systems
4GDH	Fourth generation district heating
5GDHC	Fifth generation district heating and cooling
ASHP	Air source heat pump
BEIS	Department of Business, Energy & Industrial Strategy
CCS	Carbon capture and storage
CCUS	Carbon capture, use and storage
CHP	Combined heat and power
CCHP	Combined cooling, heat and power
CHP-DH	Combined heat and power district heating
CoP	Coefficient of Performance
CSP	Concentrated solar power
DSR	Demand-side response
EfW	Energy from waste
EIBM	Extended Infrastructure Business Model
ESCo	Energy Services Company
GHG	Greenhouse gas
GSHP	Ground source heat pump
HNDU	Heat networks delivery unit
kWh	Kilowatt-hour
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LEP	Local enterprise partnership
LCITP	Low Carbon Infrastructure Transition Programme
NPPF	National Planning Policy Framework
MLP	Multi-level perspective
PCM	Phase-change materials
RHI	Renewable Heat Incentive
SGHE	Shared ground heat exchange
TES	Thermal Energy Storage
TIC	Techno-institutional complex

1 Introduction

In this thesis I explore the role of thermal energy storage (TES) in supporting the transition to decarbonised urban energy systems. The study builds on existing frameworks within sociotechnical transitions by exploring the current deployment of TES in the UK and considering sociotechnical factors shaping future prospects. I examine critical success factors for ground-based TES technology and explore how local authorities can create the conditions for low carbon heat deployment.

This chapter sets out the context and motivations for conducting this research, and is structured as follows. In section 1.1, the urgency of global decarbonisation, the importance of heating and cooling, and the potential role of TES in achieving that are established. In section 1.2-1.4 I outline the international and UK context as well as the justification for focusing on cities as key sites for the net-zero carbon transition. I introduce the research aims and focus in section 1.5 and set out the structure of the thesis and focus of the empirical chapters.

1.1 Context and rationale

The scientific consensus is clear that human-induced climate change is already affecting every region of the globe, and the heating trend will overshoot 2°C during this century unless the curve of greenhouse gas (GHG) emissions is bent sharply downwards (Masson-Delmotte et al., 2021). Climate change threatens the food security, water supply, personal safety, health, and livelihoods of humanity, with the most vulnerable and least responsible likely to suffer most (IPCC, 2018; Kartha et al., 2020). Radical and system-wide change is required to transition to a post-carbon society in the shortest possible timeframe, although there is little to suggest sufficient progress is being made (Keyßer and Lenzen, 2021; Lamb et al., 2021)

The drive to bring down GHG emissions first requires an understanding of what human activities are responsible for causing it. The exercise to understand the drivers of climate change is value-laden, because whether this is considered on a sectoral, historical, per capita, consumption, wealth or income basis determines where the greatest burden of responsibility lies for tackling the problem. On a simple sectoral basis, buildings are responsible for around 30% of global energy-related GHG emissions, with space and water heating accounting for over half of global energy use in homes (Lucon et al., 2014; Ürge-Vorsatz et al., 2015). In the coming decades, a hotter climate is likely to dramatically increase the demand for cooling (IEA, 2018; REN21, 2017).

The transition to low carbon heating and cooling is particularly challenging. Unlike in the electricity system where generation is largely distant from end users, heating infrastructure is distributed and change requires direct intervention in countless homes and businesses (Knobloch et al., 2019). Moreover, the experience of warmth and comfort is personal and is tied to feelings of security and family life in ways which electricity is not (Luo et al., 2018; Tweed et al., 2015).

The transition to sustainable energy will require much greater levels of intermittent electricity generation in addition to decarbonisation of heat (Bettencourt et al., 2013; Braff et al., 2016; Jacobson, 2009; REN21, 2019, p. 21). TES can help balance the electricity grid by making use of intermittent renewable electricity to supply heating and cooling when needed by coupling with other technologies such as heat pumps (Arteconi et al., 2013; Fernandes et al., 2012; Heier et al., 2015; Lund, 2018). One of the advantages of heat pump / TES combinations is that they tie heating together with the electricity grid; therefore, as the grid decarbonises, so will the carbon intensity of heat provision. Furthermore, instead of acting merely as an additional load and strain on the grid, incorporating TES into electrified heating through heat pumps can support greater levels of intermittent renewables and further decarbonisation, whilst reducing the need for costly electricity grid reinforcements (IRENA, 2020). Despite the potential benefits it can deliver, practitioner and research consideration of TES has received less attention than electrical energy storage and the role of the electrical power system in isolation (Kittner et al., 2017; Mathiesen et al., 2015a; McKinsey Global Institute, 2013; Taylor et al., 2013).

Because of the wide range of potential storage types, configurations and characteristics of TES, for the purpose of this thesis I define thermal energy storage as: **any technology which prevents the loss of thermal energy by storing excess heat or cold until it can be consumed**.

Storage is typically classified into three types: *sensible*, *latent,* and *chemical*. Sensible heat TES materials store energy in the specific heat capacity of a material, which does not change during the charge and discharge cycle. Sensible heat storage includes water in tanks, ceramic bricks in electric night storage heaters as well as rock, sand and gravel for earth storage through boreholes. Sensible heat storage is by far the most mature, ubiquitous, and lowest cost approach (Eames et al., 2014). Because of the temperature range and non-toxicity, water heat storage is seen as particularly suitable for domestic applications (Alva et al., 2018). Latent heat storage takes place when a material stores heat through a phase transition. This includes liquid to gas transfer as well as molten salts often used in conjunction with concentrated solar power (CSP) plants as well as phase-change materials (PCMs) in a variety of configurations. Whilst some PCM technologies have reached commercialisation, they have yet to achieve a significant market impact (Alva et al., 2018; Eames et al., 2014; Fernandes et al., 2012). Finally, thermochemical storage involves the use of reversible chemical reactions. This approach features potentially very high storage density by volume and can store heat for long durations without significant heat losses, but is yet to develop beyond the laboratory stage (Fernandes et al., 2012). TES can be distributed within the properties of end users, such as in the case of domestic hot water tanks, or it can be centralised within district or communal heat network configurations (Eames et al., 2014). Likewise thermal storage can provide heating or cooling directly to the user, such as with electric night storage heaters where air is passed over high temperature ceramic bricks, or delivered to the end user through a transfer medium, typically water in a district or communal pipe network.

The work presented in empirical Chapters 5 and 6 focus on a type of thermal energy storage known as **geoexchange**[1]. In geoexchange systems the ground is used as both an energy source and storage medium which is actively recharged, often from the waste energy created through providing summer cooling (Sarbu and Sebarchievici, 2016). A simplified model of a geoexchange system is shown in Figure 1.1.

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[1] Geoexchange is known by various names including 'geothermal heat pumps', 'ground-coupled heat pumps', 'ground-coupled heat exchangers' (Self et al., 2013).

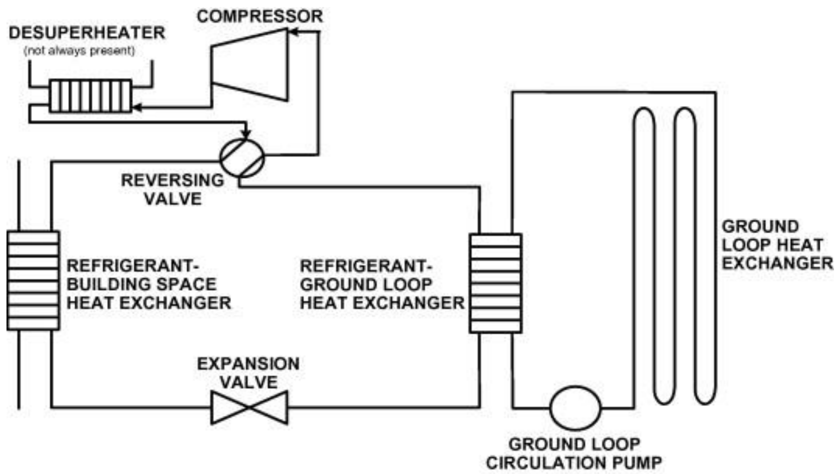


Figure 1.1 Basic layout of geoexchange heat pump system (Self et al., 2013)

Like other heat pump arrangements, geoexchange systems use electricity to drive compressors which capture heat energy from the environment and raise it to a useful temperature (Omer, 2008). However, unlike traditional ground source heat pump systems which use the ground only as an energy source, the capture and storage of waste energy in the geoexchange approach aims to prevent system decline and reduce the amount of additional energy required (Chua et al., 2010).

Geoexchange is well suited to use as part of ambient or fifth generation (5GDHC) heat network approach, which can combine multiple heat and cooling sources and consumers (Boesten et al., 2019). Whilst not requiring geoexchange specifically, large and long-term TES is seen as fundamental to 5GDHC (Revesz et al., 2020). In the remainder of the thesis the combination of geoexchange and low temperature heat network is identified as **shared ground heat exchange** (SGHE) and is the focus of empirical Chapter 6. Fig. 3 shows the evolution of district heating towards fifth generation, reflecting temperature decrease to below 45^{o}C, and efficiency increase to potentially well above 100%.

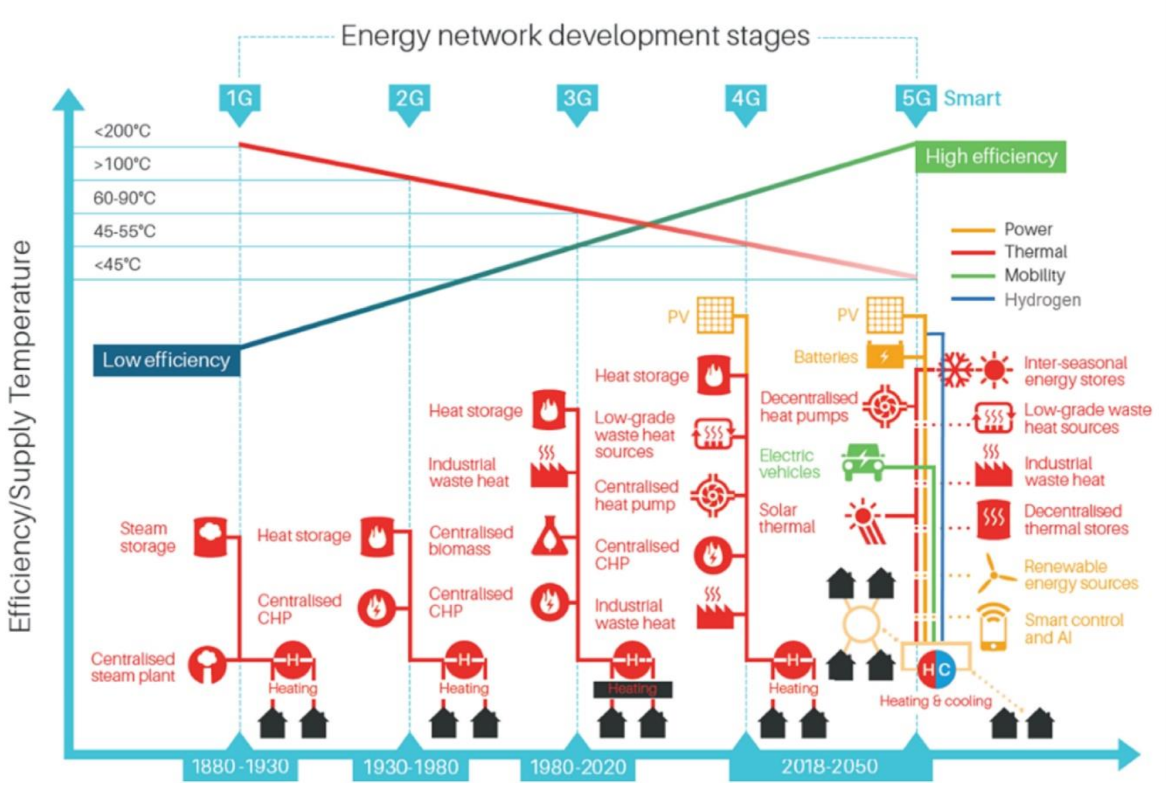


Figure 1.2. Evolution of energy networks over five generations. From Revesz et al (2020), adapted from Lund et al (2014a)

The concept identified as 5GDHC is new and contested (Schweiger et al., 2019). However, in the work which established the concept in around 2019, the consensus was that the latest set of advances marked a fundamental evolution, particularly in the bidirectional operation that marks out 5GDHC from any earlier generation of district heating, which operates on the principle of centralised heat generation supplying heat outwards to distributed users (Boesten et al., 2019; Buffa et al., 2019a; Bünning et al., 2018; Revesz et al., 2020; Wirtz et al., 2020). The key aspects of the 5GDHC concept are identified as:

- *Bidirectionality / non-linearity – heat energy is shared across the network and different substations can extract or supply heat simultaneously;*
- *Free-floating fluid temperature meaning pipes do not suffer high thermal losses or require insulation;*
- *Simultaneous provision of heating and cooling;*
- *Network topology of distributed heat pumps increase or decrease the temperature as needed for each separate building or use;*

- *Short-term and seasonal TES for bridging temporal gaps in supply of heat and cold, as well as availability of renewable electricity and heat pump operation.*
- *Can facilitate multiple types of heat and cold sources. Since the system is intrinsically modular new sources can be added as the system expands.*

1.2 International context

Many countries have made commitments to achieve net-zero emissions and are struggling with energy system decarbonisation, especially in transitioning to fossil-free heating, hot water and cooling (Collier, 2018; Eisentraut and Brown, 2014; IRENA et al., 2020; Knobloch et al., 2019). Progress against heat decarbonisation goals is highly variable, with the UK's European neighbours Sweden, Finland and Denmark having made significant gains, supported by an abundant biomass resource combined with incumbent municipal district heating networks (Collier, 2018; Gross and Hanna, 2019; Majuri, 2018). As well as the USA, Canada and South Korea, the UK is comparable to some other European countries with a temperate climate and extensive incumbent natural gas grids providing domestic heating, including Italy and especially The Netherlands (IRENA, 2020; Quarton and Samsatli, 2020; Schüppler et al., 2019). The chart shown in Figure 1.3 emphasises the lack of progress towards heat decarbonisation made by countries with a high dependency on natural gas. It is notable that the UK remains second only to The Netherlands in reliance on natural gas.

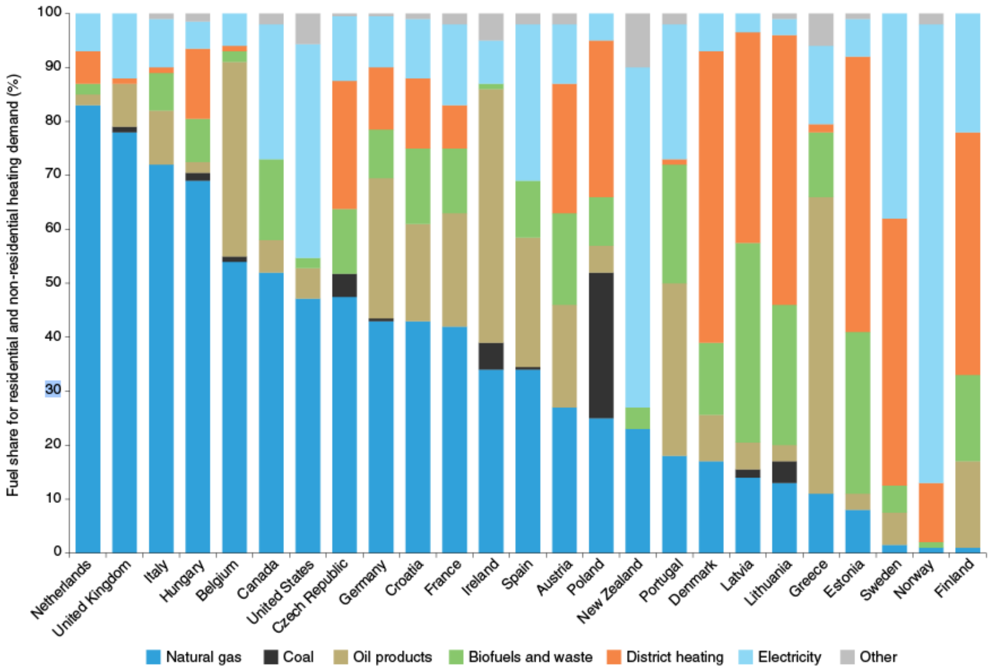


Figure 1.3 Fuel shares for residential and non-residential heating in selected countries. From Gross & Hanna (2019), adapted from Sahni et al (2017).

Little peer-reviewed research is available on the current global or UK deployment of different TES technologies. Much of the literature has focused on the use of TES in combination with concentrated solar power (CSP) plants rather than for local heat provision, or focused primarily on electricity storage such that little detail on thermal storage was included (Aneke and Wang, 2016; Gibb et al., 2018; Liu et al., 2016; Palacios et al., 2020; REN21, 2019, p. 21; Siegel, 2012).

From what research there is, TES deployment appears to be highly country and context dependent and is impacted by physical factors such as climate, geography and geology; determining both the heating and cooling requirements and the availability of natural resources, as well as historical and sociocultural trends which have shaped heat provision arrangements (Lowes et al., 2020; Navarro et al., 2016; Self et al., 2013). Sometimes this has resulted in more predictable outcomes, with Sweden, Germany and Denmark's ubiquitous district heating systems rather than gas grids also featuring most of the world's installed capacity of district heating-based TES (IRENA, 2020). In other contexts the links are more complex. Despite their extensive incumbent gas grids and reliance on gas for heating, the Netherlands has become a global leader in aquifer TES, and the US in ground thermal storage along with ice storage to mitigate summer peak cooling loads (Fleuchaus et al., 2018;

IRENA, 2020; Nordell et al., 2015; Sahni et al., 2017; Schüppler et al., 2019; Self et al., 2013; US Department of Energy, 2017).

Geoexchange is used widely in China, in some European countries, and in the US which is the world leader with over 600,000 installations (Self et al., 2013). The technology features strong annual growth of 10%, or 1.7m annual installations, with hotspots of current activity in some European countries such as France, the Netherlands, and Poland, as well as globally in China, Japan, Russia, Argentina and Iran. However, it remains a relatively novel technology in the UK especially for residential applications (Omer, 2008).

1.3 UK context

The United Kingdom serves as a useful example through which to examine this problem and is the primary focus of this study. The UK set a legally binding target to reduce greenhouse gas emissions by 80% from 1990 levels by 2050, amended to 100% by 2050 in 2019 (*The Climate Change Act 2008 (2050 Target Amendment) Order 2019*, 2019). On a territorial basis UK carbon emissions fell by 49% from 1990 to 2020, driven in part by climate policy which has delivered electricity sector decarbonisation through grid-scale renewable generation developments which are remote from consumers (CCC, 2018; HM Government, 2021a). Territorial emissions have also fallen relative to imported consumption emissions, suggesting the UK's apparent success in decarbonising is in part due to shifting patterns of global trade rather than targeted climate policy (Barrett et al., 2013; Ritchie, 2019). What is clear is that current progress on heat decarbonisation is woefully adrift of the trajectory needed to reach the UK's legally-binding carbon reduction target (CCC, 2020a).

Around 37% of UK carbon emissions come from heating and cooling, with 20% from the natural gas grid that serves the heating and hot water needs of 86% of UK homes, through individual gas boilers (Dodds and McDowall, 2013; Furtado, 2019; Goater and Squires, 2016; HM Government, 2018). Current non-fossil heat provision in the UK is very low, with 5% of the total heat demand met by low carbon sources (CCC, 2019; Rosenow et al., 2020a). This thesis focuses on residential settings and Figure 1.4 shows the current make-up of the UK's residential heat supply, with very high gas boiler penetration compared to all others.

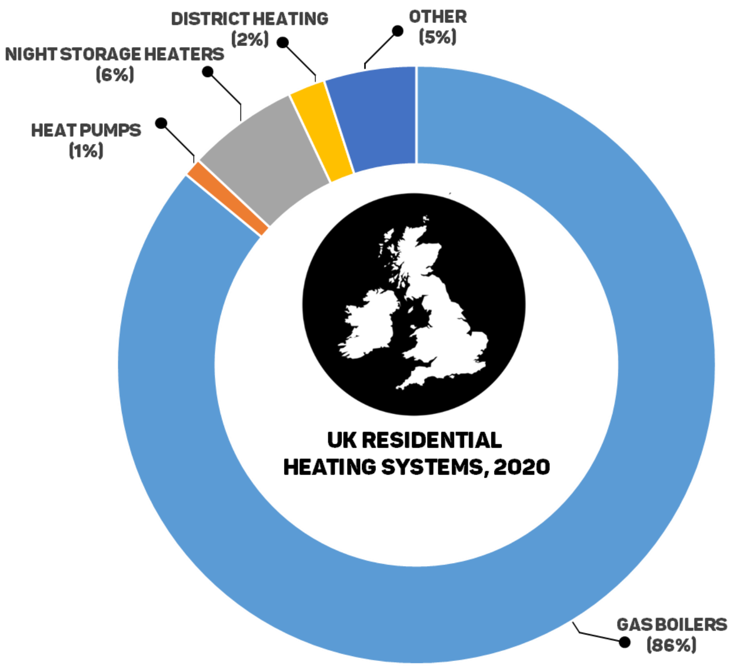


Figure 1.4 UK residential heating system usage by type, 2020. Data from Rosenow et al (2020a)

The UK government has committed to 600,000 heat pump installations per year by 2028, but current installations in the UK reflect the significant gap between the 36,000 heat pump installations and nearly 1.7m gas boilers annually (CCC, 2021; HM Government, 2020a; Rosenow et al., 2020a).

The UK's continued dependence on natural gas for heating is in part due to the extensive reach of the natural gas grid as well as the physical disruption needed to replace the distributed infrastructure and appliances (Eyre and Baruah, 2015). The UK is often considered a 'single-endowment' country with a fossil-based heating regime because of the share of heat met by the incumbent natural gas grid, initially from North Sea gas but latterly more reliant on imports (Collier, 2018). Gas boilers to provide home heating are seen as convenient and familiar, and the technology enjoys generally high levels of user satisfaction (Parkhill et al., 2013). In addition, central government has to date passed on the costs of decarbonisation to electricity bills but not to gas bills, resulting in the UK having one of the highest gas-to-electricity price differentials (CCC, 2016; Gross and Hanna, 2019; Ofgem, 2021a; Wolf et al., 2021).

In addition to these sociotechnical factors contributing to continued lock-in of natural gas, the UK is also beset by climactic geographical and historic features which complicate the transition away from fossil-based heating. Despite experiencing milder temperatures than other regions on the same latitude, with a temperate climate the UK experiences peaks in winter demand many times greater than summer lows (Krüger and Emmanuel, 2013; Watson et al., 2019; Wilson et al., 2013). This problem is exacerbated by relatively poor building efficiency standards, leading to the UK being dubbed 'the cold man of Europe' (Guertler et al., 2015). The natural gas supply system in the UK has so far managed to satisfy the significant fluctuations in heat demand through storage in depleted oil and gas fields, although the system was tested to its limit during the 'Beast from the East' cold snap in early 2018 (Evans and Chadwick, 2009; National Grid SO, 2018). One of the UK's largest gas storage facilities was recently closed however, and this is expected to lead to greater reliance on liquefied natural gas (LNG) imports (Devine and Russo, 2019; Thomas, 2017; Vaughan, 2017; Wilson et al., 2020).

1.4 The role of cities

Cities will play a crucial role in tackling climate change (OECD, 2010; UN, 2009). They are hotspots of greenhouse gas emissions but also demonstrate huge economies of scale in energy use and emissions (Jan et al., 2013). Globally, cities are already responsible for 75% of energy consumption (Grubler et al., 2012; Seto and Dhakal, 2014). With 3 million people moving to urban areas every week, global urbanisation trends mean that thermal storage applications which support decarbonisation in cities are particularly important (Allegrini et al., 2015; Grubler et al., 2012; IOM, 2015, 2015; Seto and Dhakal, 2014).

In the UK around 80% of the population lives in urban environments and they are responsible for 70% of the UK's GHG emissions (Sullivan et al., 2013). It is acknowledged there is no way for the UK to achieve its greenhouse gas reduction targets without addressing city-level carbon emissions (Dixon, 2012; Martin et al., 2014). Local authorities in the UK are expected by central government to contribute to carbon reduction commitments, but they are limited by the powers and funding they have at their disposal (Morris et al., 2017; O'Brien and Pike, 2019; Tingey and Webb, 2020).

For these reasons, the focus of this thesis is on the application of TES in urban settings. It is important that solutions are applicable to small and medium sized cities and towns as well as large conurbations and as such the research will consider applications of TES over a range of scales. In addition, given that most of the housing and infrastructure that will be in place in 2050 has already been built (Ofgem, 2016), it is important that solutions are applicable for retrofit applications as well as new developments.

1.5 Research aims and thesis structure

The overall aim of this research is to gain a greater understanding of the urban energy transition for heat. This is explored through a study of the role of TES in the development of zero carbon heating and cooling in UK cities.

As a technological solution to address the climate emergency, renewable heating and cooling solutions are available but they are not being used at scale. This suggests this issue is primarily an economic and social challenge, rather than a technological one. This thesis investigates how greater use of low carbon technologies can be enabled through an empirical investigation into the adoption of TES in UK cities.

This research project explores the complex set of issues presented above through a three-part study of the following overarching research question:

How can cities unlock the potential for thermal energy storage to support the UK's net-zero transition?

Beyond this introduction, Chapter 2 highlights relevant prior work in the field including some of the technical, economic, institutional, and regulatory aspects of TES deployment. The chapter then moves on to the theoretical basis for the sociotechnical approach taken in this research, including an exploration of relevant theories including the *multilevel perspective (MLP) of sociotechnical transitions* and the *coevolutionary framework* (Foxon, 2011; Geels, 2002). Other relevant frameworks to support closer study of specific elements are considered including the *extended infrastructure business model canvas* (EIBM) (Foxon et al., 2015) and the role of *intermediaries* in nurturing niche-innovations (Bush et al., 2017; Kivimaa, 2014). The *diffusion of innovations* (Rogers, 2003) framework is proposed to support a consideration of organisational decision making, and the role of local authorities in the energy transition is explored.

In Chapter 3, a review of the study methodology is provided. I take a tripartite approach, beginning with the philosophical and methodological foundations which guided the qualitative research endeavour. I then detail how the study was brought to life through a flexible research design. The majority of the chapter covers the specific research methods employed at each of the three research phases. This includes a survey of thermal energy storage schemes in the UK before application of a novel project classification matrix followed by analysis through several sociotechnical frameworks. A template analysis approach to a sociotechnical thematic analysis of semi structured interviews is undertaken in Chapter 5 as part of a case study of geoexchange technology. In the empirical work reported in Chapter 6, a comparative case study of two UK cities further applies and tests the sociotechnical frameworks to analyse a combined dataset of documents and interviews.

1.5.1 Focus of the empirical chapters

The thesis comprises three empirical chapters, with each covering one phase of the research. Chapter 4 presents the results of a study into sociotechnical factors shaping the prospects for TES in the UK. I undertook this pilot study to identify areas for deeper investigation in later work, and addressed this through the following research question:

> *RQ1. What is the current state of UK thermal storage deployment and how do sociotechnical characteristics shape deployment prospects?*

The chapter first presents the results and analysis for a series of sociotechnical aspects of TES deployment, drawing on pre-existing sociotechnical frameworks to conduct a series of crosstabulations against important technical and project-level characteristics. In the second part of the chapter, a discussion section assesses the significance of the findings in the context of the UK and internationally.

Chapter 5 presents the results of a study looking specifically at the case of geoexchange TES which remains a novel approach in the UK. This is undertaken to address the following research question:

> *RQ2. What are the factors that have led to successful geoexchange deployment in UK cities?*

Chapter 5 draws together results of a sociotechnical analysis using the MLP, coevolutionary and EIBM frameworks, and proposes a 'critical success factors' framework to support project developers and practitioners within organisations attempting to secure positive geoexchange investment decisions. In the following discussion I explore how the findings may shape the prospects for urban geoexchange deployment in the UK and what this means for the UK's heat transition.

The third and final research phase is outlined in Chapter 6, where the results of a comparative case study of two UK cities, Leeds and Bristol, is presented. A study of thirty residential developments across the two cities explores the role of municipal governance in empowering niche-innovation technologies such as shared ground heat exchange, from the perspective of urban local authorities. I address this through the following research question:

> *RQ3. Within the same legal and planning framework, what actions are local authorities taking to support or constrain the deployment of shared ground heat exchange, and what effect is this having?*

The results and subsequent discussion highlight how the alignment of careful policy design and enforcement, political commitment and supportive intermediary activities can make a meaningful difference to the course of a city's decarbonisation efforts and create the conditions necessary for niche technologies to break through.

The research provides both applied and theoretical contributions. In applied terms, the fundamental challenge of heat decarbonisation is addressed through: 1) new knowledge on important sociotechnical factors shaping TES deployment; 2) a novel framework to support geoexchange developers and other organisational actors seeking to deliver successful geoexchange projects; 3) a novel framework to support local authorities seeking SGHE deployment in place of fossil-based heating within the limitations of the national spatial planning framework. From a theoretical perspective, several sociotechnical frameworks are combined, adapted and applied to new technologies and new empirical data to examine the prospects for developing low carbon heat technologies.

2 Literature review

2.1 Introduction

In an effort to support the net-zero carbon transition, I consider how TES might displace conventional high carbon technologies such as individual gas boilers or fossil-based district heating. To do this I adopt the principles of the sociotechnical transitions literature, which recognises that technologies do not exist in isolation, but are part of wider systems incorporating individuals and firms, supply chains, infrastructures, markets and regulations, norms and traditions (Arthur, 1989a; Geels, 2002, 2010; Rip and Kemp, 1998).

In this chapter I review and evaluate the existing literature which helped identify a gap in knowledge and establish the basis for the empirical research questions and shaped the investigation set out in this thesis. I first review the existing research around thermal energy storage (TES) including the potential for the technology to support energy system decarbonisation and what is known about current deployment characteristics. Section 2.2 includes an examination of the prior work on city-based geoexchange and shared ground heat exchange (SGHE) configurations. In Section 2.3-2.7 I explore sociotechnical literature and frameworks which helped inform the research. I take a closer look at cities as sites of transition and how local authority policies and practices can support or constrain deployment, before concluding the chapter and summarising how the literature review led to the research gap this work intends to fulfil.

2.2 Thermal energy storage technology review

In this section I explore prior work on the role and benefits of TES in the energy system. I examine the different types of TES and what is known about current deployment characteristics, before moving on to consider two specific configurations, geoexchange and SGHE.

2.2.1 The role of thermal energy storage in deep energy system decarbonisation

A set of studies modelling sector roadmaps for transitioning to fully renewable energy systems (100% RES) by 2050, for 139 countries (Jacobson et al., 2017, 2018b), cities (Jacobson et al., 2020, 2018a) and US states (Jacobson et al., 2015) found that energy system decarbonisation is possible at low cost[2]. Covering all energy sectors including electrified heating and cooling, the studies modelled different combinations of technology in various scenarios which achieve a 100% RES and demonstrated that TES can play an integral role in delivering energy systems that are affordable, resilient, significantly better for population health, whilst creating millions of new jobs. Jacobson et al (2018a), highlighted three alternative fully renewable scenarios with TES present in two of the three suggesting that while TES can support the transition to fully renewable energy systems, it is not the only technological option.

In a UK-focused study, Hewitt et al (2012) modelled a combination of domestic TES and heat pumps under increased wind power penetrations in the UK and Ireland and found that TES helped smooth out variable wind generation and reduced costs. Matheison (2015a) and Lund (2016) used an optimisation model to present a 'Smart Energy Systems' approach to achieve 100% RES through the integration of different energy systems. They found that TES combined with large scale heat pumps are key to connecting the electricity and heat sectors, enabling the exploitation of low value heat resources, and reducing overall costs. In a review of the literature on fourth generation district heating (4GDH) as part of smart energy systems, Lund et al (2018) found that both short-term and seasonal TES helps to integrate increasing amounts of fluctuating renewable energy and reduce overall system costs. However, the studies that this finding is primarily based on are located in mainland Europe including Denmark (Ommen et al., 2016) and Croatia (Mikulandric et al., 2015), with different sociotechnical characteristics to the UK.

Two further studies based around 100% RES principles focused on the UK specifically. Hooker-Stroud et al (2014) found that it was possible for the UK to meet

[2] It should be noted that the validity of 100% RES studies is subject to vigorous academic debate, see (Brown et al., 2018; Heard et al., 2017; Jacobson and Delucchi, 2013)

demand with renewable energy for 99.9% of the time where heating and hot water were provided through a combination of solar thermal, geothermal and heat pumps. Short-term thermal storage helped cover shortfalls in generation to a small extent, but more importantly was able to reduce the shortfalls from the peaks at times of surplus. It was not clear whether seasonal thermal storage was included in the model, however. To cover the periods of prolonged low temperatures and low wind speeds, hydrogen and synthetic gaseous fuels were produced and stored. Alexander and James (2015) modelled a 100% RES UK system for electricity only, but which met domestic heating needs through electrification with air source heat pumps (ASHPs), and some transport demand through the addition of electric vehicles (EVs). They found it was possible to meet the power needs of the UK in 2050 with no carbon capture and storage (CCS) or nuclear generation through variable wind, solar and tidal, in combination with dispatchable hydro, geothermal and bioenergy. There was no attempt to model a scenario which involved the use of large-scale thermal storage, however they assumed that 10% of the demand of the top six hours in each day was shifted to the lowest six hours, suggesting short-term thermal storage was integrated into the model.

As outlined in Chapter 1, this thesis focuses on cities as important locations of thermal storage deployment. Considering city-level applications of 100% RES modelling, Prina et al (2016) produced a range of scenarios for a case study town in southern Italy. They found it was possible to replace gas boilers through a district heating network combined with seasonal thermal storage and large heat pumps that exploit the excess electricity production from solar PV, and that this was the most cost-effective approach. The viability of this scenario was contingent on the existence of the district heat network however, which necessarily limits its wider applicability. Noting the lack of studies for UK locations, Renaldi and Friedrich (2019) took the real-world data available for a district heating site in Canada which delivers almost 100% heat demand from solar thermal combined with seasonal thermal storage and applied it to model two urban sites in the UK. Despite the lower solar irradiance of the two UK sites compared to the base case, it was technically possible to achieve over 95% heat demand from solar through the additional seasonal storage capacity.

The studies explored here feature TES to a more or less explicit extent, and provide evidence that thermal storage can help reduce the costs of the transition by combining different sectors of the energy system. However, they contain little granular detail about the applications of different types of TES, and tend to focus more on using different electricity storage technologies over seasonal thermal storage. Whether on a country, state or city level, the studies suggest that TES has the potential to support the deep transition to full decarbonisation, although there are alternative possible pathways to 100% RES. Whilst the literature establishes the relevance of the focus on TES for this thesis, the techno-economic modelling studies give little insight into broader sociotechnical dimensions of TES deployment, such as what policy and regulation might support wider adoption or what kinds of business models might deliver viable investments. Also, they do not establish a baseline picture of the current state of thermal storage deployment.

2.3 Geoexchange

Geoexchange is a particular approach to thermal energy storage in which the ground is used as an energy store and balancing mechanism. Through this approach the system is operated to actively recharge the ground with waste energy rather than deplete energy only, as would happen in a heating-mode only system. Here I explore prior work on geoexchange, beginning with attempts to find a common identifier.

In their review of technical developments in ground heating systems, Self et al (2013) in clarifying their preferred nomenclature *geothermal heat pumps*, included within this the variously described, *"ground source heat pumps (GSHPs), earth energy systems, GeoExchange heat pumps, ground-coupled heat pumps, earth-coupled heat pumps and ground-source systems"* (2013, p. 342). For this thesis I adopted the term *geoexchange* to identify the technology and to emphasise the regenerative storage functionality of the approach, made possible through the *exchange* aspect. In describing that, *"Many systems include a cooling mode that removes thermal energy from a space and rejects it to the ground. In the cooling mode, a reversing valve is used to move the fluid in the opposite direction in the cycle"*, Self et al (2013, p. 342) help to clarify the restorative mode of geoexchange, but implies their definition can, but does not necessarily require, this restorative functionality.

In another technology review of various ground source heat pump approaches, Sarbu and Sebarchievici (2014) found that, because of the higher ground temperatures made possible by the heat recovery aspect, ground-coupled heat pumps featured greater system efficiency and subsequently lower total energy consumption, as well as reduced heat pump capacity compared to other types of ground source heating. Chen (2010) also adopted the term ground-coupled heat exchangers whereas Omer (2008) defined all geothermal heat pumps as being able to operate in restorative mode, whilst noting that because of this functionality they have come to be known as *Earth Energy Systems*. Omer found the technology is well established in North America and parts of Europe, but at the time of writing remained at the demonstration stage in the UK. The main barriers to greater deployment were identified as awareness and acceptance by users and system designers, higher capital costs, and limited availability of skilled and experienced designers and installers. Cost-effectiveness was improved if the systems were implemented at the time of building construction, and in areas where natural gas is unavailable.

A detailed case study of an active geoexchange project is provided by Verhoeven et al (2014a) in their review of the Minewater 2.0 scheme in the Heerlen municipality of south west Netherlands. Based around the use of two abandoned coal mines, in the original version 1.0 operated only as a heat source. With version 2.0, depleted heat is recharged by waste heat from a data centre, supermarket refrigerators and from various small-scale industrial processes, as well as the warm return flow from space cooling in the connected buildings (Boesten et al., 2019).

In their UK-focused market and technology review, Rees & Curtis (2014) found a reluctant uptake of all ground energy systems in the UK, noting that it lags behind other several northern European and North American countries by more than a decade. The authors attributed this to a range of factors including the UK's historic abundant fossil fuel reserves, leading to less of a requirement to seek alternatives to gas boilers, and a lack of a national skills and knowledge base driven in part by the UK's mild climate, meaning air conditioning to provide summer is not commonly installed. This was contrasted to the US, where air conditioning is widespread, and customers accept central air systems without difficulty. The mild UK climate also means the comparative efficiency of ground source heating compared to ASHPs is less pronounced. The lower need for summer cooling in the UK is likely to change as global temperatures rise, and the ability of geoexchange to provide both winter heating and summer cooling may therefore become more important in the UK market (Christidis et al., 2020). Rees & Curtis documented UK government attempts to boost deployment of through various funding mechanisms and found increased deployment was highly correlated with increased capital funding.

2.4 Shared ground heat exchange

Geoexchange on its own is limited in applicability especially in multi-residential settings because of the need for a direct connection between the dwelling and the ground array. This can be addressed through combination of geoexchange with some form of heat sharing network. In this study I adopt the term shared ground heat exchange (SGHE) but the approach also known as fifth generation district heating and cooling (5GDHC). Revesz et al (2020) found that 5GDHC presents a unique opportunity in urban areas to capture and use low-grade waste heat sources. A point emphasised by the claim that 5GDHC offered *"the exploitation of quasi-infinite indigenous heat sources"* (Buffa et al., 2019a, p. 505). The systems can also integrate thermal and electrical storage to create additional flexibility for the network and smart control for demand-side management. Revesz et al (2020) and Boesten et al (2019) emphasise that long-term heat storage is fundamental to effective 5GDHC.

Buffa et al (2019a) conducted the first major survey to explore 5GDHC deployment across Europe. They found Switzerland and Germany to be pioneers, with 75% of the 40 projects, driven in Switzerland by bold central government policies around the "2000-Watt Society" energy policy concept backed up by a 2008 referendum, and a ban on active cooling in residential settings. Twelve of the projects included in the survey used boreholes for seasonal TES. They show a significant ramp-up in recent years noting that this was deployment only in terms of the sample and so the numbers are very low. In consideration of the main opportunities and challenges to 5GDHC deployment, Buffa et al (2019a) found that because of the novelty of 5GDHC, there are no guidelines of technical standards available and technological knowhow remains in the hands of a few companies. Boesten et al (2019) proposed that consideration of the users and citizen trust in new technologies was key, including a perception of distributive fairness inherent in any system. Thus, in the case of 5GDHC, which involves complex connections of heat producers and consumers, the optimal technical solution may not be the best for users, and this should be considered carefully in system design.

I found one example of a UK scheme in government literature around heat pumps in district heating (Foster et al., 2016). The scheme was a small rural site serving 18 local authority apartments which were not previously served by the gas grid, where residents reported high costs and poor control of the old electric night storage heater system. The system installed included the geoexchange element of three boreholes, with a low (although not ambient) temperature heat network to supply heat to residents. There were some initial challenges reported included the vagaries of grant funding deadlines resulting in a more disruptive work schedule, poor user understanding of how to operate the system properly and at low cost, and internal local authority uncertainty about how to charge residents, but now the residents reported high levels of satisfaction with the system.

2.5 Theoretical approach

The chapter has set out some of the technical underpinnings of the research focus broadly on TES and more specifically on geoexchange and SGHE. In this section I explore the transition away from fossil-based heating to low carbon TES alternatives in the context of various theoretical approaches and establish the rationale behind adoption of the sociotechnical transitions literature to undertake the study. In remainder of the chapter I then explore a number of specific frameworks within sociotechnical transitions in greater detail.

Consideration and application of appropriate theories is an important aspect of rigorous academic work, can provide roadmaps to carry out empirical research and can support researchers to make sense of data, especially when this is large and complex (Sovacool and Hess, 2017). The judgemental rationality inherent in the critical realist approach adopted (see Section 3.1) establishes grounds for favouring the explanatory power of some theories over others (Sayer, 2000). TES can be considered as a form of local energy infrastructure as well as part of a complex system with no overall control exhibiting complex social and technological dynamics (Bale et al., 2015; Busch et al., 2017). Considering how systems of infrastructures with complex properties undergo transitional change is subject to a large and constantly evolving body of literature (Sovacool et al., 2018). Edomah et al (2017), Markard et al (2012) and Sovacool & Hess (2017) provided useful reviews of some of key analytical frameworks. These include, amongst many others, Social Practice Theory which focuses attention on human behaviour but may not support researchers to consider underlying systemic forces, or Actor-Network Theory which seeks to explain the interaction of technologies and social relations but may suffer over-abstraction and overlook structural inequality.

Sociotechnical transitions however are defined by a "*a set of processes that lead to a fundamental shift in socio-technical systems*" (Markard et al., 2012, p. 956). The fundamental shift which this work focuses on concerns the currently carbon-intensive sociotechnical system of heat generation and supply which must transition to one based on low carbon renewable technologies in the shortest possible timeframe. As set out in Chapter 1, this will require direct intervention in homes and businesses and requires a complex set of decisions, actors and processes. A simple techno-economic analysis may explore how the economics of certain renewable technologies can be improved, but this assumes actors within the system make only rational choices (Edomah et al., 2017). One of the key authors in sociotechnical transitions field outlined the central proposition that, *"technology, of itself, has no power, does nothing. Only in association with human agency, social structures and organisations does technology fulfil functions."* (Geels, 2002, p. 1257). The sociotechnical transitions approach sees social structures and changes in them as the primary driver of technology and technological transition (Edomah et al., 2017). I adopted the sociotechnical transitions literature to take a wider systemic perspective of thermal storage in the energy transition which recognises that fundamental change is complex and involves a range of aspects including user practices and institutional structures (Geels, 2012; Kemp, 1994).

In the remainder of the chapter I explore in more detail various frameworks within sociotechnical transitions to see how they may support the analysis the role of TES in the energy transition, beginning with the most established framework in the field, the multi-level perspective (Geels, 2002). This theory is not without its critics (Sovacool and Hess, 2017) and I explore some challenges and attempts to address these. I bring in an alternative and more recent theory within sociotechnical transitions, the coevolutionary framework (Foxon, 2011), which has been applied to provide one of the few sociotechnical analyses of energy storage in the UK including thermal energy storage (Taylor et al., 2013). These two primary frameworks are supplemented with others which focus on specific areas such as the role of business models, and literature which attempts to apply sociotechnical transitions at a more local level.

2.5.1 Multilevel perspective

Several theories have been proposed to help understand and analyse sociotechnical change, with the multi-level perspective (MLP) pioneered by Geels (2002) emerging as the dominant framework (Markard et al., 2012). Geels combined concepts from evolutionary economics and technology studies with the concept of 'technological regimes' (Nelson, 1982) and the inclusion of 'rules' (Rip and Kemp, 1998) to propose a multilevel perspective (MLP) of sociotechnical transitions, as shown in Figure 2.1.

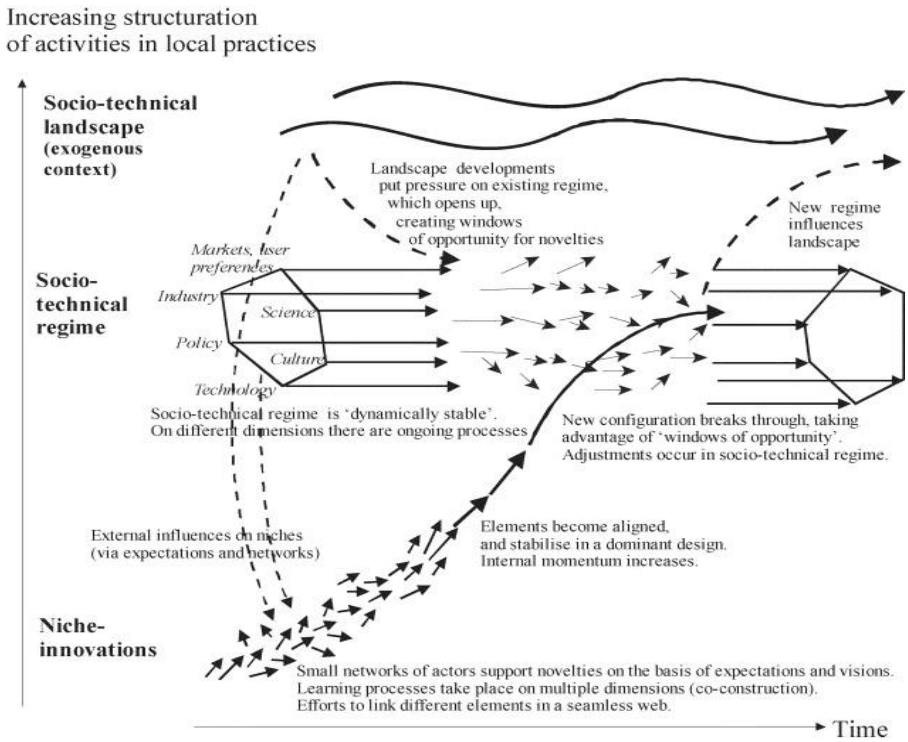


Figure 2.1 Updated multilevel perspective. Geels and Schot (2007) adapted from Geels (2002)

Based around three analytical levels of micro (niche), meso (regime) and macro (landscape), Geels (2002) proposed that the primary source of stability in sociotechnical systems emanates from the regime level, through shared norms, rules, beliefs and expectations which guide the behaviour of the different actors and lead to lock-in of dominant technologies and infrastructures. In the case of domestic heating in the UK, the stable fossil-based regime may encompass the established infrastructure of the extensive natural gas grid, the shared norms of the many thousands of independent heating engineers experienced and trained in gas boiler installation only, and the low price for gas maintained by successive policymakers, for example. The concept of incumbency is important here, which can describe the overall incumbent fossil-based regime, or specific incumbent technologies or actors operating to maintain the regime (Bolton and Foxon, 2015; Geels, 2014, 2011). In the UK domestic heating regime this may include the gas network companies, boiler manufacturers, and gas and electricity utilities (Bolton and Foxon, 2013; Lowes et al., 2020).

It is sometimes possible that exogenous landscape influences can put pressure on existing regimes and open up opportunities for novel technologies (Geels, 2012). The adoption of the 2015 Paris Agreement and the landmark IPCC 1.5°C report of 2018 contributed to the adoption of the UK national net-zero target and bringing forward of the date by which new homes must adopt non-gas heating technologies can be considered in these terms (Harrabin, 2019; IPCC, 2018; Priestley et al., 2019; UNFCCC, 2015). Innovations and new approaches can also develop in niches where they are actively shielded from the pressures of the incumbent regime, such as the novel thermal storage concepts explored in this thesis, supported by one-off innovation funding streams to insulate from normal commercial competition. However, incompatibility with the values and norms of the regime may mean novel technologies are confined to niche applications (Geels, 2002; Raven, 2006; Rogers, 2003; Taylor et al., 2013). It is possible for niche innovations to develop in such a way that they can successfully compete with incumbent approaches however (Kemp et al., 1998). This can take place either within a largely unchanged regime; or alternatively, where the innovation may influence the regime such that it becomes more favourable to the niche (Smith and Raven, 2012).

More than anything transitions are about the change from one dominant regime to another (Geels and Schot, 2007; Verbong and Geels, 2010). In considering how change happens, Geels (2002) proposed that it is alignment of successful processes within the niche with changes in both the regime and landscape levels which determine if sociotechnical transitions will occur. This was neatly summarised as:

> *"…the core logic is that niche-innovations build up internal momentum (through learning processes, price/performance improvements, and support from powerful groups); changes at the landscape level create pressures on the regime; and destabilization of the regime creates windows of opportunity for the diffusion of niche-innovations."* (Geels, 2014, p. 23)

The general pattern by which radical innovations break out of niches is by what Geels described as *niche-cumulation*, whereby innovations are used in multiple and subsequent niche settings. Geels & Schot (2007) attempted to address some of the criticisms of the MLP (that it is unclear how the three conceptual levels should be applied empirically, that it neglects the importance of agency, context and uneven power relations in regime transformation, and that it places too great an emphasis on niches as the primary source of regime change) (Berkhout et al., 2004; Smith et al., 2005; Truffer et al., 2015) through elaboration of four transition pathways exploring multilevel interactions: *transformation*, *dealignment and realignment*, *technological substitution* and *reconfiguration*, as well as a fifth involving some combination of these. Whilst the pathways emphasise the importance of landscape pressures, what appears to be key in assessing progression down one of the pathways is the state of niche-innovations (i.e. whether they are 'ready') at the time the landscape pressure arises, for which four tests are proposed:

> (a) learning processes have stabilised in a dominant design,
> (b) powerful actors have joined the support network,
> (c) price/performance improvements have improved and there are strong expectations of further improvement, and
> (d) the innovation is used in market niches, which cumulatively amount to more than 5% market share
> (Geels and Schot, 2007; Hoogma et al., 2002; Kemp et al., 1998)

Because of the importance of niche-innovation readiness, the work retains a significant focus on the impotence of niche-driven change and says little about the regime level. However, the four tests may be useful in assessing the state of different TES niche-innovations encountered in the thesis. The diagram shown in Figure 2.1 is the slightly updated version proposed in the same work by Geels & Schot (2007) featuring downward arrows from the landscape and regime towards the niche-level to reflect that perceptions of niche actors and the size of support networks are influenced by broader regime and landscape developments. The 'structuration' Y-axis was added to add to reflect how structures such as shared rules, social networks, market structures, etc. become more stable and embedded at the regime level than the niche level, and can be either constraining or enabling. Further up the Y-axis, rather than influencing action directly, sociotechnical landscapes provide *"deep-structural 'gradients of force' that make some actions easier than others"* (2007, p. 403).

A challenge to sustainability transitions research including the dominant MLP was put forward by Feola (2020), who proposed that capitalism permeates throughout all levels of the MLP but found little to suggest the frameworks enabled a healthy critique of capitalism and its effects (as well as being overtly rooted in the perspectives of the Global North). This challenge is relevant to the thesis because it may prompt the consideration of underlying power structures and dominant narratives which have created and shaped the stable UK regime for domestic heating. Swilling et al (2016) proposed that the technocratic bias of transitions research could be addressed through application of the socio-political regime concept. This described the *"constellation of actors who have agreed on a set of ground rules for conducting the business of everyday politics within and outside the formal institutions of the political system [...] in essence [to] the way the political game is conducted across various arenas (parliament, executive, media, civil society) in order to manage the overall stability of the political system and the direction of policy."* (2016, p. 656). Because policies tend to reflect *power dynamics* and *paradigm commitments*, unless change happens in those higher order dimensions, change is unlikely to take place in government and state institutions or in the policies themselves. In attempting to address some of the criticisms about the MLP's lack of attention to power and politics, Geels (2014) highlighted four ways that incumbent regimes pose a resistance to transitions:

1) Use of instrumental forms of power: By leveraging their access to resources such as money, staffing capacities, media and decision makers, regime actors can advance their own interests.

2) Use of discursive strategies: By using their existing resources and powers, regime actors can frame what is discussed, shape what people think is important (or not), and what they see as the 'best' solutions to problems.

3) Use of material strategies: By leveraging their existing technical and financial resources, regime actors may be able to enhance the technical sub-regime, preventing radical innovations from being required.

4) Use of broader institutional powers: An established regime may feature embedded political, ideology and governance structures such as a liberalised market ideology, which discourages the idea of state institutions to be seen to ‘pick winners’ and therefore grants privilege to actors with established capabilities, market positions and resources. (Geels, 2014)

The power of incumbents to shape the socio-political regime and resist the UK energy transition has been explored for heating (Lowes et al., 2020, 2019) and electricity (Lockwood et al., 2020). Lowes et al (2020) found a ‘discourse coalition’ of incumbent regime actors with an interest in the UK gas sector, including gas networks, hydrogen generation and CCUS developers, were having a reforming effort on policy development and national discourse away from electrification and towards ‘green gas’. Lockwood et al (2020) found major energy supply and second tier generation companies influenced the policy development process and steered policymakers away from renewable-supporting demand-side response (DSR) during a period of market reform in the early 2010s. They achieved this by effectively sowing doubt in the minds of policymakers about the ability of DSR to operate effectively and creating a sense of fear of a looming capacity crunch.

2.5.2 Coevolutionary framework

Whilst not identified with the same multilevel terminology, the importance of focusing on regime actors was emphasised by Unruh (2000) building on Norgaard (1994) to describe the alliance of policymakers and incumbents which maintain the status quo as the 'techno-institutional complex' (TIC), and the systemic interactions among technologies and institutions within the TIC which contribute to carbon lock-in. Unruh described how a TIC may develop through a "*path-dependent, co-evolutionary process involving positive feedbacks among technological infrastructures and the organizations and institutions that create, diffuse and employ them*" (Unruh, 2000, p. 818). Importantly, once TICs are locked in, they can lock-out potentially superior or more sustainable alternatives for extended periods of time. This can be technological, in the broad sense of the technological system as inter-related components connected in a network or infrastructure that includes physical, social and informational elements, such as development of the road network; or institutional, in the formal sense such as establishment of government agencies which collect taxes from road use, and informal, including the culture, norms and values which develop around a particular trajectory.

Combining MLP concepts with Norgaard and Unruh's coevolutionary principles, Foxon (2011) developed a coevolutionary framework to recognise the mutual causal influences between systems which influence transitions. Whilst not claiming to cover all elements, the coevolutionary model considers sociotechnical change through a focus on five interlocking systems: *technologies*, *institutions*, *business strategies*, *user practices* and *ecosystems*, as shown in Figure 2.2. Foxon proposed that any transition analysis should examine the evolution of each of these systems and their causal interactions.

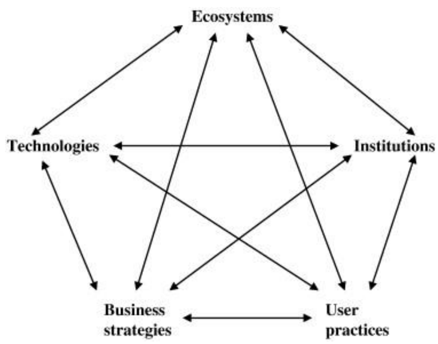


Figure 2.2. The coevolutionary framework. Foxon (2011) adapted from Norgaard (1994)

Foxon invoked Nelson (2005) and North (1990) to define of institutions as *"ways of organising or structuring human interactions."* (2011, p. 2262) to include aspects such as regulatory frameworks, property rights and standard modes of business organisation; explaining that while each system evolves under its own dynamics, two or more systems coevolve when they each evolve, and they have a causal influence on each other's evolution. Foxon argued that the framework is related to but is more flexible than the MLP because it enables more explicit consideration of the role of actors and gives greater emphasis to economic factors through an explicit role for business strategies. However, it is not immediately clear how the framework might draw attention to pervasive effects of power, politics and underlying ideology. Bolton and Foxon (2011) applied the coevolutionary framework to a case study of the UK electricity sector, focusing on the coevolution of technologies and institutions since privatisation in 1989. They found institutional dynamics stymied technological innovation, in part because of the way innovation incentives were designed along neoliberal norms to mirror market principles. The lack of progress was facilitated by technological/institutional dynamics, with the privatised companies inheriting an over-engineered system as a result previous high levels of investment, meaning they could get by without the need to further innovate. Underlying questions of power and politics (including underlying political ideology) were recognised primarily within the *institutions* system, but also inherent within the coevolving link between the systems.

In their analysis of sociotechnical factors affecting thermal and electrical energy storage deployment, Taylor et al (2013) employed the coevolutionary framework to explore how the systems of *technology*, *ecosystems*, *institutions*, *business strategies* and *user practices* might coevolve to shape future deployment. They found that the energy system, as infrastructure, is complex, interconnected, displays a public good character, and is influenced by a wide range of actors including government, regulators and lobby groups. Whilst considering cost and performance of any particular technology is important to understanding potential deployment, it is not enough to consider these in isolation without respect to the institutional environment, governance structures and willingness of users to engage with new technologies.

Taylor et al (2013) proposed three potential pathways for how energy storage technologies might develop in the UK: *user-led*, *decentralised*, and *centralised*. Whilst there was a role for electrical storage in all three pathways, thermal storage was limited to user-led (featuring household-level storage, active user participation), and decentralised (involving local network storage, deployed at community and city scale, with a key role for local authorities and other intermediaries) pathways. Notably, the study includes no reference to the potential for a repurposed gas grid to impact on the prospects for thermal storage deployment. This contrasts with the recent findings which highlight the increasing references to a hydrogen future for home heating, and the impact of gas industry incumbents in driving this agenda (Ketsopoulou et al., 2019; Lowes et al., 2020; Lowes and Woodman, 2020). Considering this situation and the wider UK energy system since the time of writing, it may be that the UK is progressing down a *centralised* pathway, based on continued reliance on the authority of central government and the belief in the market mechanism as the most efficient way of delivering decarbonisation. This pathway was one which the authors did not see as compatible with widespread thermal storage deployment. The recent discourse around the decarbonisation of the gas grid could be more suggestive of the *reconfiguration* pathway of the MLP perspective, with incumbent regime actors seeking to co-opt supposed niche innovations, which may lead to a largely unchanged regime without a prominent role for thermal energy storage.

The focus given to one work in this review reflects the paucity of sociotechnical analyses of TES in the literature, a fact acknowledged by Taylor et al (2013) especially in the UK. An extensive literature search revealed no other sociotechnical analyses of TES since.

2.5.3 Extended Infrastructure Business Model Canvas

Because energy infrastructure such as thermal storage tends to be undervalued through traditional cost-benefit/neoclassical economic appraisal methods, the *business strategies* component of the coevolutionary framework can help focus attention on business model innovation and to facilitate investment and deployment (Brown et al., 2014; Busch et al., 2017; Foxon et al., 2015; Hall and Foxon, 2014). Tools and frameworks which capture a range of values beyond simple financial returns can potentially help guide decision-makers through the challenges of appraising sustainable infrastructure options and their complex values (Boons and Lüdeke-Freund, 2013; Hall and Roelich, 2016). A classic commercial business model tool was applied to smart grid and heat network infrastructure investments (Foxon et al., 2015; Osterwalder and Pigneur, 2010), finding that both are complex investments which face high upfront costs and other lock-out challenges, but can deliver a range of other values to users, wider society and investors, which can help business case viability if they are factored in. Local authorities were found to pursue fuel poverty reduction and other social benefits as primary drivers in heat network investments, alongside carbon reduction (Bush et al., 2016; Foxon et al., 2015). An enhanced version of the tool, the *infrastructure extended business model canvas (EIBM)*, was proposed, which specifically recognises *social*, *environmental* and *economic development* values to aid those making infrastructure investment decisions (see Figure 2.3).

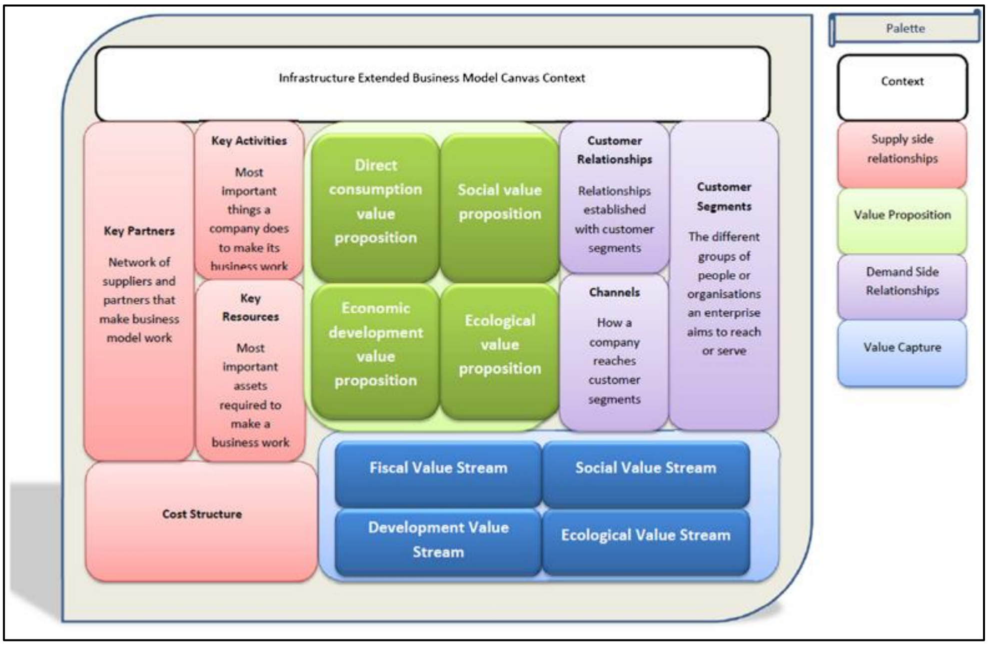


Figure 2.3 Infrastructure extended business model canvas. From Foxon et al (2015)

Despite central government recognition that consideration of social and environmental values in infrastructure procurement is best practice (HM Treasury, 2015), it appears that in general crude residual valuations continue to be used to demonstrate viability (Town and Country Planning Association, 2018). The extent to which organisations developing TES consider non-traditional forms of value in their investment decisions may offer some insights into potential future deployment.

2.5.4 Diffusion of innovations

An alternative framework sheds more light on how innovations become widespread (Rogers, 2003). Focusing on the process of how an innovation-related decision comes to be made, *diffusion of innovations* describes how individuals move through various stages from initial *knowledge* via *persuasion*, *decision* through to *implementation* and then *confirmation*. The focus on the work is weighted heavily towards the role of the individual in such diffusion. Given that the complexity of TES deployment, particularly with regards to the larger-scale geoexchange and shared ground heat exchange projects, innovation decisions and resultant diffusion is likely to be organisational rather than individual (noting that organisations are systems comprised of individuals). Rogers acknowledges a much greater complexity with regards to situation of organisational diffusion and mapped the five stages into an organisational context, shown in Figure 2.4.

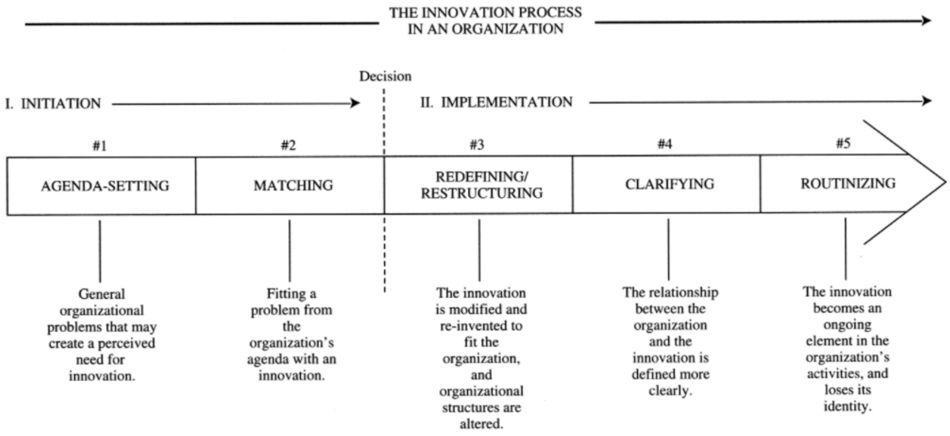


Figure 2.4 Five stages in the innovation process within organisations (Rogers, 2003)

Whilst devoting significant attention to the role of *change agents* in communication, persuading and influencing "clients" (Rogers, 2003, p. 225) in the innovation decision process, it is not clear how readily that externally-focused role maps on to what the sociotechnical literature might describe as *niche actors* (Smith and Raven, 2012) within the organisational innovation decision process in Figure 2.4. There is acknowledgement, though little detailed analysis of the importance of *champions* within internal organisational innovation decisions, and their role in *"overcoming indifference or resistance"* (Rogers, 2003). Because of the thesis focus on large-scale TES projects such as geoexchange, rather than individual consumer decisions, it is potentially important to consider these questions, as well as how such roles are impacted by and are able to shape the local regime, for example.

2.5.5 Theoretical approach to considering cities as sites of transition

In Chapter 1, the importance of cities in the energy transition was established. Cities may be important sites where local policy interventions which may impact on thermal storage and associated heat network deployment (Bush, 2016; Sullivan et al., 2013; Webb et al., 2016). They are also agglomerations of consumers and producers of heat with the potential to be connected through heat networks employing thermal storage (Buffa et al., 2019b; Lund et al., 2014b). Here I explore the literature on what it means for sociotechnical transitions to be considered at a city level.

Coenen et al (2012) argued that much of the sustainability transitions literature, including MLP studies, have neglected spatial dimensions, with a national scale often presumed. They proposed that by not paying enough attention to local diversity, interpretations and institutional contexts (on a regional, city or neighbourhood level), the MLP has difficulty explaining why niches emerge in one place and not in others. For example, location defines the relationship dynamic between regime and niche actors, be it routine informal face-to-face conversations in the canteen (local scale) to formal publishing in journals for example (global scale). The work by Coenen et al was more of a challenge to the field than a proposed methodology for taking sociotechnical researchers to the local scale. Raven et al (2012) acknowledged the need for a framework which more explicitly recognised spatial dimensions of transitions and proposed a second generation MLP to support this endeavour. Noting that space can be both physical (e.g. a city, region or country) and relational (emerging out of the interaction between particular economic or social entities), a third spatial scale was added to the elements of time and structure to the MLP formulation. This is summarised in Table 2.1.

Table 2.1. Adding the spatial scale in to the MLP. Adapted from Raven et al (2012)

MLP Level	Time	Structure	Space
Landscape	Long-term, but sometimes rapid change caused by disruptive events	Exogenous environment	Typical landscape networks exhibit high degrees of proximity and power across incumbent socio-technical system
Regime	Decades	Endogenous structures enacted by extensive organisational networks and embedded in institutions and infrastructures	Typical regime networks exhibit high degrees of proximity and power within an incumbent socio-technical system
Niche	0–10 years	Protective space that enables development of alternative structures	Typical niche networks exhibit low degrees of proximity and power within an emerging socio-technical system

Hodson & Marvin (2010) sought to conceptualise the role of cities in sociotechnical transitions and proposed that the creation of shared visions and a collective understanding was key to reconfiguring the sociotechnical regime at the scale of the city. In terms of urban infrastructure this process is likely to involve representatives of utilities, municipal government, regulators, developers, business, citizens, 'users' etc. They proposed a key role for intermediaries in supporting the creation of such shared visions. The role of intermediaries was further explored in relation to place-based analysis of transitions, in terms of the creation and nurturing of local niches (Bush et al., 2017; Hodson and Marvin, 2010; Kivimaa, 2014; Raven et al., 2012; Truffer et al., 2015; Verbong et al., 2010). Intermediaries were defined by Stewart and Hyssalo as *"actors who create spaces and opportunities for appropriation and generation of emerging technical or cultural products by others who might be described as developers and users"* (2008, p. 296). Research focused variously on the roles of innovation intermediaries, energy intermediaries and cities as intermediaries in urban transitions (Kivimaa, 2014). Focusing on the latter, Hodson & Marvin (2010) argued that the creation of intermediaries outside existing urban governance and socio-technical regimes is necessary to *"coordinating capacity and mobilising capability"* (2010, p. 482).

Smith and Raven (2012) descried three key niche processes which support transitions: shielding, nurturing and empowerment. Bush et al (2017) expanded on this to explore the role of intermediaries in nurturing and empowerment activities through application of Kivimaa (2014)'s intermediary roles framework, where they mapped findings against three phases of district heating development, as shown in Figure 2.5.

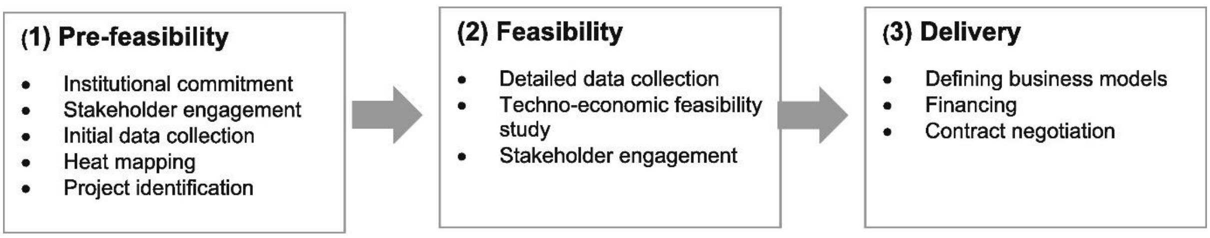


Figure 2.5 Three stages of district heating development process and types of activities within each stage. Bush et al (2017)

Bush et al (2017) found that for district heating development, intermediaries played a number of key niche nurturing roles at various stages in the development process, summarised in Table 2.2.

Table 2.2 Intermediary roles in niche nurturing processes at each stage of district heating development. Adapted from Bush et al (2017). Bold text = primary activity. Italic text = intermediary activity.

Intermediary role	**(1) Pre-feasibility stage**	**(2) Feasibility stage**	**(3) Delivery stage**
Articulation of values and visions	**Awareness raising -** *local authorities* internally and externally with key decision-makers	**Creating evidence base to demonstrate viability:** *local* & *regional authorities* gathered data for feasibility studies, *consultants* carry out studies	
Building social networks	**Aligning interests and establishing cooperation between key-stakeholders:** *local authorities* & *regional LEPs* created partnerships between potential partners though hosting consultation meetings		**Acting as a catalyst for new schemes and expansion:** *local authorities* through planning powers to compel developers, use of public estate as anchor load. **Enable access to low cost finance:** *local authorities* through borrowing power
Exchange of knowledge and supporting learning processes	**Creation of an evidence base to demonstrate viability:** *consultant* commissioned by *local authority*, made possible with funding from *specialist central gov't support units*	**Sharing case studies to overcome high perceptions of risk:** unclear, *specialist central gov't support units* e.g. HNDU, other national bodies / trade associations e.g. Core Cities, Vanguards Network, ADE, DEA	**Facilitating access to technical, financial and legal consultants:** *central gov't* funding *local authorities* to commission *consultants*

Bush et al (2017) concluded that local authorities were the only local actors with responsibilities and interests across all intermediary activities and were key to empowering niche innovations to become part of the regime. This could be done through setting strategic and spatial planning policies that require district heating consideration, as well as by housing sustainability or energy teams responsible for connecting and persuading local stakeholders internally and externally, building social networks required to deliver projects, as well as bringing together of multi-skilled teams of planners, mapping specialists, lawyers, finance specialists etc. to facilitate district heating development. The primary limiting factors to local authority intermediary activities were lack of resources and limited policy powers.

A potentially important factor in considering the role of cities and urban governance is the context of forty years of neoliberal reforms which have reinforced centralised control through budget cuts and market fundamentalism, and further eroded local authority competencies and resources (Chatterton et al., 2018; Rose and Miller, 2010; Tingey and Webb, 2020). Taking a deeper look at the structural issues surrounding the role of urban governance and the local state, Jessop (2002), Harvey (1989), and Rose & Miller (2010) explored the impact of the rise of neoliberalism on the ability of cities to shape the local regime. Harvey noted the shift from a 'managerialism' to 'entrepreneurialism' from the 1960s onwards has resulted in an urban governance (in Harvey's conception a broader network of forces than just local government institutions) focus on competing with other cities to chase highly mobile transnational capital and create a *"good business climate"* (1989, p. 11). This is an important consideration when examining why city authorities might adopt high-growth / low-standards in urban planning policy setting. The outcome of this broader trend is that city governments are reduced to acting as intermediaries, because that is the only option they have.

Webb et al (2016) analysed local government action on sustainable energy such as district heating in the context of the UK's privatised and liberalised energy system. They found that local authorities are recognised by central government as critical intermediaries in the energy transition, but they struggle to operate effectively in the context of the neoliberal central government framework of competing for scarce austerity resources. In absence of direct powers over the local energy system, local authorities must enact plans for low carbon provision through their various statutory responsibilities, such as the planning system, economic development, housing, welfare and environmental protection. The reality of local energy system governing under these conditions amount to a *"dispersed form of rule"* (2016, p. 29) dependent on a wide actor network involving state, market and civil society agencies and experts, which may include consultants, financial investors, utilities, public or private ESCOs, and community groups. They found local authority and dispersed governing characterised by resourcefulness and ambition, but the neoliberal context acted as a limiting factor on systemic transition, and the 'green growth' narrative risked co-optation as 'greenwashing' by those who see climate change as a new opportunity for capital accumulation and reliance on mass consumption.

The emphasis placed on local authorities as key agents in supporting local transitions suggests a consideration of their role, and the challenges they face, in supporting the deployment of low carbon heating technologies such as TES is justified. Tingey & Webb (2020) analysed empirical data on 434 UK local authorities' energy planning activities, finding that whilst some have developed clean energy in niche areas, they lack the resources to undertake meso-scale planning and innovation. In line with prior research, they found activity was opportunistic rather than strategic, based on sporadic and turbulent government funding streams, as well as the lack of a statutory remit (Bush et al., 2016; Rosenow and Eyre, 2016). Engagement was highly correlated with local authority type, with the highest level of engagement across the single tier unitary, London and metropolitan district authorities more typical of urban areas. At the other end of the spectrum were the lower tier district boroughs of the two-tier system more common to rural settings. Scottish local authorities were found to be leaders, underpinned by a more supportive policy environment which is devolved to the Scottish Government. This was notably absent in Wales and Northern Ireland where similar powers are not devolved. Across the English local authorities, the hotspot of activity in London was attributed to the devolution of strategic powers to the Greater London Authority, including greater control over the planning system as well as energy, waste and climate policy. Scale and resources were important considerations that contributed to higher single tier and upper tier County Council activity compared to lower tier district boroughs. Bristol, Nottingham and Islington were recognised for their sizeable in-house energy teams. Tingey & Webb concluded that current structures are hindering the potential for local authority action to catalyse systematic change but that ongoing devolution processes across the UK present an opportunity to understand more about the trajectories of local energy activity over time.

Considering a case study of Copenhagen, Huxley et al (2019) focused on regime-level measures to explore how these enabled or constrained the process of translation between the city's long-term vision and short-term actions to achieve it. Expanding prior work on *institutions* as 'rules of the game', they analysed this over three aspects of regulatory (explicit rules and targets), normative (softer standards and values) and cultural-cognitive (underlying beliefs and customs, ways of thinking). They found the normative level most important, where local sustainable city actors could intervene and mobilise power to shape selection pressures and influence the transition, compared to the regulatory and cultural cognitive process which were more embedded and less locally determined. If city actors are serious about transformational change, Huxley et al concluded they must coordinate power including decision-making and resource allocation and be prepared to change municipality structures.

2.6 Chapter summary and research gap

This chapter has set out an applied and theoretical basis for conducting the study. The research discussed establishes the relevance of the focus on TES for this thesis and highlights the need for an up-to-date study of the current UK TES deployment. Whilst several techno-economic studies were useful in providing a basis for exploring TES deployment, they did not consider the complexities of political and institutional challenges which are essential to the transition required. Combined with low UK deployment, there is a lack of UK-focused research on TES, especially considering wider sociotechnical issues.

The value in taking a sociotechnical approach to explore TES deployment was established, with the key frameworks explored and discussed. The main developments, challenges and refinements to the MLP were examined and the importance of considering underlying issues of power, ideology, and pervasive effects of capitalism on the course of transitions was recognised. The coevolutionary framework was introduced as an alternative to the MLP and the one prior coevolutionary exploration of UK TES deployment was discussed whilst establishing the need for an updated study.

TES was recognised as a form of energy infrastructure which brings certain challenges and complexities for those attempting to value investment decisions, and the EIBM was proposed as a potentially useful tool for exploring the search for non-traditional forms of value by project developers. The organisational innovation-decision process and the importance of champions as internal change agents was recognised through the diffusion of innovations framework.

Spatial dimensions of transition research were emphasised, noting how this aspect has traditionally been absent from sociotechnical studies. This was introduced through considering the potential role of cities and especially local authorities to create and shape niches and fulfil key supportive roles in traditional district heat development. The challenges that local authorities face through many years of budget cuts shaped by underlying political ideology were noted. The general picture of UK local authority energy engagement, and suggestions about the lengths city actors must aim for to bring local transitions about, were established.

3 Methodology

In this research I set out to gain a greater understanding of the urban energy transition for heat and explore how greater and more rapid deployment of low carbon technologies such as thermal energy storage (TES) can be enabled. This was carried out through a three-part study, with the initial phase exploring current deployment of TES in the UK, and two subsequent phases focusing on particular technological approaches to TES known as geoexchange and shared ground heat exchange (SGHE). The overarching research question is as follows:

How can cities unlock the potential for thermal energy storage to support the UK's net-zero transition?

The three studies summarised in empirical chapters 4-6 took place in broadly chronological order but involved significant overlap, and the results from each helped to guide the focus and research question of the subsequent. As each part of the research focused on a different aspect of the urban energy transition for heat, they serve as standalone studies as well as research phases.

In Chapter 4, I applied a sociotechnical perspective to explore factors shaping the development, application and carbon reduction impact of TES through a qualitative survey of schemes in the UK. In Chapter 5, I explored the factors that have led to successful geoexchange deployment in UK cities through case study involving a thematic analysis of semi-structured interviews with local energy actors. In Chapter 6, I undertook a detailed exploration of the role of urban governance in shaping the local transition for heat through a comparative case study of two UK cities and a focus on SGHE deployment.

In this chapter I set out the philosophical and methodological foundations which guided the research, and the specific research methods employed at each stage to address the overarching and specific research questions. This chapter follows the hierarchy structure of the three elements of the research approach as set out by Cresswell (2014) in order of the level of abstraction, as shown in Figure 3.1.

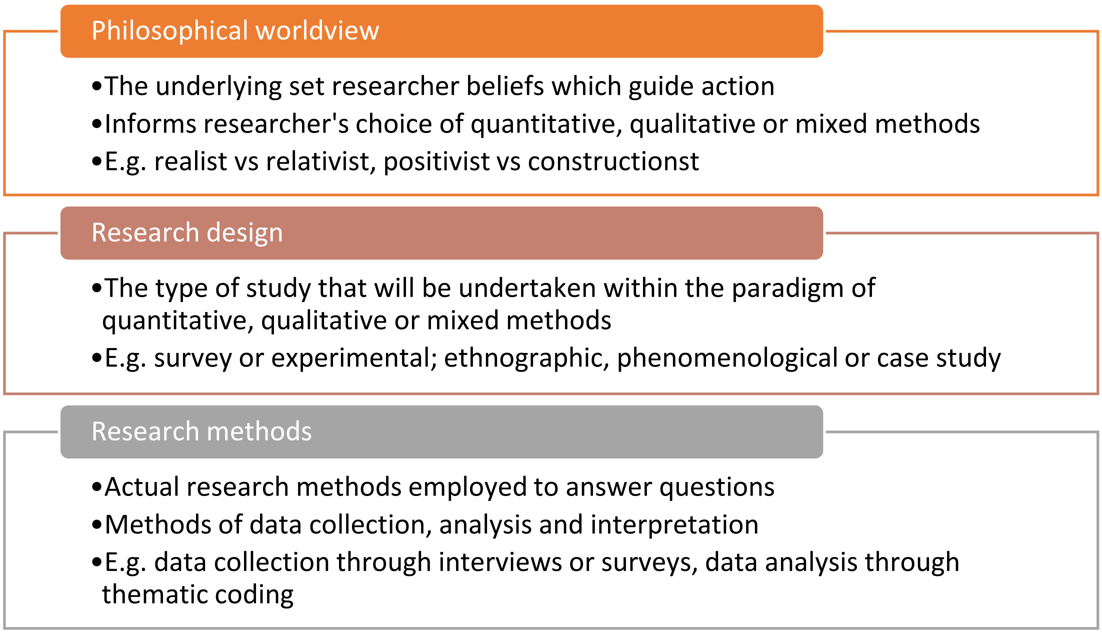


Figure 3.1: Three intersecting levels of research approach, adapted from Creswell (2014)

First, I set out the basis for operating within the qualitative paradigm including the ontological and epistemological underpinnings which shaped my worldview as a researcher. In section 3.2, I set out the overall research to address the overarching research question. The chapter then moves on in sections 3.3 to explain how the research design applied a range of qualitative research methods to enact the theories set out in Chapter 2 to answer the research questions in each phase.

3.1 Philosophical worldview

Recognising that the first step to producing rigorous research is to understand the research paradigm within which I operate, here I explore the set of basic beliefs which underpin my worldview as a researcher (Given, 2008). Because the research paradigm includes underlying assumptions about the nature of reality, this affects how as a researcher I interact with that reality, and therefore which methods are appropriate to investigate that reality (Guba and Lincoln, 1994). Within a spectrum of positions, broadly a realist/positivist perspective would lead to favouring quantitative methods, whilst a relativist/constructionist worldview would lead to favouring qualitative methods (Sovacool et al., 2018). This section first sets out the distinctions which mark out qualitative, quantitative and mixed methods modes of inquiry and what it means for this research study. The philosophical positions which underlie these approaches are then outlined and I introduce the critical realist perspective that I applied to the research.

3.1.1 Mode of inquiry

A key distinction in academic inquiry that I considered when developing this study is whether to investigate through a qualitative or quantitative approach, or in some combination through a mixed methods study. The decision on which paradigm to operate in rests on the research question under investigation, but also on philosophical understanding about the nature of reality and relation of the researcher to what is being researched. Whilst quantitative research typically tests objective theories by examining the relationships between variables, qualitative research on the other hand attempts to elicit understanding and meaning, and generate findings that are richly descriptive (Creswell, 1994; Merriam, 1998). Qualitative research is recognised as being especially useful when the researcher does not know all the important variables to examine (Creswell, 2014). I adopted a primarily qualitative approach in an attempt to seek an understanding of the social reality facing those trying to develop TES projects (Flick et al., 2006). However, I supplemented this with quantitative elements to triangulate sources evidence, for example in Chapter 6 when assessing the carbon reduction impact of different heat technologies.

Whilst quantitative methods typically apply 'top-down' deductive reasoning based on testing hypothesis, and qualitative, 'bottom-up' inductive reasoning generating wider insights from insights empirical data, I adopted the third-way abductive reasoning approach which aims to infer hypotheses which explain empirical data (Coffey, 1996; Kelle, 1995; Robson, 2002; Sovacool et al., 2018). I recognised that as a researcher I came to the study with my own stock of knowledge and experiences of comparable phenomena, including knowledge of theories and frameworks. This included, for example, my previous professional experience within a local authority working on district heating projects, which involved going into residents' homes to talk about how they used their heating. I was also aware of the MLP and coevolutionary frameworks, for example, and this shaped how I interpreted the data to see what slotted into existing theories but also what did not, and how else it could be explained. Using the data in Chapter 5 I combined the MLP and coevolutionary frameworks and developed an alternative framework for trying to understand critical success factors for geoexchange deployment. In Chapter 6 I tested and extended the sociotechnical framework based on the new dataset. In this way I believe I successfully employed an abductive approach to zigzag dynamically between theory and data to find explanations which best fit the observations.

3.1.2 Researcher worldview

In Chapters 5 and 6 I chose case study designs to illuminate the real-world contemporary phenomenon of the development of TES in the UK as a means to generate insights in pursuit of an urgent transition to a net-zero carbon energy system. Participants' perspectives and interpretations were an important part of this, to illuminate the case study in a richly descriptive way. As part of developing the research I considered my general philosophical orientation towards the world and towards research. Such a consideration is important because the research approach chosen to address a specific research challenge will likely depend, consciously or unconsciously, on my understanding as a researcher of what can be known about reality and how such 'knowing' can be brought about. Here I establish how I explored the concepts of ontology and epistemology, and why I adopted a critical realist perspective to understand and navigate the conceptual landscape.

3.1.2.1 Navigating ontological and epistemological positionality

Ontological assumptions concern the nature of reality, whether there is any truly objective 'knowable' reality or whether reality is multiple and only exists through human interpretation (Braun and Clarke, 2013; Creswell, 1994; Sovacool et al., 2018). Epistemological assumptions however describe how we can know something about the nature of the reality under investigation, or "how we know what we know" (Crotty, 1998). The carton in Figure 3.2 represents a light-hearted way of how I conceived the research endeavour through these concepts.

Figure 3.2 The role of the researcher to the researched in a positivist and constructionist worldview

With an objective reality separate from the left-hand researcher-cat, the goal is to uncover the truth through external observation and testing, outside the bowl looking in. Accepting no such objective reality, the right-hand researcher-cat must therefore focus on the understanding, meanings, social construction and the subjectivity of those being researched through human-centred methods including interviews, focus groups and rich textual data (Flick et al., 2006). The researcher-cat must get into the bowl and become part of the research.

In considering my own philosophical understanding of these concepts, I found that critical realism offered me a useful navigational aide which reflected my orientations. Featuring a realist ontology combined with a relativist epistemology (Archer et al., 2016), critical realism recognises that an external reality can exist independently of human experience, but accepts that multiple interpretations and perspectives of that reality are possible. Therefore, in critical realism an objective world exists which has properties can be known through scientific endeavour. However, that knowledge is a subjective and constantly changing social construction (Easton, 2010). In short, the world has a reality outside of our human understanding of it, but that understanding is limited by our position in it (King, 2017). When undertaking my research, this enabled me to accept aspects of external reality I was investigating. This included basic concepts such as that thermal energy storage is a technology for storing heat energy, but also more substantive matters such as that geoexchange developments are happening to differing degrees in some locations more than others and that there are individuals involved in geoexchange development with their own knowledge, understanding and subjective interpretations.

Important to critical realism is an acceptance that causation is real, and such an investigation can be conducted into what may have caused certain outcomes (Maxwell, 2012). This provided the basis for my own confidence that a study could be designed to investigate the issues around this, including what may be causing TES projects to happen or not, for example. Accepting that knowledge is socially-constructed was an important part of the way I approached the semi-structured interviews and the analysis of the subsequent interview data Chapter 5 and 6. As an example, in the investigation of a SGHE development in Chapter 6, it was clear that an energy consultant, a private sector housebuilder and a local authority development manager each had different interpretations of the same situation, including what had caused the change in approach from gas boilers to SGHE in that development.

Key to the commitments of critical realism is an understanding that careful methodological practices form a bridge between epistemological knowledge and ontological reality, essentially that good research helps us to understand the world better (Vincent and O'Mahoney, 2019). As outlined in more detail in section 3.3, I attempted to apply rigorous research techniques such as to triangulate evidence from multiple sources of evidence where possible. In the example of the analysis of SGHE deployment, this included written planning application documents, reports and minutes of meetings, to go alongside interviews with their subjective testimony.

Critical realism also features a 'judgemental rationality' (as opposed to judgmental relativism) in allowing that there are rational grounds for preferring some theories and explanations over others (Sayer, 2000). Accepting this proposition enabled me to explore multiple theories to aid understanding and make choices about which theories to include for further use and testing with the empirical observations generated. This led to me to investigate several theories within the field of sociotechnical transitions, because I wanted to explore systemic and structural issues affecting how energy infrastructure change happens.

3.2 Research design

Taking account of the philosophical worldview is essential to understanding what lies behind the nature of the research endeavour. The relationship between this and the practice of research can be summed up as, *"epistemological [and ontological] commitments that underpin, and methodological practices that animate, qualitative inquiry"* (Kapiszewski, 2019). Whilst research methods refer to techniques for gathering and analysing data, the research design outlines how such a method, or methods, become executed in a particular study (Sovacool et al., 2018). With an overall objective to gain a greater understanding of the urban energy transition for heat, I employed a flexible mixed methods study design on the role of thermal energy storage in the transition to zero carbon heating and cooling in UK cities.

3.2.1 Flexible research design

Throughout the course of this study, I undertook a flexible approach to research. Whilst this is a common approach taken in qualitative case study research, it is important to identify this and manage the potential implications. A flexible design approach implies that the detailed framework of the study design emerges throughout the course of the research rather than being fixed from the point of beginning data collection. A flexible approach involves continual revisiting of the purpose, theory, questions and methods and sampling strategy of the research project (Robson, 2002). This may be done, for example, to follow up interesting and unintended lines of inquiry, refine and modify the research questions once some data analysis has been completed, adapt to a changing context or events which may impact the research.

In the first phase of the study, I undertook a qualitative survey of the TES in the UK, following initial research which suggested a gap in this area. Findings in Chapter 4 suggested geoexchange held particular promise for enabling the transition to net-zero heating and cooling but was under exploited in the UK at present. This led me in Chapter 5 to explore sociotechnical success factors in geoexchange development. For this inquiry, my aim was to gather perspectives from a range of actors involved in various aspects of the geoexchange development process. This led to the selection a semi-structured interview technique which I carried out with fourteen key actors involved in geoexchange development in the UK. The findings in Chapter 5 suggested differences in place-based city regimes were having an impact on housing developers and leading to greater adoption in some UK cities over others. These findings led to my decision for Chapter 6 to explore this issue through a comparative case study of two UK city regimes. The role of urban governance in the two case cities was explored through an in-depth analysis of thirty subcases, including documentary evidence to build up a detailed quantitative and qualitative picture of each subcase supplemented with semi-structured interviews of key actors. The three phases of the study are outlined in section 3.3, along with a detailed review of the particular research methods employed.

3.3 Research methods

Within the broad philosophical worldview and research design set out in sections 3.1 and 3.2, this section explores the specific research techniques chosen to answer the research questions in each of the three phases.

3.3.1 Research methods employed in Chapter 4

In the UK there has been relatively little focus on the potential role of TES to support decarbonisation of the energy system, or to explore the range of factors which could impact on deployment (Ma et al., 2018; Taylor et al., 2013). Within the initial research phase, I aimed to address this through an exploration of sociotechnical factors in the development, application and carbon reduction impact of TES through a qualitative survey and document analysis. This was conducted the following research question:

RQ1. What is the current state of UK thermal storage deployment and how do sociotechnical characteristics shape deployment prospects?

In this section I set out the data collection and data analysis techniques used to undertake this inquiry.

3.3.1.1 Data collection

To carry out this research I undertook two-stage approach to data collection. First was a survey of potential projects and review through a classification matrix prior to inclusion. Projects were assigned an alphanumeric identifier and mapped geographically. Once each project was ruled eligible for inclusion, a more detailed document search exercise was conducted, with each document reviewed through a source evaluation matrix. This process is outlined in the following sections.

Stage 1 - project identification, classification and mapping

First was a desk-based survey of TES projects in the UK between January 2018 and February 2019. The search for projects began with author experience and snowballing from personal contacts, attendance at industry and policy events as well as UK government publications and prior research (Birch et al., 2016; Eames et al., 2014). I applied a criterion approach to purposeful sampling to include a range of technology and project types without attempting to achieve data saturation (Emmel, 2013).

I created a matrix of TES attributes through which each potential project was assessed to determine project eligibility for inclusion and later to support the data analysis. Technical aspects were included in the framework, such as what type of storage was used, how the storage was used in the provision of heating, the temporal horizon of how the storage was to be operated, and whether it provided heating, cooling or both. Project-level attributes included whether the scheme supplied residential customers, commercial customers, or a mixture of both, and what type of organisational model was used by the instigator of the project. The matrix with attributes and attribute values is shown in Table 3.1.

Table 3.1 Project classification matrix with all attribute values

Attribute	Attribute values
Storage type	Aquifer, Borehole, Cryogenic, Electric storage heater (ceramic bricks), Phase-change material, Tank, Heat sharing network, Mine shafts
Storage horizon	Short-term, Seasonal
Storage approach	Sensible, Latent

Attribute	Attribute values
Heating system type	Domestic, Communal (one building), District (several buildings), District (neighbourhood), District (city-scale)
Location of storage	Within end-user property, Centralised within network, Distributed throughout network
Grid-balancing function	Yes / No
Devolved powers involvement	City Deal, Devolved government support, Local Growth Fund, Strategic regional authority
Ownership model	Community energy group, Local authority, Private landlord, Registered Provider, Public sector - non-housing, Utility company
Operational model	Community energy group, Local authority, Private ESCo, Private landlord, Public-private ESCo, Public sector - non-housing, Utility company
Heating and cooling	Heating, Both heating and cooling
Main heat generation or supply	Air source heat pump, Balancing heating and cooling, CHP/CCHP, Grid electricity, Locally generated electricity, Energy from Waste, Geothermal, Sewerage, Solar thermal, Water source heat pump
Type of development served by thermal storage	Commercial customers only, Residential customers only, Mixed
Project status	Operational, In-development
New build or retrofit project	New build, Retrofit, Both
Project involved change of heating type	Yes, No
Location type	Urban, rural

The standard I adopted for project eligibility was that each of the classification attributes from the classification matrix could be applied. In some cases, a project which was interesting and in scope was ruled out because this standard was not met. An example of this was where a shared thermal store was due to be included along with communal battery, as part of a new housing development in the city of Nottingham aimed at showcasing community energy options. All attribute values could be assigned aside from ‘project status’ because there was no clear evidence that the thermal storage element had progressed beyond the theoretical stage. As such, the project was discounted.

A sample of thirty-three projects met the required standard and were included in the sample. To identify TES projects, each was given an alphanumeric identifier. Appendix A lists the identifiers along with a brief description of the project including the type of thermal storage. Classification of each project by attribute is included at Appendix B.

Projects were then mapped in ArcGIS according to the XY coordinate location of the storage device, with the results of this shown in Figure 4.1. In some instances, the storage technology was not based in a single location but dispersed across a wide area. An example of this was with the HEATBATT1 project where the dwelling-based TES devices were installed in 766 dwellings in a belt across south-east Scotland. In this case I identified that the leading organisation’s central office was broadly in the centre of that belt and chose this as the mapped location.

Stage 2 – detailed document search and evaluation

Following the inclusion of the project in the sample, the next step was to collect and analyse information from a variety of secondary sources. Source materials included local authority meeting minutes and officer reports, planning application submissions and a range of other published material including public information videos, resident engagement leaflets, and conference presentations etc. Planning application documents were found to be a useful source of information about the technical aspects of the thermal storage when the technology was being included to help a developer meet local carbon reduction targets for new developments. A summary of sources by type is shown in Table 3.2, with a full list of sources provided at Appendix C.

Table 3.2 Desk survey data by source type and number included

Source type	Number of sources
Web page	73
Report	37
News article	20
Planning application	19
Conference paper or presentation	11
Brochure/advert/pamphlet	13
Other	13
Total	**186**

Data availability was variable depending on the type of developer involved. Local authority project initiators tended to make good information publicly available through published reports and public records of meetings. Social housing developers aside from local authorities, known in the UK as Registered Providers (RPs), and other public bodies, provided reasonable but somewhat lower levels of data. It was challenging to collect enough data from developments led by private companies where there was no obligation for them to make documents available. However, several projects of different developer types were included as part of research or demonstrator schemes. In these instances, published data was more readily available.

The type of data collected was 'secondary data', where it was produced regardless of the existence of the study. A key challenge I recognised when using this type of documentary evidence is whether the documents being studied will be recognised as sufficiently credible to provide a commentary (Lee, 2012). In addition, a potential weakness of the use of documentary evidence is that it is limited to the perspective, agenda and biases of those who produced the documents under review (Sovacool et al., 2018). To try and account for the weaknesses of secondary data, I analysed each source through an evaluation matrix extended from O'Leary (2013, p. 248). In doing this, I carefully assessed the likely motivations and intentions behind production of the source, including: who produced the material, who the intended audience was, why it was published, whether the source is directly related to the thermal storage or not, what the relation of the source material is to the project overall and to the thermal storage specifically. A summary of this framework is shown in Table 3.3 which lists several examples of each attribute. Whilst I did not include or exclude documents based on the source evaluation matrix, I undertook to acknowledge and explore the impact of non-neutrality through the analysis reported in Chapter 4.

Table 3.3. Source analysis matrix, adapted from O'Leary (2013). Illustrative examples provided.

Attribute categories	**Example attribute values**
Reference type	Brochure/advert, News Article, Planning application, Report
Type of organisation that produced the source	Community Energy Project, Consultant, Local planning authority, Private project developer

Attribute categories	Example attribute values
Relation of producing organisation to project.	Contractor building part of project, Landowner where technology can be used, Local government covering area, Technology provider
Why was this source material produced?	Analysis of project by funding organisation, informing public bodies about sustainable options, meet planning requirements, Seek approval (officers to councillors)
Who is the intended audience?	Customers or potential customers, Planning authority decision-makers, Project developers, Trade journal readers
How does the source relate to the project?	Information and promotion of the project, Journalism about the project, Part of planning application, Source covers technology but not project specifically
How does the source relate to the thermal storage specifically?	Direct, Indirect
Why is the thermal storage being referred to?	Helps meet planning requirements, Part of innovative nature of project, Thermal storage enables other aspects of the project, Thermal store requires permission

3.3.1.2 Data analysis

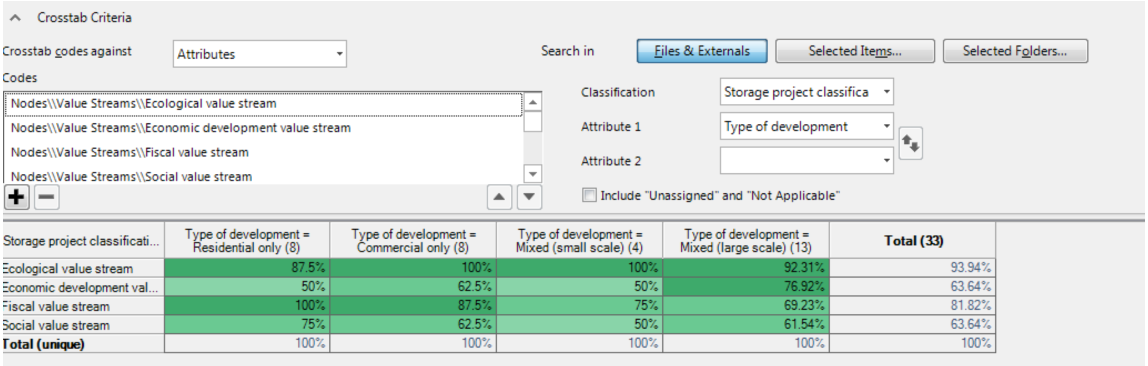
To try and understand the current state of thermal storage deployment in the UK, I employed the sociotechnical project classification matrix shown in Table 3.1. The development of this framework reflects the abductive approach outlined in section 3.1 because I created it based on interesting aspects of the data which I felt might be relevant in comparing and contrasting different technological and organisational configurations, their interaction with sociotechnical factors and the search for non-traditional values. However, this process was also informed by my prior understanding of the technology, of organisational structures, and so on, as well as being guided by the literature discussed in Chapter 2. The classification matrix enabled me to undertake a series of analyses on sociotechnical aspects of the thermal storage such as project location, ownership model, what type of technology was being used, how heat was supplied to end users, whether it was residential or commercial project, or a combination, and so on.

To explore sociotechnical factors and their impact on deployment, I interrogated the documentary evidence through application of sociotechnical frameworks including the coevolutionary framework (Foxon, 2011) and multilevel perspective (Geels, 2002). I used the results of this in conjunction with the classification matrix to build up a picture of the survey field in relation to key sociotechnical attributes. Finally, to explore search for non-traditional values by project developers, I conducted a qualitative thematic analysis on the source materials through application of extended infrastructure business model (EIBM) (Foxon et al., 2015). Below the four headline themes of non-traditional values (*social*, *environmental*, *economic development*, *fiscal*), a set of 50 sub-themes were created from the data through a process of thematic coding broadly following Braun & Clarke (2006). Table 3.4 provides a summary of the framework with examples under each headline value.

Table 3.4 Thematic analysis framework with illustrative examples

Attribute categories	Example attribute values
Fiscal values	Direct income from sale of energy, Cost saving on grid reinforcement, Energy bill reduction for end users, Cost saving by use of cheap energy when it is available
Social values	Fuel poverty reduction, Health improvements, Reduces subsidies on fuel bills from network reinforcement, User comfort through better design or control
Ecological values	Carbon reduction, Air quality improvement, Making use of low carbon energy when it is available
Economic development values	Enhancing reputation of area, Local job creation, Create new business growth by offering low cost energy to new commercial development

I employed the NVivo software to undertake a series of cross-tabulations to identify spread of variables and undertake comparisons of value coding against project classification variables (e.g. whether local authority or housing association projects were more likely to target social value streams such as fuel poverty reduction, in comparison to other landlords). Figure 3.3 shows an example of how this was done for headline themes against 'Type of development' attribute. The percentage figures were not used numerically but as a basis to apply a colour gradient to support the search for correlations and connections.



Storage project classificati...	Type of development = Residential only (8)	Type of development = Commercial only (8)	Type of development = Mixed (small scale) (4)	Type of development = Mixed (large scale) (13)	Total (33)
Ecological value stream	87.5%	100%	100%	92.31%	93.94%
Economic development val...	50%	62.5%	50%	76.92%	63.64%
Fiscal value stream	100%	87.5%	75%	69.23%	81.82%
Social value stream	75%	62.5%	50%	61.54%	63.64%
Total (unique)	100%	100%	100%	100%	100%

Figure 3.3 Example output crosstab query results for 'value stream by type of development', displaying column percentages and colour gradient shading

3.3.2 Case study design employed in Chapters 5 and 6

Case studies can be considered both a research design and more specific research method (Yin, 2018). In Chapters 5 and 6, I applied an overall case study design which involved several methods including semi-structured interviews and document analysis. Defined as a research strategy involving an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence, case study methods are, regardless of the unit of analysis, dedicated to describing the subject in depth and in detail, holistically, and in context (Fallon, 2002; Robson, 2002). By their nature case studies are inductive and explanatory, seeking to assess a particular perspective rather than test a hypothesis (Sovacool et al., 2018). A challenge of case study research is defining and setting the boundaries to the 'case' under investigation, and it is now accepted that a case can be any *object of research which is limited in space and time,* including for example a country, a region, a city, an organisation, a decision process, a sector, a policy, or an event (Hancké, 2009). A case should however be representative of the phenomenon under investigation (Buchanan, 2012). The cases I selected were limited to approaches which:

- involved geoexchange or shared ground heat exchange as part of the provision of heating and cooling;
- are applicable in urban scenarios;
- are applicable in the United Kingdom;
- are non-fossil based, low carbon and compatible with zero carbon (through the UK's decarbonising electricity grid);

- are applicable to new developments as well as retrofitting (given that most of the building stock we currently have is likely to be standing in 2050).

One of the primary motivations for choosing case research was because it allowed me opportunity to tease out and disentangle a complex set of factors and relationships, albeit in one or a small number of instances, to attempt to discern meaningful findings beyond just that case. Through the rich examination of this overarching case, I attempted to reach wider conclusions about the impact of city regimes on the wider urban transition for heat.

3.3.3 Research methods employed in Chapter 5

Findings in Chapter 4 suggested that a particular approach to thermal storage, geoexchange, remains relatively niche in the UK. Results indicated that whilst projects so far tend to be small-scale and limited to supplying one heat user, the approach is applicable at a larger scale and there is a desire amongst developers to expand geoexchange projects to different types of mixed developments. This requires some of form of heat distribution system, and so comes with added complexity and challenges for developers which may have contributed to the low levels of deployment. I decided to investigate this issue in more detail through a case study of geoexchange thermal storage deployment in cities, and addressed this through following research question:

RQ2. What are the factors that have led to successful geoexchange deployment in UK cities?

This section outlines the data collection process through a series of semi-structured interviews and data analysis applying a thematic analysis to interview data to draw out success factors to wider deployment of geoexchange projects. Geoexchange is a contested definition as explored in Chapter 2, and in this study, I limited the case to systems which have the ability to actively recharge the source with waste heat.

3.3.3.1 Data collection

To gather primary data for analysis in this case study I conducted a series of interviews with local energy actors from a range of backgrounds and perspectives.

Practitioners were invited to discuss their experience of implementing geoexchange projects. Taking a critical realist stance, I accepted that there were potentially many valid perspectives, and I chose this qualitative research strategy to elicit participants' rich perspectives and interpretations.

To recruit suitable interview participants, I initially identified potential candidates through their involvement in the geoexchange projects explored in the prior research phase and through attendance at various industry and policy events and workshops. Further participants were recruited through a purposive snowball selection process. As a qualitative study, there is no equivalent to the calculations of sampling error used for quantitative survey research. However, I attempted to achieve a representative sample, based not on being comprehensive of all positions, but on seeing the role of interviewees as key informants from who I could elicit rich accounts from a range of perspectives (Alvesson and Ashcraft, 2012). When setting out I aimed for a sample size of between fifteen and twenty interviews based on understanding of the complexity of the study topic, the depth of the data collection from each participant, as well as on prior research (Hall and Foxon, 2014, Bush et al., 2016, Foxon et al., 2015, Hall and Roelich, 2016). The recruitment period began following ethical approval on 04 March 2019, and to achieve the sample I contacted twenty-nine potential interviewees between March and October 2019. Interviews took place between April and November 2019, with ten being conducted face-to-face and four remotely via video link. Table 3.5 details the roles and experience of the interviewees and the type of organisations they represented. I ended the recruitment process after fourteen interviews were successfully completed when the richness of the data collected was sufficient to undertake a worthwhile analysis.

Table 3.5 Phase 2 interviewees by descriptor, brief description and location of organisation represented

Descriptor	Type of organisation and experience	Location
LA1	Commercial Sustainability Manager of local authority who led on a large retrofit geoexchange project.	London
LA2	Former manager of sustainability service for local authority involved in heat network development. Currently heat networks consultant for national standards body.	London

Descriptor	Type of organisation and experience	Location
RSL1	Managing Director of energy services arm of Registered Provider (RP) which has installed geoexchange/SGHE.	North of England
RSL2	Regional Asset Investment Manager for RP involved in development of geoexchange and SGHE.	Properties across England
RSL3	Compliance Manager for RP involved in the delivery of several geoexchange projects of different typologies	East of England
INT1	Sustainability Manager for not-for-profit supporting RPs through procurement and management framework for heat pumps including geoexchange.	North West England
INT2	Senior Project Manager for a not-for-profit advice and expertise centre for renewables with a focus on community-led heat projects.	South West England
INT3	Independent consultant and policy specialist in heat networks. Technical Manager for international chartered institution	London
INT4	Global Lead for Geothermal and Groundwater Engineering at international professional services provider.	London
INT5	Specialist in legal and contractual aspects of decentralised energy including geoexchange and SGHE.	London
CEC1	Director of company which designs and installs heat pump projects in UK and Europe for the private and public sector	Scotland
CEC2	Managing Director of company which designs and installs geoexchange projects mainly for commercial customers	London
CEC3	Managing Director of company which designs and installs systems of geoexchange and SGHE	South West England
CEC4	Business Planning and Strategy Manager for global technology company specialising in heating and cooling solutions including heat pumps with ambient heat networks	London

I adopted a semi-structured interview approach due primarily to its suitability for addressing ‘how’ and ‘why’ questions of key events and get to insights which reflect participants’ perspectives (Yin, 2018). The interview style and questions were designed to prompt participants to report what they know as well as what they think and feel (i.e. their beliefs and attitudes) (Robson, 2002) about their experiences of implementing projects and their wider perceptions of the regime in which geoexchange operates. A copy of the ethically approved indicative interview script is included at Appendix D. Because the semi-structured approach allowed me to take interesting lines of enquiry, in each interview I modified the questions to follow-up interesting responses and investigate underlying issues. As an example, during the INT1 interview I was able to explore what was for me a previously unknown area of counterfactual business cases for social landlords relating to legal fees in securing access to conduct gas safety checks. To address challenges of rigour and my own researcher bias in the semi-structured interview process, during the interviews I encouraged participants to speak with as little prompting as possible, through phrases such as 'could you say a bit more about…'. I also found the tactic of being patient and allowing silences to be particularly helpful eliciting rich data because it gave participants the chance to think of other things that did not immediately spring to mind.

To support later analysis, each interview was recorded with the permission of the subject. The transcriptions were uploaded to NVivo for qualitative thematic analysis of the interview data.

3.3.3.2 Ethical considerations

I applied careful ethical standards to the planning, design and execution of the interview process. This included obtaining full ethical approval from the University of Leeds MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC) on 04 March 2019, under approval reference MEEC 18-024. A copy is included at Appendix E. The original approval was updated on 10 July 2019 to approve a 'notice of change' request. This was submitted to amend the period in which participants could request withdrawal following the interview from a fixed date to a rolling 4-week date following the date of interview. A copy is included at Appendix F.

During the interview process, at the point of first contact I provided a Participant Information Sheet to enable potential interview participants to make an informed decision about participation in the study (see Appendix G). On the date of the interview, I checked that participants had received and read the information sheet and asked them to sign a Consent Form (see Appendix H). If the interview was undertaken remotely, I asked the participant to sign the consent form electronically and email it after the interview. In all cases I countersigned the consent form, created a PDF, and emailed it to the participant for their records.

The information sheet and consent form instructed participants that their name would not be used in any published material, and they would be described using a descriptor such as CEC1, LA3 etc., which reflected the organisation type. I made it clear that there was a small risk they could be later identified from the answers they gave. Participants were informed they had four weeks following the date of the interview during which they could strike any answers from the record or decide to withdraw entirely and have their interview data deleted. No interview participants exercised this option. I followed data management procedures as set out in an ethically approved Data Management Plan. This included deleting audio recordings once transcription was completed and I had checked and corrected any pertinent missing or incorrect text.

3.3.3.3 Data analysis

Following interview and transcription, I analysed the interview data through a qualitative thematic analysis. I chose this approach to identify, analyse and report patterns in the interview data. Within the broad definition of thematic analysis lies a range of approaches and whilst they are all intended to interpret meaning from textual data, they involve different approaches including development of coding schemes and to what extent codes are based on pretexting theoretical frameworks (Hsieh and Shannon, 2005). I adopted a template analysis approach which is not wedded to any distinct methodology or theoretical commitment (King, 2012). Central to this technique is the creation of an initial coding template using a subset of the data, and a more flexible approach is taken to how the hierarchical coding structure is built up as opposed to the more rigid structure of generic coding proposed e.g., by Braun & Clarke (2006) and others (King, 2017).

Here I outline the process I undertook to carry out the template analysis, guided by the seven-step approach outlined by King (2017).

Step 1 – Data familiarisation

Following manual transcription of the first three interviews, for the subsequent eleven interviews I relied on an external transcription provider to get the audio data into text format. Undertaking manual transcription of the first three interviews enabled me to become closely familiarised with that data subset. However, this was very time consuming. I tested the alternative approach using a transcription service and compared the outcome in terms how well I felt able to get to know the data by reading closely. I found that it did not make a significant difference and so adopted this approach for the remaining interviews. The process involved at least one initial close reading of the whole transcribed interview without attempting to code and filling in any words the transcriber had missed by referring to the audio recording.

Step 2 – Preliminary coding

I began with a subset of five interview transcripts to undertake preliminary coding. This involved identifying and labelling fragments or chunks of data which I felt related to a particular topic or theme (Coffey, 1996). Examples of the types of codes developed at this initial stage included 'why gas boilers are popular,' 'saving residents money,' or 'just liking the cut of their jib.' I adopted a selective rather than complete coding strategy whereby I only coded text that I thought might help to understand the topic, and therefore was worthy of inclusion and further analysis (Braun and Clarke, 2013). This reflected the abductive approach because it involved use of prior knowledge and understanding to search for potentially interesting points about what might be acting as a barrier to geoexchange developments, what might unblock those barriers, or other areas I thought at that stage might be interesting to explore further. During this initial coding stage, I did not attempt to link or group themes and kept the structure flat.

Step 3 – Clustering

At this stage I began grouping and clustering the themes which appeared to be related. Mostly this was grouping themes within one hierarchy level, such as with a grouped theme of 'patient capital' referring to a situation where a developer maintains a long-term ownership or interest in a site. Within that group included the lower level of 'long-term view,' and 'need for legacy ownership' which I felt fitted well under that rubric. In some cases, the clusters quickly developed several levels of hierarchy, such as a theme of 'Renewable Heat Incentive' with sub-themes including 'impact of RHI closure with no replacement' and 'dithering by central government.' This small group was then clustered within a higher level 'National government policy' theme which included other multi-level themes such as 'Building regulations'.

Step 4 – Producing an initial template

Within stage four I used a set of *a priori* themes based on the coevolutionary framework. Rather than providing a set of direct themes to include in the analysis, I found that the five nodes of the framework made sense in helping me to further group and order the themes and clusters of themes. A majority of coding was located under the *institutions* and *technology* nodes. Finding that some themes clearly sat outside of coevolutionary framework but did align with the *landscape* and *niche* levels of the MLP, I introduced this framework into the template. The themes I was able to place under the nodes of the coevolutionary framework were broadly aligned with the *regime* level of the MLP so I placed the coevolutionary framework under the regime level in the emerging template, as indicated in Figure 3.4.

1. Multi-level perspective – Landscape
2. Multi-level perspective – Regime
    2.1. Coevolutionary – Ecosystems
    2.2. Coevolutionary – Technology
    2.3. Coevolutionary – Institutions
    2.4. Coevolutionary – Business strategies
    2.5. Coevolutionary – User practices
3. Multi-level perspective – niche level

Figure 3.4 Implementation of MLP and Coevolutionary frameworks into emerging template

At this stage the overall template down to the lowest level codes had become much more hierarchical, now being over five levels.

Step 5 – Applying and developing the template

I then began applying the template to the remaining interview transcripts, and continued to modify, refine, and develop the clustering of the template. This involved bringing in additional frameworks where I felt these might be helpful in the analysis to explore particular areas in more depth. This included the EIBM which I used to group the themes around aspects of business models including where developers were seeking to leverage non-traditional social or environmental values from their geoexchange project. I placed the seven EIBM elements as themes within the broader *business strategies* theme of the coevolutionary framework hierarchy. The *non-traditional values* theme was the most common, referenced by thirteen interviewees. I also brought in the *intermediary roles* framework within the *niche* theme of the MLP to help cluster different roles which intermediaries in the geoexchange development process seemed to be playing. In addition to the top-level *a priori* themes, I added several key themes as I applied the template to more data both within and outside of the hierarchical framework. For example, I found repeated examples of themes occurring that I felt could appropriately be grouped as *location-specific issues* and *actor decision-making*. Rather than sitting within the hierarchy, I felt these were more appropriate to be considered cross-cutting or integrative themes which linked across various nodes and levels of the template. This was because, for example, the main coding cluster within the *location-specific* issues theme was regarding different cities where interviewees felt that local policies, especially local planning policies, were being used effectively to support greater geoexchange rollout. The issues raised by the integrative theme cut across *institutions* cluster within the coevolutionary framework as well as the *regime* cluster of the MLP. As shown in Figure 3.5, because the structure of NVivo does not allow positioning of codes outside of the hierarchy, and I placed the cross-cutting themes within the hierarchy for the purposes of creating the template.

1. Multi-level perspective – Landscape
2. Multi-level perspective – Regime
2.1. Coevolutionary – Ecosystems
2.2. Coevolutionary – Technological systems
2.3. Coevolutionary – Institutions
2.4. Coevolutionary – Business strategies
2.4.1. Business model framework – Key partners
2.4.2. Business model framework – Key activities
2.4.3. Business model framework – Value proposition
2.4.3.1. Extended infrastructure business model framework – Fiscal value
2.4.3.2. Extended infrastructure business model framework – Social value
2.4.3.3. Extended infrastructure business model framework – Economic value
2.4.3.4. Extended infrastructure business model framework – Ecological value
2.4.4. Business model framework – Customer relationships
2.4.5. Business model framework – Channels
2.4.6. Business model framework – Customer segments
2.4.7. Business model framework – Cost structure
2.4.8. Business model framework – Org or financial structure
2.4.9. Business model framework – Business model
2.5. Coevolutionary – User practices
3. Multi-level perspective – niche level
3.1. Intermediary roles
3.1.1. Articulation of expectations and visions
3.1.1.1. Strategy development
3.1.2. Building of social networks
3.1.2.1. Gatekeeping and brokering
3.1.3. Learning processes and exploration at multiple dimensions
3.1.3.1. Communication and dissemination of knowledge
3.1.3.2. Provision of advice and support
3.1.3.3. Technology assessment and evaluation
3.1.4. Other
3.1.4.1. (Long term) project design, management and evaluation
4. Actor decision-making
5. Location-specific issues

Figure 3.5 Full template reflecting MLP, coevolutionary, EIBM and intermediary roles frameworks, as well as added cross-cutting themes (in yellow)

Step 6 – Applying the final template

I continued to develop the template throughout the process of coding of the whole dataset. The final template reflects the four frameworks I included in its creation – the MLP, coevolutionary framework, extended infrastructure business model, and intermediary roles frameworks – as well the added integrative themes.

I searched for patterns in the data and conducted a hotspot analysis to highlight areas of coding intensity to guide further investigation. This was based on the number of interviews in which each theme was mentioned (rather than the total number of mentions), and coded up from child nodes to parent nodes across the five levels. A visual representation of the hotspot analysis is shown at Figure 5.2 in Chapter 5. In the process of conducting the final analysis I often returned to the raw interview data to clarify uncertainties and examine how particular themes were presented by the interviewee in the context of their experience or the type of project they were involved in. In the analysis I considered questions about the themes such as what they might mean, what conditions may have been important to bring them about, and how the interviewee's perceptions and experiences may have shaped the way they talk about the issue etc.

Step 7 – Writing up

By the stage of writing up the coding template was very complex, over many levels and branches. As I looked for relationships between themes, tried to interpret the data, and began writing up the analysis, I grouped important themes into five logically connected elements which I mapped onto the geoexchange development process and formed that basis for developing a 'critical success factors' framework. A description of this is provided in Chapter 5, with a copy of the full framework displayed at Appendix I.

3.3.4 Methods employed in Chapter 6

The findings in Chapter 5 emphasised the importance of the local regime, institutional factors and location-based impacts on geoexchange deployment. In residential settings, geoexchange combined with ambient temperature heat distribution (which I termed shared ground heat exchange) addressed some of the challenges associated with density and the lack of space for borehole fields, as well as some of the issues common to traditional high temperature district heating. I decided to explore these areas in more detail in the final phase of research, focusing more explicitly on the role of municipal governance and its impact on the place-based selection environment for shared ground heat exchange (SGHE). I addressed this through the following research question:

RQ3. Within the same legal and planning framework, what actions are local authorities taking to support or constrain the deployment of shared ground heat exchange, and what effect is this having?

I chose to undertake this as a qualitative case study because I wanted to understand the issue in depth and in detail, and where context, especially the locational context, appeared likely to be key to understanding why geoexchange was successful in some cities and not others. One UK city, Bristol, was cited repeatedly during the research conducted in Chapter 5 as an example of where local policies and practices are being successfully enacted to support the shift to SGHE. I elected to undertake a comparative case study with Bristol as a critical case, compared to another broadly comparable UK city. As a local activist on climate emergency and social justice issues in Leeds, including campaigning successfully for the local authority to declare a climate emergency and pledge to achieve net-zero carbon by 2030, I am to some extent embedded in the city's sociotechnical regime including for domestic heating. I chose to exploit this and selected Leeds as the comparison case. This was backed up by evidence from Chapter 5 suggesting that Leeds City Council was seen by practitioners to be something of a laggard in this area.

The two case cities were suitably comparable for the research purpose because they:

- Are major UK cities with large populations;
- Feature large unitary-type planning authorities which deal with many hundreds of planning applications annually;
- Are subject to the same planning framework (covering England and Wales, with different regulations for Scotland, Northern Ireland and the Greater London area);
- Have made broadly similar commitments to achieve net-zero carbon by 2030.

This section outlines the scope of the case study and describes the data collection process through a desk survey of planning application and supplemented by a series of semi-structured interviews. The data analysis technique is outlined in section 3.3.4.3 which included chronological and thematic analyses.

3.3.4.1 Data collection

Data gathering took place from June 2020 – May 2021 and involved collecting a repository of both documentary and interview evidence on a range of sub-cases. The case boundary in each city was set as the limit of the planning authority. In each case city, I identified fifteen subcases of new or retrofit residential projects for inclusion in the sample. This included all instances of the use of SGHE I could find. The search strategy for subcases was based on Chapter 4 and 5 data, snowballing from interviewees and personal contacts, and searching through the online planning portal in both case cities.

I set the inclusion criteria for the search as:

For SGHE subcases:

1. Where SGHE approach was used in the development. This included instances where the system had the potential to act in geoexchange mode, even if this functionality was not activated at the time of construction.

For all subcases:

2. Where the technology was used in a residential development supplying multiple dwellings.
3. Where the scale of the project was over 10 dwellings.

Beyond the SGHE subcases, I included a range of other heating technologies through a typical case approach to purposeful sampling which sought to include a range of heating types but based on what was happening in each case city (Emmel, 2013). I did not attempt to achieve saturation but ended the search once I had achieved fifteen subcases in each city featuring a range of heating types that reflected the trend of chosen heating technologies in each case city.

The final sample included eight SGHE subcases as well as a range of others. Table 6.1 shows a summary of the sample by primary heating technology type.

Documentary data collection

Most documentary data on the individual subcases was retrieved from the planning portal in each case city. This is a publicly available source of information on all planning applications that are published prior to planning authority review to allow public scrutiny and support or objection. Most of the information relating to the heating technology proposed for each subcase was contained within the Sustainability Statement or separate Energy Strategy. These documents frequently went through many iterations during the course of the planning process, and I collected all versions in order to undertake a chronological analysis of the timeline in each instance.

In addition to planning application documents, published minutes and recordings of local authority meetings (e.g., panels where councillors decided on planning applications) provided a useful resource to examine the decision process. I also collected documentary evidence relating to local planning policies from the websites of the two local authorities. A summary of all reference material by source type and number is shown in Table 3.6, with a full reference list at Appendix J.

Table 3.6 Phase 3 data by source type and number of documents included for each case city

Source type	Bristol	Leeds
Planning application submission document	46	56
Planning officer report to councillors	19	25
Planning officer intervention (usually email)	16	0
Planning authority committee minutes and video recordings	12	26
Planning authority decision and conditions statement	19	22
Non-planning report	2	17
Interview transcript and follow-up with participants	8	5
News article	6	13
Non-planning policy document	3	2
Planning policy document	5	15
Brochure / website / social media post about subcase	8	7
Practice note	1	1
Total subcase documents	**145**	**185**
Non-city specific document	5	
Total documents	**335**	

Because I was looking for certain key information to compare and contrast subcases and conduct the analysis, the document search was targeted to elicit that specific data. This included various types of technical, numerical and descriptive data, such as modelled carbon reduction figures against different heating technologies and narratives around why certain approaches were chosen or not.

Interview data collection

The second phase of data collection was conducted through a series of semi-structured interviews with key informants involved in the subcases. The interviews were undertaken to generate qualitative data for a subsequent thematic analysis, as well as to supplement the documentary analysis and explore participants' perspectives and interpretations of how and why decisions were made to choose geoexchange or other approaches.

Potential interview participants were identified from the publicly available planning documents as well as internet searches and snowballing from prior interviewees. Table 3.7 details the roles and experience of the interviewees and the type of organisations they represented.

Table 3.7 Chapter 6 interviewee descriptors and overview

Identifier	Type of organisation and experience
DEV-1	Senior Development Manager for local authority responsible for delivering new local authority social housing schemes
DEV-2	Regional Development Manager for large construction company delivering new housing developments
CON-1	Energy and Sustainability Specialist for energy consultant responsible for producing energy strategies for new developments
PLANNING1	Senior Planning Policy Officer with responsibility for climate related planning policy for planning authority covering case area
CON-2	Principal Sustainability Consultant for energy consultant responsible for producing energy strategies for new developments
DEV-3	Mechanical, Electrical and Heating Manager for local authority responsible for heating and retrofit project for existing social housing
DEV-4	(Formerly) Regeneration Team Leader for community development trust responsible for delivering community-led affordable housing
BUILD-1	Associate Director for medium-sized construction company responsible for delivering new housing developments
CON-3	Director of small energy consultant responsible for producing energy strategies for new developments
DEV-5	Managing Director of private developer. Development model based around low-car, low energy developments with modern methods of construction
PLANNING-2	Principal Planner with responsibility for climate related planning policy for planning authority covering case area
DEV-6	Founder and current resident of community-led low energy housing development responsible for finding solution to replace gas boiler top-up

I repeated the successful approach previously taken in Chapter 5 research regarding the semi-structured approach and use of an institution-approved transcription services provider.

3.3.4.2 Ethical considerations

Applying the same rigorous ethical standards to this research as in the previous set of interviews, I obtained ethical approval from the University of Leeds Engineering and Physical Sciences Research Ethics Committee, under approval reference LTSCPE-004, on 16 June 2020. A copy is included at Appendix K. Copies of the ethically approved Participant Information Sheet, consent form and indicative interview script are included at Appendix L-N. No participants exercised the option to have any data struck from the record, although in one instance, the participant asked that their connection to another subcase within the study was not revealed, and I met this request.

3.3.4.3 Data analysis

I initially classified each subcase according to a set of thirteen pertinent attributes and built up a table of key subcase information. In a similar approach taken in earlier work, I created the framework abductively based on the data as well as my understanding of the topic from prior research and literature. Table 3.8 shows a summary of the framework attributes, with a description of each subcase included at Appendix O.

Table 3.8 SGHE subcase attributes and attribute values

Attribute	Attribute values
Scheme type	New build / retrofit
Number of dwellings	Provide number
Developer type	Local authority, private, community-led, registered provider
Developer name	Company name
Energy consultant name	Company name (if this changed, list multiple entries)
Initial heating type	SGHE, direct electric panel heaters, individual gas boilers, ASHPs, connection to district heating, onsite communal
Final heating type	As above, highlighted if changed from initial
Planning application reference	Provide alphanumeric reference (if multiple applications list multiple entries)
Planning status	Current, not current
Build status	Construction underway, construction not yet started, occupied
Deciding committee	E.g., Development Control A (Bristol), City Plans Panel (Leeds)

Attribute	Attribute values
Date of planning decision	Provide date (if multiple dates list multiple entries)
Planning decision	Approve subject to conditions, approve not subject to relevant conditions, refuse
Conditions imposed	Brief summary of planning conditions imposed, e.g., provision of updated sustainability statement

I then conducted a chronological analysis of the data to build up a timeline of events for each subcase. Following Lee (2012), the intention was to establish a sequence of events which included the period of document composition, their use, and an assessment of their impact. The document date was key to a chronological analysis, where I was particularly interested to explore where the heating technology changed during the decision process, for example from individual gas boilers to shared ground heat exchange. This also helped establish which planning policies were in force at the time of the planning application. I also conducted a quantitative analysis of the carbon reduction impacts of various planning policies and heating technology measures. The results are shown in Table 6.3 to Table 6.14.

To build up the final analysis, I undertook a 'case-based' approach to cross-case synthesis to retain the integrity of each case and then compare or synthesise any within-case patterns across the cases (Yin, 2018). With a replication research design, I analysed each case in turn before bringing them together through a cross-case comparison to compare and contrast the findings from each. To search for deeper aspects of causation behind the organisational decision process, I carried out a thematic analysis applying the combined sociotechnical frameworks developed in Chapter 5 to guide the analysis. This included a hotspot analysis to identify areas of coding intensity for closer investigation. Because of the large numbers of documents in the sample, I conducted this on a subset of 90 documents, with 45 from each case city including the interview transcripts. I continued to include documents in the analysis until I felt there were no additional insights to be gained. The hotspot analysis (see Figure 6.1 for high-level diagrammatic representation) revealed clusters of themes in both cities relating to planning policy design, implementation and enforcement activities.

3.4 Chapter summary

The overall aim of this applied research study is to gain a greater understanding of the role of TES in the urban energy transition for heat. This chapter has set out the approach to undertake the study and meet this aim. A range of quantitative and qualitative techniques were employed to address specific research questions relating to different aspects of TES in the energy transition. The chapter explored the philosophical worldview which defined the nature of the study, the research design which brought the study to life, and the specific range of research methods employed to answer the overarching research question and three more specific research questions, with one for each empirical chapter. The aim of setting out the methodological backbone of the study in this way is to recognise the vital importance of considering these aspects in detail throughout the course of the study, to produce robust and reliable research.

4 Sociotechnical factors shaping the prospects for thermal energy storage

4.1 Introduction

In this chapter, I applied a sociotechnical perspective to explore important factors affecting the development, application and carbon reduction impact of thermal energy storage (TES) in the UK. The aim of this work was to fill a knowledge gap on the current state of thermal storage deployment in the UK and important sociotechnical factors in wider deployment which was established in Chapter 2. Through this I aimed to explore an array of factors including the motivations of the different actors involved, the interactions between them, and the choices made along the way.

I sought to address these issues through the following research question:

RQ1. What is the current state of UK thermal storage deployment and how do sociotechnical characteristics shape deployment prospects?

To undertake the research, I conducted a desk-based survey of thirty-three TES schemes from urban settings in the UK. The analysis included technical aspects of thermal storage technology and its role in the energy system, the geographical setting and locational context of the thermal storage projects, and the role of organisations and actors in the deployment, investment and decision-making process.

The analysis took place in two phases. I first classified thermal storage projects according to a matrix of sociotechnical attributes. A classification of each project against the matrix is included at Appendix B. For each project, I then explored sociotechnical factors using the nodes of the coevolutionary framework, including through a qualitative thematic analysis on the source materials, applying the *extended infrastructure business model framework* (EIBM) to identify the types of traditional economic values and non-traditional social, environmental and local economic development values that project developers sought to capture. The results of this work are set out in section 4.2.

4.2 Presentation of results

In this section, I present the results to the research question through a series of sub-sections highlighting the current state of UK TES deployment. The results presented below including a detailed analysis of *technology* types and combinations, along with geographical and organisational aspects of TES deployment. Then other important sociotechnical factors shaping deployment are introduced through the remaining four nodes of the coevolutionary framework: *ecosystems*, *business strategies*, *institutions* and *user practices*.

4.2.1 Current state of UK thermal storage deployment

4.2.1.1 Technology

To examine the technical and technological aspects of UK TES deployment, I classified each of the thirty-three projects according to a range of key attributes. These included the physical storage medium itself, whether the technology provided short-term internal or external system balancing or longer-term seasonal storage, and what types of heat generation and supply arrangements the thermal storage was combined with. The matrix shown at Appendix B shows how I assigned and classified each project against this framework. The sample featured a vibrant mix of technology and organisational combinations but found little evidence of convergence around particular alignments between these. Table 4.1 shows a summary the projects in each classification, and in the remainder of this section, I explore the most important aspects in further detail.

Table 4.1 Summary of TES types and combinations [no. of projects with each attribute] (Note some projects feature multiple attributes so numbers do not equal 33 in all attribute class sections.)

Storage type	Location of storage	Heat source	Heating system type
Aquifer [6] Borehole [3] Cryogenic [3] Electric storage heater (ceramic bricks) [3] Phase-change material [1] Tank [15]	Centralised within network [27] Distributed throughout network [2] Decentralised within end-user property [5]	Balancing heating and cooling [6] Air source heat pump [2] CHP/CCHP [7] Grid electricity [3] Locally generated electricity [2] Energy from Waste [2]	Domestic [5] Communal (one building) [3] District (several buildings) [10] District (neighbourhood) [8] District (city-scale) [6]

Heat sharing network [2] Mine shafts [2] Underground mass transit [1]		Geothermal [4] Sewerage [2] Solar thermal [1] Water source heat pump [5] Waste heat [7]	
Heating/cooling	**Storage horizon**	**Grid balancing**	**Heat network type**
Heating only [16] Both heating and cooling [17]	Short-term [23] Seasonal [12]	Yes [14] No [19]	High temperature [11] Low/ambient temperature [6] Not applicable / unknown [17]

4.2.1.1.1 Storage type, approach and horizon

As shown in Table 4.1, projects in the survey adopted a wide array of different technological options and combinations for thermal storage. Tank-based storage was the most common of nine types in total. Considering the type of storage as being sensible, latent or thermochemical, most employed a sensible approach. This included energy storage through water in tanks but also in slow-moving aquifers, through the heating of ceramics in electric storage heating, or in the earth through boreholes. There were no thermochemical storage projects in the sample, but two latent heat approaches were included. In one example, ice storage was used to reduce peak cooling demand in commercial premises. In the other, phase-change materials (PCMs) were deployed as part of a dwelling-based 'heat battery' system, where the batteries were charged through both off-peak grid and on-site solar PV-generated electricity.

I found several approaches to the use of thermal storage that I collectively termed 'geoexchange'. As explored in Chapter 2, instead of the continual removal of heat typical of most GSHP projects, in these arrangements the ground is actively recharged with heat over the year using waste energy to prevent system decline and enable constant balancing. This included a series of university buildings connected to a shared borehole thermal storage via an ambient temperature heat network, or standalone commercial sites recycling internal heating and refrigeration with ground thermal storage through novel directional drilled boreholes. Other geoexchange approaches involved capturing of summer heat from within a local authority facility with large cooling needs, and one where an ASHP powered with excess summer solar PV electricity generated heat for winter storage. This served a community facility and nearby homes through a small ambient heat network.

Twelve projects in the sample operated on a seasonal basis where heat energy was stored to meet some winter peak demand. Table 4.2 shows some technical and configurational characteristics of these seasonal storage projects.

Table 4.2 Seasonal storage project characteristics [no. of projects with each attribute]

Storage type	**Heat generation**
Aquifer [6] Abandoned mine shafts [2] Borehole [3] Cryogenic [1]	Balancing heating and cooling [2] Air source heat pump [1] Energy from Waste [1] Geothermal [3] Water source heat pump [4] Waste heat [1]
Location of storage	**Heating system type**
Centralised within network [12]	Communal (one building) [3] District (several buildings) [7] District (neighbourhood) [1] District (city-scale) [1]

The seasonal projects featured centralised network storage primarily through aquifers, abandoned mine shafts and boreholes, and in all cases were combined with heat networks to deliver heat to end-users. I did not identify any dwelling-based seasonal storage technologies, with the smallest scale being single commercial supermarket buildings. As an example of how seasonal storage was delivered, in one case a new wing of a national museum had been constructed to use the underlying chalk aquifer to meet some seasonal heating and cooling needs. To mitigate summer cooling demands, the temperature of the aquifer was reduced over winter as a result of the removal of heat energy to provide heating, and vice versa.

4.2.1.1.2 Heating system type and storage location

Most projects in the sample employed storage centrally and connected to end users through heat networks for heat delivery. Some of these employed traditional third generation high temperature heat networks. These were associated with gas or Energy from Waste (EfW) fired combined heat and power (CHP) heat generation in most cases, but also included some examples where thermal storage was facilitating additional waste heat sources. Five of the projects combined thermal storage with low or ambient temperature (fourth or fifth generation) heat networks, and these included some of the geoexchange projects as well as another which combined river source heat with an 'energy loop' where heat was stored and shared through a low temperature network serving a mixed commercial and residential site.

Five projects employed decentralised dwelling-based storage to supply heat either directly through electric storage heaters, which store heat in ceramic bricks, or through water tanks forming part of the dwelling heating system. There was one decentralised storage project where a novel phase-change material 'heat battery' approach was deployed in residential dwellings, to make the most of onsite solar electricity generation from roof-mounted panels, and supply heat from a smaller volume than from a typical hot water tank.

4.2.1.1.3 Heat generation source and the role of thermal storage

Eleven types of heat generation were used across the projects, and all apart from the CHP projects relied on electricity (either from the mains electricity grid or locally generated) as either a primary energy source, or to power the capture and provision of waste heat from the environment. CHP generation is not low carbon when fired with natural gas, but tank thermal stores were employed to reduce the amount of fuel required by maximising heat recovery and allowing the CHP to modulate in line with renewable generation without sacrificing the efficiency of the system. One project employed trigeneration CHP (cooling, heating and power, or CCHP) and a 500,000-litre thermal store to "*improve utilisation of the low-carbon plant*" [TANK11] and enable the use of renewable plant-oil fuel.

Other heat generation concepts were being explored in many cases and thermal storage was employed to facilitate the use of low carbon heat sources. This ranged from solar thermal capture and onsite renewable electricity, but also included the use of grid electricity, where the thermal storage was enabling time-shifting electric heat generation when the carbon content of grid electricity was lowest.

Thermal storage was enabling the capture and use of waste heat as the primary energy source in seven projects. This included capturing heat from the sewage system, as well as onsite cooling which generates waste heat as a natural by-product. In one case a large air source heat pump was employed to recover waste heat from the London Underground train network, where a tank thermal store had been installed within the energy centre to complement two gas-fired CHPs which supply electricity directly to the heat pump when power from the grid was most expensive.

To assess connections between primary heat generation and type of thermal storage, I crosschecked the two characteristics. The results are shown in Table 4.3.

Table 4.3 Heat generation type with associated thermal storage type [no. of projects with each attribute]

Storage type	Heat generation
Aquifer [6]	Water source heat pump [4], Waste heat [2]
Borehole [3]	ASHP [1], Waste heat [1], Balancing heating and cooling [1]
Cryogenic [3]	Locally-generated electricity [1], EfW [1], Geothermal [1]
Electric storage heater [3]	Grid electricity [3]
Phase-change material [1]	Locally-generated electricity [1]
Tank [15]	ASHP [1], CHP [7], Locally-generated electricity [1], EfW [2], Geothermal [1], Sewerage [2], Solar thermal [1], Waste heat [3]
Heat sharing network [2]	Water source heat pump + balancing heating and cooling [1], Waste heat + balancing heating and cooling [1]
Mine shafts [2]	Geothermal [2]
Underground mass transit [1]	ASHP + waste heat [1]

As shown in Table 4.3, some thermal storage types were closely aligned to heat generation, such as all CHP projects utilising tank thermal storage, and all electric storage heater projects used grid electricity. Others were more flexible however, with tank storage being the most versatile approach, although this was also the most ubiquitous storage type which supported this range of uses.

4.2.1.1.4 Grid balancing provision

Fourteen projects in the survey fulfilled an electricity grid-balancing function. These included decentralised dwelling-based storage through electric storage heaters, hot water cylinders and PCM heat batteries, where many separate systems were aggregated together to provide a storage resource to the grid through demand-side response services. Other projects employed large centralised thermal storage through tanks or boreholes to provide this service. Project business models reflected this, with income from grid flexibility payments or savings from dynamic pricing tariffs forming part of the viability of the project. Table 4.4 shows a summary of key attributes of grid balancing projects. The results demonstrate that this functionality is compatible with a range of thermal storage types, heat generation and supply arrangements.

Table 4.4 Grid balancing project characteristics [no. of projects with each attribute]

Storage type	**Heat generation**	**Heat network type**
Tank [6] Borehole [3] Electric storage heater [3] Heat sharing network [1] Phase-change material [1]	Balancing heating and cooling [3] Air source heat pump [1] CHP/CHP [4] Grid electricity [3] Locally generated electricity [2] Energy from Waste [1]	High temperature [5] Low/ambient temperature [3] No heat network [6]
Location of storage	**Heating system type**	**Business strategy**
Centralised within network [8] Distributed throughout network [1] Decentralised within end-user property [5]	Domestic [5] Communal (one building) [2] District (several buildings) [2] District (neighbourhood) [3] District (city-scale) [2]	Experimental/demonstrator [6] Commercial basis [2] Non-commercial basis [6]

4.2.2 Geographical context

To assess connections and interplay between thermal storage applicability and geographical context, I mapped the projects by primary location to examine geographical spread. Figure 4.1 shows a map of project distribution across the UK.

Figure 4.1 Map showing geographical location of UK thermal energy storage projects (Reproduced from Ordnance Survey map data by permission of the Ordnance Survey© Crown Copyright 2020).

Figure 4.1 shows that projects were located across England, Scotland and Wales (although not in Northern Ireland), with hotspots of activity visible in London and the Thames Valley, Southern Scotland, the South West and the Midlands.

Location had an impact on the type of storage when it depended on geological features such as aquifers or previously worked coal seams leading to now abandoned flooded mine shafts. There were hotspots of activity in developing aquifer storage in London, using the London Basin chalk aquifer, with another in Birmingham making use of the Birmingham sandstone aquifer. The UK is considered as viable for greater rollout of aquifer storage with suitable geological conditions across the South East, Birmingham, Liverpool and East Anglia (HM Government, 2016a). This was also an important consideration for the projects exploring abandoned flooded coal mines, illustratively titled 'anthropogenic aquifers' to emphasise their scale and human origins (Adams and Younger, 2001). I also found activity in urban centres above previously worked coal seams in South Wales, the Midlands, and central Scotland. This potential is significant as many UK towns and cities developed due to their proximity to coal reserves, with around 28% of homes in the UK suitably located to benefit from this resource (Bailey et al., 2016).

I found a clear clustering of projects in urban locations with only one site in a non-urban setting. In Table 4.5, I identified the projects by area and ranked according to population. This illustrates the weighting of thermal storage projects in urban areas, with a hotspot of projects visible in the #1 ranked population centre in the UK.

Table 4.5 Project locations identified by broader 'built-up area' (ONS, 2011) and areas ranked by relative population and population density

Location	Number of projects	Ranking in relative UK population	Population density ranking
Greater London Built-up Area	14	1	1
West Midlands Built-up Area	2	3	31
West Yorkshire Built-up Area	1	4	55
Greater Glasgow Built-up Area	4	5	68
South Hampshire Built-up Area	1	7	11
Tyneside Built-up Area	3	8	17
Bristol Built-up Area	2	11	18
Edinburgh	1	14	23
Stoke-on-Trent Built-up Area	1	19	59
Coventry Built-up area	1	20	12
Others	2	N/A	N/A

With only two projects from outside urban centres, and the major activity taking place in London, this highlights the suitability of thermal storage for use in urban settings. This may be due to agglomerations of heat producers and consumers and this is discussed further in section 4.3.

4.2.3 Organisations

To investigate the role and importance of organisations in the context of thermal energy storage, I first identified each of the 195 named organisations then mapped them to their involvement with each project and classified them using a framework of organisational types derived from literature and self-description in the data. Fig. 4.2 summarises the results of this classification, showing that the most prominent types of organisations involved in thermal storage projects were local authorities, technology developers, consultants and universities.

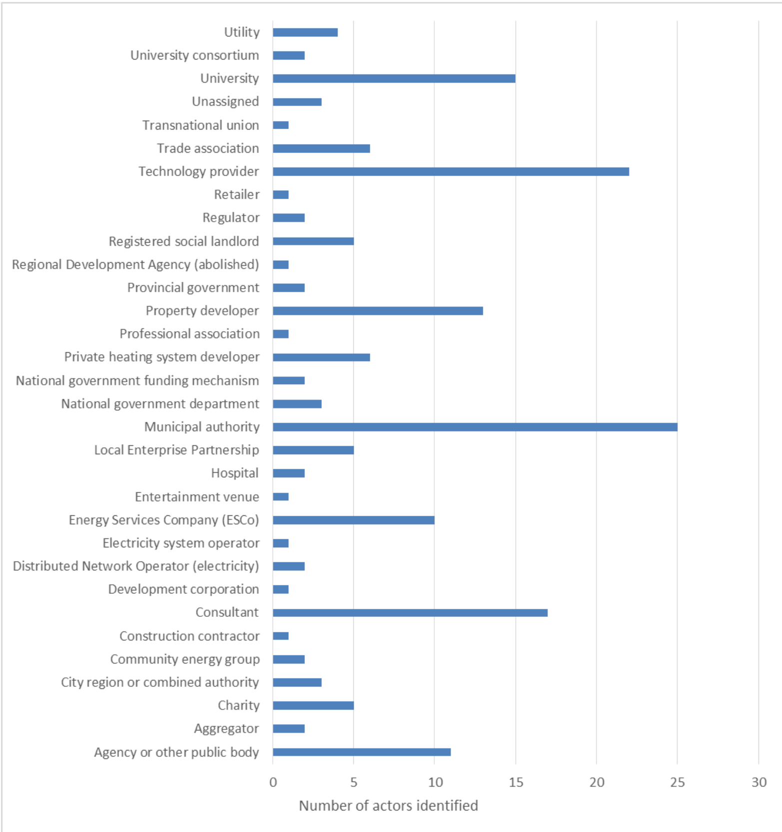


Fig. 4.2. Organisations involved in survey projects classified by organisation type

To assess the roles of different organisations in the project development process, for each of the source materials included in the desk survey I considered the type of organisation producing the material, what relation they had to the project, and why they produced the source material. Table 4.6 shows a summary of this analysis.

Table 4.6 Organisations producing materials on thermal storage, their relation to the project, and motivation for production [no. of materials]

Type of producing organisation	**Relation of organisation to project**	**Reason for production**
Central government (departmental) [4] Central government (non-departmental) [6] Community Energy Project [2] Consortium (primarily research) [3] Consultant [15] Development Corporation [2] Electricity grid DNO [4] Industry association / standards body [10] LEP/Innovation partnership [5] Local authority [29] Local government body (non-local authority) [9] Newspaper / news outlet [8] Private project developer [9] Project developer contractor [2] Registered Provider [4] Retailer [1] SPV Project operator [1] Technology developer [34] Third sector body [7] Trade journal [12] University [6]	Academic partner [2] Connected to local government covering area [3] Consultant providing a service to project [17] Contractor building part of project [3] Landowner where technology can be used [1] Local government covering area [14] National government covering area [1] No relation [37] Prior owner/operator of scheme [1] Project developer [47] Project funder [9] Project operator [7] Technology provider [30] Unclear (paid content) [1]	Analysis of project (internal or external) [10] Award of funding [1] General interest [22] Informing planning authorities about sustainable technologies [1] Informing public bodies about sustainable options [8] Informing reader about sustainable options [3] Internal information about project [2] Meet planning requirements [16] Meet statutory requirements [7] News article [10] Promotion of project [59] Promotion of technology [12] Promotion of wider area including project [1] Promotion to attract customers to scheme [3] Promotion to attract inward investment [3] Seek approval (officers to councillors) [14] Seek developers to come into area for regeneration [1]

The data in Table 4.6 shows the complexity of roles that organisations take in relation to the successful rollout of thermal storage projects. Based on the sample, consultants, local governments, and technology developers appeared to be particularly important in thermal storage development. The organisations involved played a wide variety of roles, with technology developers being the most prominent. In addition, thirty-seven related organisations were unconnected to the projects, such as independent news providers or trade associations.

Documents were frequently produced within and between organisations at the point of investment decision, to demonstrate business case viability and seek approval, or were submitted to planning authorities to demonstrate that thermal storage was delivering benefits that helped the development to meet planning requirements. A considerable proportion of the documents were produced to promote the project or technology, suggesting that actors in thermal storage development see the technology as a ‘selling point’ for a project, development, or area, and that documentary materials must be treated with healthy scepticism especially when referring to the range of potential scheme benefits.

4.2.4 Sociotechnical characteristics of thermal energy storage in the UK

Following the review of the current state of TES deployment in the UK focusing on technologies, locations and organisations, I undertook a broader sociotechnical analysis to explore a range of factors which appeared to be impacting on deployment of thermal energy storage. I undertook this analysis through the lens of the other four categories in the coevolutionary framework: *ecosystems*, *institutions*, *business strategies* and *user practices*.

4.2.4.1 Ecosystems

One of the key dynamics identified was the desire by developers of thermal storage projects to reduce carbon emissions, which was the most prominent non-traditional value in the data as explored in section 4.2.5. Developers also recognised the ability of TES to help reduce air pollution as part of an alternative to gas boilers, with nine of the projects identifying this as a driver. As an example, one of the city-scale district heat networks powered by an EfW CHP plant used thermal storage to maximise heat capture, and the local air quality benefits enabled by the removal of gas boilers in council dwellings was cited by officers seeking a decision to proceed with the project from senior councillors. Air pollution caused by domestic coal heating and the Clean

Air Act of 1956 was also a key driver for a large district heating scheme in central London, where a prominent thermal storage tank supported the heat network to make the most of waste heat from a nearby coal power station.

There were also potential negative ecosystems consequences of some types of TES that were recognised, especially for aquifer-based systems. I found five projects making use of the London Basin chalk aquifer as storage. The UK Environment Agency regulates licensing for water abstraction for heating or cooling purposes, and they had reported increased aquifer temperatures caused by demand for cooling in central London. This was driving the agency to actively seek greater use of the aquifer for heating purposes to reduce the temperature or for schemes which are in overall balance (Environment Agency, 2018; Fry, 2009). Similarly, for heat schemes employing abandoned coal mines, the UK's Coal Authority is responsible for actively managing the legacy of fossil fuel extraction, which requires significant ongoing management and costs, hence the Coal Authority is keen to explore the use of these assets for energy purposes (Coal Authority, 2020).

4.2.4.2 Institutions

Within the institutions node I found energy policy and governance arrangements clearly impacting on the deployment of TES. This included a prominent role for central government policy and mechanisms to support low carbon heat provision, which had a subsequent impact on TES deployment. Twelve of the projects identified the government's Renewable Heat Incentive (RHI) as important to the project's financial viability. The RHI was established in 2011 with the aim of bridging the gap between lower-carbon but higher-cost heating options and their fossil fuel alternatives, with the non-domestic arm closing to new applications in March 2021 (Ofgem, 2021b). The mechanism relied on willingness from scheme developers to incur the higher initial cost on the basis that this is recovered over time. Whilst the RHI focused on the low carbon generation aspect of a development rather than thermal storage, it included support for ground, water and air source heat pumps which were then combined with TES in the research sample. This suggests coevolutionary dynamics between *technologies-institutions-business strategies* are impacting on TES deployment, as project developers appraised technologies on a financial return basis. Another central support mechanism, the Energy Company

Obligation, which places a requirement on energy supply companies to fund energy efficiency measures, was also referenced as part of the funding arrangements in five projects.

I considered the impact of local policy and governance arrangements by searching for references to devolved powers instruments relevant to urban locations, such as strategic regional authorities, city deals, and national devolved powers instruments. I found a significant impact, with eighteen projects in the sample where funding or other support was provided through these various institutional arrangements. In some cases, the development of the project was written into the city devolution award from central government, as was the case with a heat network combined with heat storage in abandoned mineshafts in a city in northern England. The projects supported by devolved powers instruments tended to feature a clear emphasis on local economic development, such as, "*The District Heat Network will support more than 200 jobs directly, with 1,350 jobs protected in the supply chain*" [TANK10].

Other areas of national energy governance impacting on local thermal storage deployment were national planning policy, building regulations and the ability of devolved administrations to have greater local control over spatial planning policies. I found seven projects which chose to include thermal energy storage technology as part of construction of a new development; six of these projects were in London and referred specifically to satisfying local planning permission requirements for carbon reduction, as part of the reason to choose heat pumps with thermal energy storage. National planning policy applies to most local planning authorities, requiring new developments to achieve a maximum 20% reduction in carbon emissions (compared to a standard model of the building). However, following devolution of powers in 1999 (*Greater London Authority Act*, 1999), the strategic regional authority for London had exercised the right to set a more ambitious requirement for new developments to achieve deeper carbon reductions of 35% or better, and meeting this target was referenced in the source materials. This suggests that the ability for local planning authorities to set (or not set) more ambitious carbon reduction targets may have an impact on the potential for TES deployment in an area.

4.2.4.3 Business Strategies

There was good evidence of innovation in business models to improve TES viability, for both ownership and operational model employed. I found several examples where a range of values was 'stacked' to attain viability. One of the geoexchange projects took this approach and combined revenue from selling heat and cold energy to their commercial client, with income from grid balancing payments along with the incentive to reduce electricity use. This aspect was driven by their contractual agreement, allowing them to capture some of the financial benefit from energy and fuel cost reductions.

I identified eight TES schemes that appeared to be commercially viable in traditional profit-making terms. This included aquifer thermal storage in London and Birmingham serving private housing developments, and mixed commercial developments where the capital cost of the thermal storage element was rolled up in the overall build cost of the site, to be recovered through sale of apartments, office space, etc.

Taking a broad definition of commercial viability to include schemes designed to be independently financially viable (rather than being undertaken as research or demonstrator projects supported by one-off or time-limited funding streams), I found twenty-two projects in this category, including many of the local authority heat network projects employing centralised thermal storage. Whilst these were not profit-making in traditional economic terms, they were viable as 'going concerns' for public or other non-profit bodies, and they demonstrated wider applicability of thermal storage business models on this basis.

Finally, there were eleven projects where TES developers were piloting the technology as part of experimental or subsidised demonstration projects, and to do this they relied on research or central government innovation funding. These included novel concepts such as the PCM heat batteries and minewater storage schemes but were also used where more traditional hot water tanks were being combined with new types of control systems to respond to grid balancing signals. Taking a multi-level perspective, I identified these as *niche* developments operating within 'protected spaces' where they are isolated to some extent from the commercial pressures of the regime.

To assess the types of ownership and operational models that TES project developers were using to enable successful deployment, including how the two aspects were combined, I conducted an analysis of types according to the data available. This is summarised in Table 4.7.

Table 4.7 Business models for project ownership and operation

Organisation type	**Ownership model No. of projects**	**Operational model No. of projects**
Local authority	14	6
Private landlord	6	5
Public sector – non-housing	5	5
Registered provider	4	4
Private heating system developer	2	N/A
Community energy group	1	1
Utility company	1	1
Private ESCo	N/A	6
Public-private ESCo	N/A	5

Local authority ownership was the most prevalent model across the sample, especially for the large district heat schemes employing centralised TES. Of the fourteen local authority projects, six had retained full operational control, four had transferred operation to a joint public-private Energy Services Company (ESCo), and three to a fully private ESCo. As an example of this in operation, one of the central London projects featured a 2.5km heat network serving a range of civic buildings, local authority housing and private offices with heat and cooling. In this project, the trigeneration CHP engines were combined with a 330,000-litre thermal store to enable heat supply to continue overnight when the engines are not operating. Under the agreement, the ESCo is responsible for the design, development, financing and operation of the scheme, and carries the commercial risks, whilst the local authority is responsible for providing the "*anchor load*" as well as encouraging private customers to take supplies. Other than the local authority ESCo transfers, three others adopted similar models, for example a private landlord of a large mixed commercial site in central London, where the scheme including biogas-fired CCHP with TES now being operated by a private ESCo to deliver district heating and cooling.

4.2.4.4 User practices

In the collection of documentary evidence, I focused on the stage around the business case and decision to undertake the project rather than the experiences of users following installation. Therefore there was little emphasis on user practices in the data. However, in one project, follow-up analysis of user experiences was undertaken because it was part of a research and demonstrator project. The post-installation analysis of the decentralised dwelling-based heat storage project [HEATBATT1] showed that the thermal storage was delivering cost reductions to the residents, despite anecdotal feedback that they were not seeing any savings. This suggests that user experiences are unlikely to be universally positive, and that there is a need for monitoring and evaluation of thermal storage technologies to complement and support successful rollout.

Taking a broader view of *user practices* to refer more generally to the relationship of individuals to technology choices, there was evidence in some cases that individual actors within organisations were key to project deployment. This was evident in one of the projects where a private developer had constructed a mixed-use residential and hotel complex which balanced heating and cooling throughout the site via an ambient heat network and distributed heat pumps, supplemented by heat drawn from the River Thames via a water source heat pump. The managing director of the private developer was identified as key to delivery of the scheme where he acted as the "*driving force*" to the project which was "*his labour of love*" [NETWORK1]. Using the multi-level perspective lens, I interpreted these individuals as niche actors, suggestive of continued niche status of the technology at least in some more novel configurations.

4.2.5 Values of thermal energy storage

In the final part of the research, I applied a qualitative thematic analysis to explore the stated motivations and drivers behind thermal storage projects. I attempted to discover whether these were limited to a more traditional neoclassical understanding of value through simple financial returns, as would be expected in conventional economic appraisal techniques, or whether there was evidence of a wider conception of value and an attempt to capture a range of non-traditional values. I applied the EIBM of Foxon et al (2015) to classify the range of values targeted according to four headline value streams: *social*, *environmental*, *economic development* and *fiscal*. Following the EIBM approach, I expanded the *fiscal* value stream beyond the classic *revenue* category to capture fiscal flows at all levels. This included, for example, cost savings to end users, as well as traditional revenues to the organisation from the sale of energy to those customers to repay the investment costs.

The evidence suggested that TES project developers were looking to achieve multiple forms of value beyond simple financial returns. Through the thematic analysis, I identified forty-seven non-traditional values, which I coded under the four headline themes. Table 4.8 provides an overview of these values across the thirty-three projects ranked in order of prevalence. Beneath these headline themes, the table ranks the two most prevalent value targeted under each headline theme. The values and subsequent ranking are subject to my own interpretation of the situation when conducting the coding process, and this is evident when considering some of the values which spanned more than one category. An example of this being the value *reducing energy costs for end users* which could legitimately be included within either *social* or *fiscal* headline values.

Table 4.8 Non-traditional value capture attempted by thermal storage projects

Values by headline theme and sub-theme	**Projects attempting to capture value**	**Ranking** ***(#) headline rank*** *[#] sub-theme rank*
Environmental	**31**	***(1)***
• Carbon reduction	29	*[1]*
• Use energy that would otherwise be wasted	16	*[3]*
Social	**25**	***(2)***
• Reducing energy costs for end users	18	*[~2]*
• Fuel poverty reduction	14	*[4]*
Fiscal	**24**	***(3)***
• Cost saving compared to alternative	18	*[~2]*
• Direct income from sale of energy	9	*[7]*

Values by headline theme and sub-theme	**Projects attempting to capture value**	**Ranking** ***(#) headline rank*** *[#] sub-theme rank*
Economic development	**21**	***(4)***
• Enhancing reputation of area	12	*[~6]*
• Take part in research programmes	12	*[~6]*

Seventeen of the projects sought to capture values in all four value-capture headline categories. However, the most prevalent headline value was clearly the search for environmental benefits, specifically through tackling carbon emissions. This was identified by twenty-nine projects included in the survey.

To assess whether technical or organisational characteristics such as storage type, ownership model, pathway alignment etc. affected the types of values targeted, I applied the project classification framework to run a series of cross-tabulations of non-traditional values against project attributes. There was little evidence of clear patterns or correlation between value capture and particular project attributes. Local authority-owned projects sought the broadest range of social benefits including health improvements, protection of vulnerable customers, tackling inequality and user comfort. Proportionally, private operators were less likely to seek social benefit values. The residential schemes focused on the social benefits of improved user comfort through better design or control, and this was especially the case with the four projects where novel thermal storage approaches were deployed primarily to improve the experience for residents in off-gas dwellings.

4.3 Chapter discussion

In this chapter I set out to explore the current state of UK TES deployment, the significant sociotechnical characteristics of that deployment, and how consideration of the range of values sought by project developers might help to understand potential future deployment of this technology.

The analysis has revealed that TES projects in the UK exhibit a vibrant mix of technologies and supply arrangements in various combinations. The technologies range from microscale domestic storage in single homes to centralised storage integrated into city-scale heat networks serving thousands of end users. Thermal storage in different forms is enabling a variety of renewable heat sources to be used, including capturing heat that would otherwise go to waste, and is helping to link up and create synergies between isolated urban energy systems. The diversity of technology types and project attributes in the sample suggests strong potential and innovation activity in the sector. Nevertheless, the lack of clear winning technologies or supply arrangements, as was evident from the classification matrix, may indicate that thermal storage in the UK hasn't progressed beyond niche status (Geels and Schot, 2007). Alternatively, it may suggest that of the many possible thermal storage niches, none have yet emerged as a 'strategic' niche capable of transforming the environmentally unsustainable regime (Kemp et al., 1998).

There were some decentralised applications of domestic heat storage in tanks, ceramic bricks and in one case through novel phase-change materials. However, in the sample TES was most usually employed centrally with heat supplied to end users through heat networks of different types and scales. This included more advanced fourth and fifth generation heat networks supplying heat at lower temperatures than traditional district heating. Developers were using these low temperature network and thermal storage configurations in combination with distributed heat pumps to capture waste heat such as from the sewerage system, as well recycling heat and coolth between connected nearby buildings and different types of energy users in the same network. The findings support emerging research on the ability of fourth and fifth generation heat networks, combined with thermal storage, to integrate a range of low carbon heat sources, especially waste heat, as part of smart urban energy systems (Boesten et al., 2019; Buffa et al., 2019b; Lund et al., 2014b; Wirtz et al., 2020). However, this has potentially significant impacts on the future development of thermal storage given the complexity that such an undertaking involves in connecting a range of heat users and producers (Busch et al., 2017). Due to their ability to establish connections between disparate heat consumers and producers, the findings suggest local authorities might also be key local actors to promote the greater use of district heating and thermal storage (Bush et al., 2017; Hawkey et al., 2013).

A promising area of UK technology development was in the application of TES in geoexchange configurations. This was where ground-coupled heat exchangers and ground source heat pumps were employed to store captured waste energy, both on a daily and seasonal basis with active ground recharge. The geoexchange approach is well established in the US where there are now over 600,000 installations, although it remains a novel approach in the UK especially for domestic purposes (Self et al., 2013). Whilst I identified some research effort exploring the technical potential of this approach in Europe and internationally, there has been little research focusing on the UK especially with a sociotechnical focus (Galgaro et al., 2017, 2015; McCartney et al., 2012).

I also found interest in the potential for storing heat in abandoned flooded mine shafts. However, this was at an early stage, with the three projects identified in early development phases especially compared to the Heerlen project in Netherlands for example which entered development phase in 2003 (Verhoeven et al., 2014b). This is a promising area of emerging research which in the UK is focused on the technical challenges of harvesting heat energy from challenging hydrogeological environments (Adams and Younger, 2001; Bailey et al., 2016; Farr et al., 2016; Ng et al., 2019). However, in Europe these approaches are more established, and research has moved on to how minewater systems can be used in energy storage and exchange rather than just depletion, such as is the case at Heerlen (Verhoeven et al., 2014b). Contrary to earlier research which found little evidence of seasonal or long-term storage in the UK (HM Government, 2016a; Renaldi and Friedrich, 2019), a third of projects in the sample employed storage to meet seasonal peaks, suggesting the UK is beginning to make progress in this area. Prior assessment of storage types and their applicability for seasonal thermal storage found sensible storage through aquifer and borehole ground storage to be most ubiquitous (Alva et al., 2018; Xu et al., 2014). This is backed up by the findings in this study, with seasonal storage delivered through five aquifer schemes and three with borehole ground storage.

Considering the impact of the incumbent natural gas grid, I expected to see non-fossil solutions flourishing in parts of the country which are not connected to the grid (in the UK this is more likely to be rural areas). However, there was a clear trend for projects to be in urban settings which are connected to the gas grid. This suggests three things: firstly, that thermal storage connected to end users through heat network arrangements may be suited to deployment in urban settings given the proximity of heat producers and consumers (Bush et al., 2016); secondly, it supports the case for cities as sites for development and sustainable heat innovation (Hawkey et al., 2013; Webb, 2015). Lastly and most importantly, because thermal storage is enabling a range of heat sources to be captured from other city systems and processes including transport, sewerage and waste, this backs up research suggesting that thermal storage can support the transition to urban energy systems based on 100% renewables (Jacobson et al., 2018b; Lund, 2018; Mathiesen et al., 2015b).

The potential for thermal storage to deliver grid flexibility services was backed up by the findings, where thermal storage was being employed to help actively balance the electricity grid in fourteen projects. This is important because it means that thermal storage can potentially support greater renewables integration and reduce costs of grid reinforcement. Indeed, I found thermal storage being employed in all the three routes identified through which the technology can support a fully decarbonised energy system (providing grid benefits, price benefits, and facilitating renewables integration) (Fischer and Madani, 2017; Rosenow et al., 2020b). Participation in the UK's electricity grid balancing mechanism is enabling project operators to stack multiple fiscal flows to improve project viability, as well as deliver a range of wider benefits. These benefits include greater levels of control and comfort, reducing energy bills and tackling fuel poverty, as well as more indirect benefits of future reductions in the need for grid reinforcement, which would otherwise be passed on to consumers via energy bills. This is especially the case for dwellings served by electric night storage heaters. In the research I found that non-local authority social landlords retain a greater proportion of dwellings with electric storage heating (HM Government, 2016b), and the findings suggest that upgrading these systems with smart controls may allow social landlords access to a revenue stream from grid balancing, whilst delivering an improved user experience for residents. At the same time, grid balancing can deliver wider carbon reduction benefits through helping to facilitate greater renewables integration on the grid, as well as limiting the size of grid expansion required to meet future wide-scale electrification (Arteconi et al., 2013; Lund, 2018).

Following this focus on the technological aspects of thermal storage deployment, I applied the coevolutionary framework to explore other aspects of the sociotechnical transition for thermal storage and low carbon heat. This helped to identify that deployment is intertwined with a complex set of institutional and governance arrangements. These included national policy measures to drive low carbon heat which are helping attain project viability. However, national regulations also placed restrictions on the ability of local planning authorities to set local planning rules that could help drive developers to choose low carbon options over fossil-based heating. In London, where a different regulatory regime enables higher carbon reduction targets to be set, local planning authorities were exercising this option and the evidence suggested this was supporting deployment of thermal storage and heat pump combinations.

Central government decisions about the future of the natural gas grid, and whether the UK pursues a hydrogen, electrification or mixed route to heat decarbonisation are outstanding (Chaudry et al., 2015; Lowes and Woodman, 2020). These decisions are likely to have a significant effect on TES deployment, because the evidence showed that support and incentives were important to enable business model viability. Therefore, national decisions which result in support moving away from thermal storage and heat pump technology towards hydrogen solutions could limit the number of situations in which the solution is fiscally viable. Also, such decisions may impact national planning policy, which is implemented on a local basis within the requirements of the National Planning Policy Framework and was a key factor in the technology adopted in new developments. With the emphasis I found on the importance of the non-domestic RHI mechanism, the closure of the scheme in March 2021 may lead to a significant short-term decrease in rollout of heat pumps (directly supported through RHI) and thermal storage (indirectly supported through association with heat pumps).

A useful avenue for analysis was through the business strategies node of the coevolutionary framework. The results suggest innovation in business models is helping to enable project delivery, following earlier findings in regard to other aspects of the local energy system (Hall and Roelich, 2016). Business models are coevolving with the institutions and technologies systems, for example thermal storage technology developments are enabling remote control by an aggregator, leading to the ability to participate in the demand-side response arm of the flexibility market. Taylor et al (2013) highlighted that developing new business and commercial arrangements will be one of the key challenges to the deployment of thermal storage technologies. Evidence of stacking multiple forms of financial and non-financial value indicate progress in this area. A range of public and private ESCo arrangements were employed in the sample, which were found to be helping to drive improvements in system operation. Prior work proposed that ESCo models could play an increasingly important role in a low-carbon transition of the UK energy system (Fang and Miller, 2013; Hannon et al., 2013; Roelich et al., 2015). Whilst not negating the need for financial viability, finding novel business models in the sample does, I believe, provide some evidence that scheme operators and investors are being creative about how they may be able to achieve this.

In carrying out this work, I built on prior research which had found evidence of a trend towards localisation of energy infrastructure along with the devolution of responsibility for infrastructure decisions placed in the hands of a range of non-traditional actors (Busch et al., 2017; Bush et al., 2016; Fudge et al., 2016). Local authorities were prominent local energy actors along with social landlords, universities, and devolved authorities. These were in addition to the continuing importance of for-profit organisations such as technology developers, consultants, and property developers.

The coevolutionary framework was useful in focusing on the importance of business strategies, and this backs up one of the central claims by Foxon (2011) of the benefits of providing explicit emphasis on this area. However, I also found a key role for actors where individuals within organisations were acting as the primary drivers of change. Without a specific focus on this in the coevolutionary framework, I found this aspect to be somewhat split between *institutions*, *business strategies* and *user practices*. This suggests the framework may benefit from an additional element which focuses on the role of internal actors and their decision-making. A greater emphasis on the importance of individuals within organisations through their role as change agents able to overcome internal resistance to new ideas, as per the diffusion of innovations theory, is helpful (Rogers, 2003).

The multi-level perspective was useful in drawing attention to issues of the incumbent regime and technological lock-in (Geels, 2012, 2002; Rip and Kemp, 1998). This helped to recognise where some projects were operating within protected spaces where they were insulated from the incumbent regime (Smith and Raven, 2012). This was visible through research, demonstrator, or schemes reliant on otherwise one-off funding streams to support projects that would not have taken place otherwise (indeed, *additionality* is frequently a prerequisite for eligibility to apply for such funding). Overall, the positive but incremental innovation evident in thermal storage approaches may be symptomatic of a stable regime subject to lock-in mechanisms and path dependence (Arthur, 1989b). However, applying the empowerment framing of Smith & Raven (2012), suggests that thermal storage practitioners were able, in some limited regard, to stretch and transform the selection environment of the incumbent regime. The clear emphasis on the carbon reduction benefits of thermal storage suggests that technology advocates recognise the landscape-driven focus on the need to tackle the climate and ecological emergency. This was also reflected in the prominence of carbon reduction value capture by project developers, particularly exemplified by niche advocates, such as in the case of GEOX1, publicly challenging the incumbent regime of natural gas through interviews in trade and general-interest publications.

Finally, I brought in the value categories from the extended infrastructure business model canvas proposed by Foxon et al (2015) to focus in on the search for non-traditional values by project developers. The aim was to explore whether those making investment decisions in TES projects were relying on traditional neoclassical appraisal techniques, or whether consideration of a range of non-traditional values was helping to tip the balance of business case viability to support decisions to invest in lower carbon alternatives. The evidence showed that project developers are seeking to capture a broad range of values across the non-traditional categories, and beyond simple financial returns. There was a clear focus on carbon reduction but also other social, economic development, and traditional and non-traditional fiscal values being sought including cost savings by different actors within the value chain. From this I inferred that local actors are taking a range of non-traditional values into consideration when making investment decisions. However, the findings do not provide sufficient evidence that non-traditional value streams were enough to tip the balance of an investment decision of particular schemes, and the importance of financial support mechanisms such as the non-domestic RHI suggest that financial viability considerations are still primary to thermal storage investment decisions. In considering the types and range of non-traditional values sought, in line with prior research regarding district heating (Bush et al., 2016; Foxon et al., 2015), local authority-led heating projects sought to achieve health and wellbeing, fuel poverty reduction and other social benefits, although these were second to carbon reduction drivers. No patterns in the data suggested that certain thermal storage technology configuration, lead organisation type or other project attributes had a significant impact on the types of values sought.

In the search for non-traditional value capture, as with the wider analysis, it was not always possible to draw a clear line around the thermal storage component of a project and assign benefits to that element alone. In some cases, such as with the dwelling-based heat batteries, it was evident that the thermal storage was the driver behind the benefits the project was looking to deliver; the thermal storage 'was' the scheme (e.g. ELECSTOR3 or HEATBATT1). At the other end of the spectrum, when thermal storage was one component of a city-scale heat network, it was far less clear what benefits could be derived specifically from the storage itself (e.g. TANK1 or CRYO2). Thermal energy storage cannot therefore be considered in isolation from the wider local energy system.

Whilst the findings discussed here have focused on the specific UK context, I also compared the results to the situation in other countries facing broadly similar decarbonisation commitments, a liberalised energy market, and an incumbent natural gas grid. While the UK shares similar sociotechnical characteristics to the Netherlands, for example, especially in the provision of domestic heating through natural gas, the latter has become a world leader in aquifer thermal energy storage with 2,500 installations or over 85% of world capacity (IRENA, 2020; Schüppler et al., 2019). Whilst these systems have mainly been installed to serve public and commercial buildings rather than in domestic settings, this success indicates that the government policy interventions including market incentives and the active support of the technology by Dutch authorities have enabled the development of a strategic niche in this technology (Fleuchaus et al., 2018; IRENA, 2020; Nordell et al., 2015; Schüppler et al., 2019). In the case of the US, with little national federal policy or support (Collier, 2018), the country has become the world leader in geoexchange type systems (Self et al., 2013), with 27 known manufacturers serving the domestic heat market (Liu et al., 2015). There is potential for TES technologies to flourish against the backdrop of incumbent technological lock-in. The lack of progress in the UK compared to these examples, however, emphasises the stability of the fossil-based heating regime.

Overall, the results demonstrate that TES can connect electricity and heat sectors because of its ability to respond to grid price signals to deliver heat provision, whilst helping to balance intermittent renewable electricity generation. Fourteen projects in sample were operating on this basis. Coupled with a decarbonising electricity grid, the findings suggest that TES can support the sociotechnical transition in both electricity and heat potentially to a system based on 100% renewables. A sociotechnical approach such as employed here can support the research endeavour to understand the role of the technology in this transition better.

4.4 Chapter summary

In this chapter I set out to address gaps in knowledge on the current state of TES in the UK, to explore the important sociotechnical factors affecting deployment and to what extent thermal storage developers were considering a range of values beyond traditional economic measures. The overview of thermal storage technologies reveals a multiplicity of combinations of heat generation and supply arrangements with little evidence to show that any dominant types or arrangements are emerging.

The analysis implies that technical developments are inextricably intertwined with social factors such as policy and governance, local contexts, the development of new business models, and individual behaviour. TES can support a fully decarbonised energy system through three primary routes: by providing grid benefits, price benefits, and facilitating renewables integration, and I found examples of the technology being operated to pursue each of these. Thermal storage was being used to capture waste energy and was creating connections and synergies between urban systems including electricity, heat, sewerage, waste and transport. In addition, local energy actors were seeking to leverage wider environmental, social and local economic regeneration benefits from thermal storage investments. However, the findings suggest that traditional economic measures and simple financial viability have not been replaced as primary decision-making metrics.

Applying the multi-level perspective, coevolutionary framework, and extended infrastructure business model frameworks helped interpret sociotechnical factors in TES deployment. The findings suggest that TES currently remains a niche technology in the UK within a stable regime based on an incumbent natural gas grid. In this context the country lags behind others featuring broadly similar sociotechnical characteristics. Because of the ongoing importance of financial support mechanisms to the deployment of thermal storage so far in the UK, the closure of the non-domestic RHI in early 2021 may hinder the deployment of the technology in the short term. The longer-term decisions about the future of the natural gas grid may open up landscape opportunities to support the transition to a new regime for domestic heating involving thermal energy storage. However, the decision to maintain the incumbent gas grid and shift towards hydrogen as a solution for home heating, instead of electrification, may be more likely maintain the current regime.

5 Critical success factors for geoexchange deployment in UK cities

5.1 Introduction

The research presented in Chapter 4 found that a particular type of thermal energy storage (TES) known as geoexchange (ground-coupled heat exchangers combined with ground source heat pumps) has the potential for wider-scale deployment. Projects in the UK have to date been small-scale, typically supplying only one heat user, but the results indicated that the approach is applicable at a larger scale. There is also a desire to expand geoexchange projects to different types of mixed developments, but this comes with added complexity and challenges for developers.

In this study, I investigated geoexchange deployment in the UK through a set of semi-structured interviews with local energy actors involved in geoexchange projects to address the following research question:

RQ2. What are the factors that have led to successful geoexchange deployment in UK cities?

To address this research question, and as the work set out in this chapter explores in detail, I undertook a three-stage process of:

1. Using the MLP, coevolutionary, EIBM and intermediary roles sociotechnical frameworks to explore a multilevel understanding of the situation facing urban geoexchange developers and other key actors involved in the urban energy transition through a template analysis of interview data. (A full description of this process is provided in section 3.3.3, with a summary in section 5.2).

2. Using a hotspot analysis of the final coding template to identify prominent factors in geoexchange deployment for deeper exploration (see section 5.3, and the full results in section 5.5).

3. Developing a 'critical success factors' framework to bring together insights around enabling geoexchange deployment (see section 5.4 for framework overview, further discussion in session 5.6, and full version of the framework at Appendix I).

5.2 Application of sociotechnical frameworks to interview data

Through the template analysis approach outlined in section 3.3.3, I first applied the *coevolutionary framework* to explore aspects of *technologies*, *institutions*, *ecosystems*, *user practices* and *business strategies*, and how aspects of these systems may be coevolving and shaping the prospects for geoexchange deployment. The data suggested prominent issues were not readily captured by this framework, such as the impact of heightened climate change awareness and local authorities bringing in new policies because of local pressure, or the importance of intermediary organisations to connect social housing providers with novel technologies. I introduced the *multilevel perspective* and *intermediary roles* frameworks into the template to support exploration of wider landscape, regime stability and niche development factors, as well as a more detailed view of business strategies through the *extended infrastructure business model canvas*. A high-level diagram of this combined framework is shown in Figure 5.1.

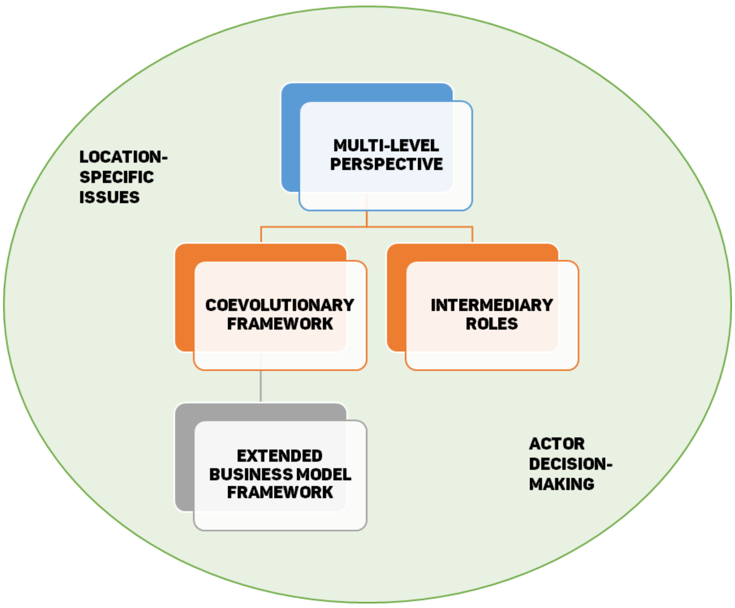


Figure 5.1 Diagrammatic representation of the integration of four frameworks in the final coding template, with two cross-cutting themes sitting outside of the hierarchy

In addition to these *a priori* themes, during template development, I added several key themes which did not appear to be captured under the existing combined framework. Examples of these were the considerable evidence of the importance of *location-specific* issues developers were facing when working with different local authorities and their policies, for example, as well as *actor decision-making* issues which concerned how the balance could be tipped in favour of an organisation to choose geoexchange over a conventional heating technology. Rather than see these as new nodes of the framework, I felt these were more appropriate to be considered cross-cutting or integrative themes, which linked across various nodes and levels. These integrative themes were added to the top level of the hierarchy, but their consideration was cross-cutting, as shown in more detail in Figure 5.2.

5.3 Hotspot analysis of interview data

Whilst approaching this research as a qualitative analysis, it was useful to identify hotspots of coding intensity as a guide to highlight where multiple interviewees raised the same or similar issues. I then used the coding hotspots to direct a more detailed exploration where I assessed differing perspectives from interview subjects. Figure 5.2 shows a diagrammatic representation of the hotspot analysis overlaid on the combined MLP and coevolutionary framework including the additional crosscutting themes of *actor decision-making* and *location-specific issues*.

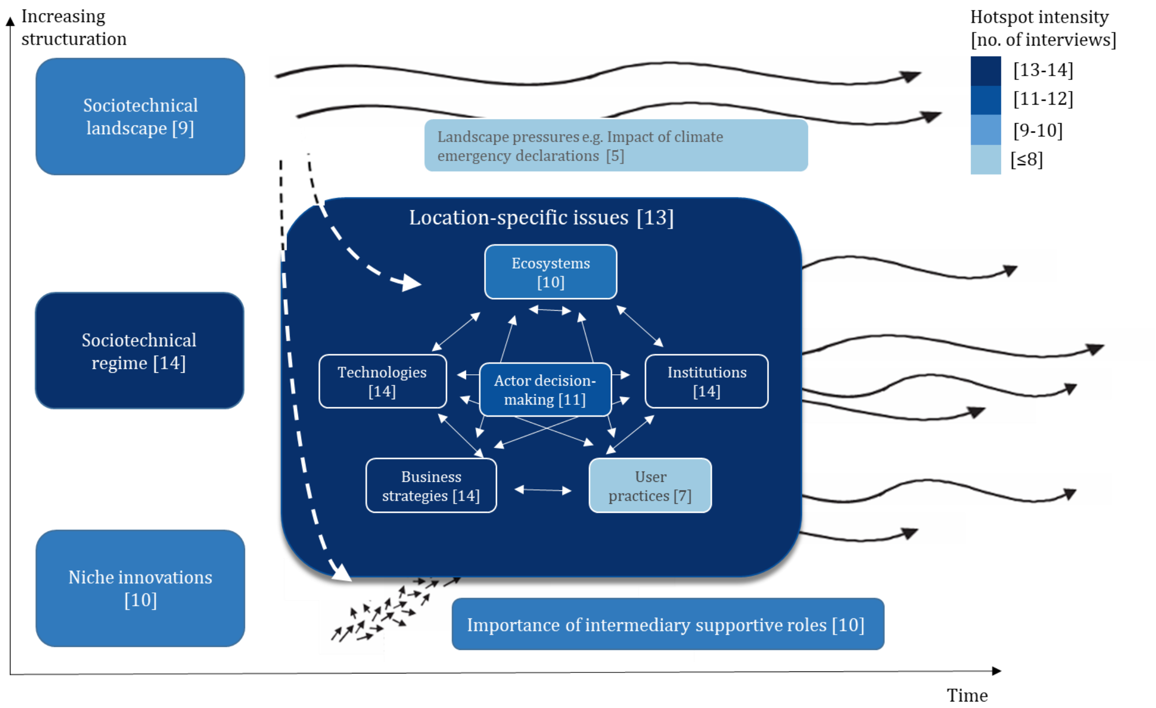


Figure 5.2 Diagrammatic representation of hotspot analysis overlaid on MLP (Geels and Schot, 2007) and coevolutionary frameworks (Foxon, 2011). Hotspot intensity shown by colour (as per key), and number of interviews referring to theme [in square brackets].

This visual representation of the strength of coding across the combined frameworks highlights the hotspots centred on the *technologies*, *business strategies*, and *institutions* nodes of the coevolutionary framework, and the *regime* level of the MLP. Also prominent were the new crosscutting *location-specific issues* and *actor decision-making* themes. Table 5.1 shows more clearly the strength of the hotspots of coding intensity, especially clear when the number of references is included in aggregated coding from lower levels.

Table 5.1 Results of thematic analysis ordered and colour-coded by coding intensity, aggregated from lower levels, with examples of lowest-level codes. Colour pattern as in Figure 5.2.

Theme by hierarchy level	No. of interviews	No. of references	Example lowest-level code
MLP - Regime level	14	733	Lack of established heat pump market
Co-evolutionary - Technologies	14	288	Requires change to wet central heating
Co-evolutionary - Institutions	14	200	New building regulations will drive attention to heat pumps
Co-evolutionary - Business strategies	14	192	Close ongoing relationship with client
EIBM - Non-traditional values	13	73	Delivers energy bill reductions
Customer segments e.g. social tenants, leaseholders	12	23	Decided not to recover capital cost from leaseholders
(New) Organisational or financial structure	11	30	Impact of customer 'patient capital'
Cost structure	8	25	Using research funding
Co-evolutionary - Ecosystems	10	17	Resilience to future weather extremes
Co-evolutionary - User practices	7	36	Importance of resident liaison
(New) Location-specific issues	13	68	Replication of Bristol approach to planning would help
(New) Actor decision-making	11	83	Importance of single decision-maker
MLP - Niche level	11	26	Reputational risk of choosing unproven technology
Intermediary – technology assessment & evaluation	2	3	Inclusion in framework agreement
MLP - Landscape	9	19	Climate emergency declarations led to change of policy

5.4 Creation of geoexchange critical success factors framework

During the template development process, I drew together the insights from the analysis around a conceptual framework of 'critical success factors' in urban geoexchange deployment. This model shown in Figure 5.3 is used to structure the presentation of results in section 5.5, and in section 5.6 I discuss and explore in more detail how I developed the framework from the results. A full version of the framework is included at Appendix I.

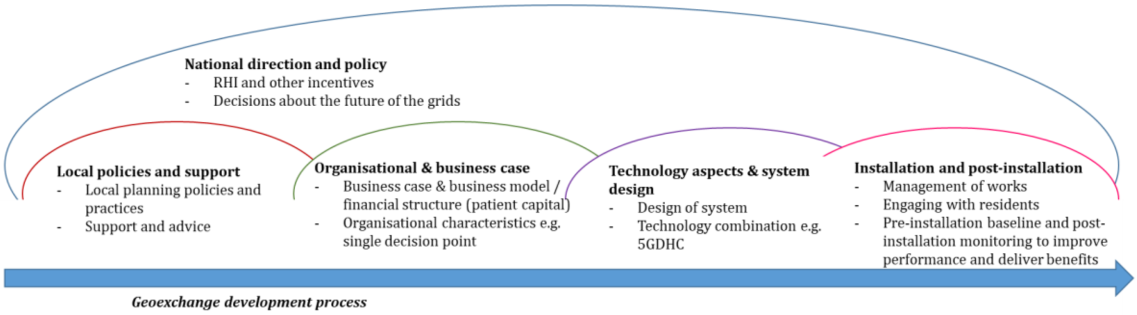


Figure 5.3 Geoexchange critical success factors framework

The design of the critical success factors framework broadly reflects the geoexchange project development process, with key factors at each stage. The background *national direction and policy* sets the broader landscape, direction and context in which geoexchange developers operate and so extends over the whole development process, although it is particularly important at the initial stages, for example in regard to the presence of support mechanisms. This includes the specific national policies which developers felt most important, as well the expectations around future policies which would follow national decisions about whether the country would pursue an electrified or hydrogen future for home heating, for example.

The *local polices and support* element covers the local circumstances that project developers were experiencing. Whilst this element reflected a place-based translation of the national direction and context into a local setting, because of the physical and temporal closeness to factors at this level with the project development process, factors here were more concrete and relevant to project decision-makers. They included for example whether geoexchange was recognised as an eligible system for housing developers to meet local planning requirements. Therefore, these local factors had a more direct influence on whether a project will happen in one location or not, at the beginning of the geoexchange development process.

Next in the process is the *organisation and business case* element, which focuses on internal organisational, decision-making and business case factors within developers and client organisations which delivered a geoexchange investment decision. This includes for example the presence of a counterfactual case of a conventional heating system replacement which the additional cost of geoexchange could be offset against thus reducing the perceived cost.

Following this were more specific technical issues, with some of these important at the point of decision and some of which, such as how geoexchange could be combined with low temperature district heating, shaped and set the terms of the decision because they effect whether geoexchange is viable in a dense urban location for example. Finally, there were a set of success factors around how the geoexchange systems are installed, maintained and monitored. These were post-decision but were nevertheless important considerations at the outset of the geoexchange development journey and are likely to have an impact on future deployment prospects, through reputational issues for example. They included how works would be managed on the ground, how residents would be engaged and supported during the works, and ensuring the systems delivered reliable heat provision.

5.5 Presentation of thematic analysis results

The following section presents and briefly discusses the key themes from the data analysis which underpinned the development of the *geoexchange critical success factors framework* presented in section 5.4. The analysis was based around the sociotechnical frameworks outlined in section 5.2 before I brought the insights together and structured them around the five elements of the framework: *national direction and policy*, *local policies and support*, *organisational and business case*, *technology aspects and system design*, and *installation and post-installation*.

5.5.1 National direction and policy

Interview participants were keen to share thoughts about the development of projects in the context of wider societal trends in the move towards a decarbonised energy system. They reported concerns around outstanding central government decisions regarding the future of heat in the UK, and what this would mean for more specific targeted polices that could impact geoexchange deployment. All fourteen interviewees raised issues regarding the importance of national government policy, and guided by the hotspot analysis, these are presented here.

5.5.1.1 Future of the gas grid and the potential for hydrogen to replace natural gas

One of the most pressing areas that participants felt was key to future geoexchange deployment was around the decisions required by national government policymakers concerning the future of the natural gas grid, especially whether the long-term future for the UK will see the gas grid decommissioned and replaced with electrified heating options, or is repurposed to carry hydrogen or biogas, for example. Six interviewees raised points about the lack of and need for a clear central government position, with comments such as:

> *"what Government is doing at the moment is having lots and lots of consultations […] and lots of small programmes of funding for various things related to heat. What there is not […] is an actual heat strategy" [INT3]*

This perspective is reminiscent of the signs of incremental but not transformational change, indicative of a stable regime (Geels, 2002). The perceived lack of clarity was reflected by conflicting viewpoints on 'which way the wind was blowing' with some seeing a trend towards hydrogen and others towards electrification:

> *"I think the national decisions seem to be orientated around electricity at the moment." [CEC2],* vs

> *"It seems hydrogen is making a comeback in policy terms, compared to even six months ago" [INT3]*

Interviewees described a powerful hydrogen / natural gas lobby pushing central government towards their approach, where the *"hydrogen guys […] they certainly* *have cash to throw around" [INT4]*. This suggests the presence of the lock-in effects of the techno-institutional complex (Unruh, 2000) through coevolutionary dynamics between the development of hydrogen technology as a potentially more symbiotic substitute with institutional policy, which may jeopardise the potential for geoexchange deployment. These also serve to back-up the findings of Lowes et al (2020) around the 'discourse coalition' of incumbents and lobbyists operating in this arena to steer the direction of policy away from electrification. Interviewees voiced concerns that incumbent lobbying appeared to be having a significant impact on central government and this would threaten future policy mechanisms to support electrified alternatives.

5.5.1.2 Near term government policy about the use of natural gas for heating

Aside from the longer-term decisions, interviewees also raised some more limited but still potentially significant policies that were having, or were expected to have, a more direct and immediate impact on geoexchange deployment. Five interviewees referred to the Future Homes Standard, a new set of national building regulations due to come fully into force in 2025. Especially noted as important was a statement by the Chancellor at the time of the announcement that these would include a ban on the installation of gas boilers in new properties. Despite only applying to new developments, participants saw the announcement as being potentially important for the future of geoexchange and associated heat pump technology because they felt it would ramp up interest in heat pumps and could act as a springboard to drive down technology costs, whilst raising public awareness and acceptance of other non-gas options. This suggests *technology – institution - business strategies* coevolution, where the ruling out of conventional technological options might benefit the niche alternative, by causing firms to explore how they can be made financially viable. This was evident in the data where an interviewee from one of the social landlords described how, since the statement, they had begun to look for ways to make new geoexchange projects viable beyond the closure of the Renewable Heat Incentive (RHI) funding mechanism. They would do this by focusing on new build properties, which would be subject to the Future Homes Standard where gas could not be used:

> *"…that would be a direct response to […] to Philip Hammond's spring statement about effectively although they didn't say that, zero carbon housing by 2025, and not use fossil fuel heating in properties." [RSL1]*

I felt here that the inclusion of *actor decision-making* as a cross-cutting theme was helpful, both in relation to how individuals within the firm responded to the coevolutionary dynamics at play, and the social landlord organisation as an institution with its own internal dynamics and stability, which may or may not be able to respond positively to such an external factor. Whilst interviewees recognised the potential importance of the forthcoming rule changes, they expressed vocal opinions about this change being too slow:

> *"I was actually personally appalled – there is no reason to be waiting until 2025 to start banning gas boilers." [CEC3]*

5.5.1.3 Geoexchange challenges narrative around the electrification of heat

Interviewees representing technology developers reported they face a common assumption amongst policymakers that moving down the electrification route to heat decarbonisation will place a significant, possibly unacceptable, additional load and stress on the electricity grid, requiring huge upgrades and additional renewable capacity. This mirrors the findings of Lowes et al (2020) that the discourse coalition raising these types of concern about 'peak heat' is not just incumbents but features an array of regime actors who promote a discursive storyline which can resist transitions.

Interviewees were keen to counter the discourse with experience of applying their specific technology, which they claimed was able to reduce overall electricity consumption, whilst also serving the heating needs of a site in place of gas as well as the cooling demand.

> *"What we've seen in the projects that we've done […] you can reduce the overall electrical consumption of a building even adding electrification of heat to it" [CEC2]*

Attendance at professional events featuring geoexchange developers as well as national and local policymakers enabled me to witness first-hand how niche actors were trying to counter the prevailing regime narrative. This would suggest that niche actors are attempting to *stretch and transform* the incumbent regime to the extent that it becomes possible for the innovation to diffuse (Bush et al., 2017).

Interviewees sought to further challenge the discourse around the electrification of heat through claims about the ability of geoexchange to take part in flexibility services, and thus help to decarbonise the electricity grid whilst saving customers money. However, one of the technology developers as well as an interviewee representing a social landlord challenged the notion that grid balancing functionality was yet being exploited:

> *"We might have done, but it [is] not part of what we plan." [RSL2]*

The limited awareness of these potential benefits of geoexchange suggested a key role for key individuals within landlord / geoexchange customer organisations acting as *champions* (Rogers, 2003), emphasised by:

> *"my job is to constantly try and be a number of steps ahead in terms of thinking around these things, and to trial and test things and to try and use the available grant money and so on around to mitigate the risk of that" [RSL1]*

The presence this type of champion role within the organisation may be a key factor in a successful geoexchange decision, and this is explored more in section 5.5.1.4 and 5.5.3.

5.5.1.4 Funding mechanism uncertainty

Participants reiterated the importance of the government's initiative to encourage the generation of low carbon heat, the Renewable Heat Incentive (RHI), to the success of their schemes. Eleven of the fourteen interviewees noted this specifically, including that the RHI played a key role in the decision to choose the geoexchange approach.

> *"we could also get the RHI [...] So, over the 20 year period, then actually the installation would be [...] a profit to provide an income to the organisation. So, that is the decision-making and process and why we went with the ground source heat pump." [RSL2]*

Interviewees described how the RHI was particularly helpful when working with potentially more risk-averse colleagues across the organisation in getting the decision over the line. Again, the importance of the innovation-decision process was evident, along with the role of key individuals within organisations acting as internal change agents or champions (Rogers, 2003). The LA1 participant, as a manager within a risk-averse local authority, described how prior to obtaining the decision to proceed with geoexchange, he had to persuade colleagues in multiple departments of the benefits of making a long-term investment that would involve a significant capital cost, but eventually provide a return to the organisation. The guarantee of 20 years funding that the RHI delivered made those conversations easier and made the investment decision possible. In relation to the geoexchange client organisations of local authority and other social housing providers, the interview data suggests these champion roles are critical in obtaining a positive geoexchange decision, including surveillance of the national policy landscape and translating that into meeting local organisational requirements.

At the time of the interviews in 2019, participants expected the RHI to end for organisational applicants in early 2020, with no replacement on the horizon. They reported with considerable frustration that this was already having a significant detrimental impact on new projects, because of the construction lead times involved. However, there were some early signs that the impending closure of the RHI was driving the development of alternative approaches and novel business models, as can be seen in the case of the participant from a social landlord who had carried out several successful retrofit geoexchange schemes to existing social housing:

> *"if RHI stops or changes I'll be looking for a model where we continue to put in renewable heat, but operate that either as a heat-as-a-service model but also engage with flexibility services with the grid." [RSL1]*

From the perspective of the local regime actors, this suggests that the closure of the RHI may act as a landscape pressure and may, as proposed by Geels & Schot (2007), start to influence regime and niche actors. The success factor in this scenario may therefore depend on how champions and others within organisations respond proactively to this landscape pressure to develop innovative business models.

5.5.1.5 Lack of established and vibrant market for geoexchange and ambient heat networks

Within the *national direction and policy* element, I found considerable evidence that one of the most acute barriers to wider geoexchange adoption was the small number of companies developing geoexchange approaches. This brought challenges of awareness, and the technology developers felt that competition in the market, including competition against themselves, would help raise the currently low levels of awareness of the technology and create more business and opportunities:

> *"If there were 40 of us doing the same thing there would literally be 40 times the number of projects happening" [CEC3]*

The current state of the market and low levels of technology awareness were linked back to national and local government policy by interviewees, with eight referring to the different local planning regime in London, made possible by an exemption in national legislation. This issue did not readily fit into the coevolutionary framework, although it partly cut across the systems of *institutions, business strategies, and technologies*. It was more usefully captured in the *actor decision-making* crosscutting theme considering that awareness is an integral prerequisite for a decision. I felt that the need for a vibrant market, facilitating ready awareness of geoexchange options, is a key background contextual success factor, hence its placement in the *national direction and policy* element of the critical success factors framework.

This issue was also a location-specific factor, whereby interviewees reported how the more ambitious London planning regime was driving change in new build developments towards geoexchange and other heat pump technologies, which was in turn raising organisational awareness and gearing up the supply chain to deliver geoexchange projects:

> *"…you finally start to see a few of them start to work it out […] They get more comfortable with the technology, they're hiring contractors who may not want to hire subs that are experienced or whatever, they start to get more comfortable with it and then it starts to grow." [INT4]*

This suggests that critical success factors lie in the development of a vibrant market for the technology and the awareness which comes along with that. In the absence of this however, local policies and practices can act to fill the gap. This is explored in more detail in section 5.5.2.

5.5.2 Local policies and support

Moving on from the national situation which shaped the likelihood of geoexchange deployment success, a common set of themes were around the impact of policies enacted by municipal authorities through the local planning system, providing advice and support, as well as direct undertaking of schemes by the organisations themselves.

5.5.2.1 Impact of the local planning system

The narrative provided by interviewees suggested that whilst the same national regulation covers all English local planning authorities outside London, some had been able to introduce policies that were having a noticeable impact in terms of technology deployment in new build settings. Five interview participants cited Bristol as a good example of this, with comments such as:

> *"Bristol is a great example…they haven't outlawed gas but they have put it a long way down their hierarchy, and effectively they are enforcing the policies quite strictly so to be able to have a gas network extension and heat properties with gas now you have to prove beyond all doubt that you can't do all the other things including shared ground loop ground source" [CEC3]*

This suggests that a local planning authority may be able to have some influence over developer technology choice through the design and enforcement of local planning policies, which may benefit geoexchange. The findings suggested that these location-specific *institutional – technological - business strategies* dynamics were having an impact locally by compelling housing developers to consider geoexchange as an alternative to conventional options, typically gas boilers. When describing why they thought this approach was not taken more widely, participants felt it might be down to levels of "*resource or the political will, or actually the legal tools, to be able to do that" [INT2].* The ability of local authorities to undertake such positive policy may therefore be limited by the impact of the neoliberal erosion of local authority competencies and resources found by Chatterton et al (2018), Rose & Miller (2010) and Tingey & Webb (2020), and how local authorities have responded to this. This may be an important consideration for this critical success factor.

Practitioners were keenly aware of the different national regulations which planning authorities in Greater London are subject to, and that the design of the London Plan under these exemptions was having a significant impact to facilitate geoexchange rollout.

> *"planners in London [...] are able to impose it as a requirement much more easily in London than they are in provincial places" [INT5*]

The primary impacts were because the carbon reduction requirement for new developments in London was 35% below national building regulations compared to 20% elsewhere, and that the London Plan mandates the use of SAP10 carbon factors (GLA, 2018). Interviewees identified that this was important because the SAP10 carbon factors reflect a more up-to-date reality about the declining carbon intensity of grid electricity compared to natural gas. They felt it was the two conditions combined which meant organisations such as housing developers could not achieve planning permission without choosing a heat pump-based system, and that this was driving demand for geoexchange. The evidence suggests therefore that different local regimes in different parts of the country can have a significant impact on the potential for geoexchange deployment. In this dynamic, the coevolution between *technologies* (the carbon content of grid electricity), *institutions* (local planning rules) and *business strategies* (how developers responded to those conditions to provide heat for their residents) were connected through *actor decision-making* processes of interpreting and selecting geoexchange or other solutions.

As well as driving demand for geoexchange systems locally in London, technology providers reported this was having a noticeable effect on commercial developers seeking to standardise their portfolio elsewhere to bring them in line with the local regime they were experiencing in London.

> *"They're picking up on the mood music within London and that's driving their thinking across their estate [...] So that effect from London does have an overspill" [CEC2]*

This suggests that for organisations with buildings or sites in multiple locations, the local regime in one can permeate to other areas with less geoexchange-friendly conditions. This also points to important coevolution between *institutions* and *business strategies* especially when considering larger organisational responses to local regime pressures.

The approaches taken through planning were not universally popular amongst interviewees, however. One participant noted their frustration that the London Plan and its tendency to favour a heat-pump installation for new sites would lead to islanding effects of buildings cut off from the community of heating and cooling needs and sources:

> *"you have a series of 10 buildings in a row, and the fifth one in the middle is a new building and it has followed the planning advice and has developed its own low carbon solution, it becomes a low carbon island" [CEC1]*

They worried that this effect would undermine the wider business case for district heating to be taken down a particular street because the 'islanded' low carbon buildings would not need to connect and buy heat from the district system. This suggests that geoexchange is not seen universally as the best solution, and that potential unintended consequences may threaten longer-term decarbonisation efforts, which must be considered further. The difference of opinion from a developer of only single building geoexchange systems was clear, with their claim that their approach is viable *"even right down to a single tower block [where developers] would still get the cost effectiveness and economics of scale to make it worthwhile" [CEC3]*.

Finally, interviewees recognised and expressed concern that the impact of the planning system is limited because it only touches new buildings under most circumstances. Because of this, they felt national government policy is required to deliver heat decarbonisation at the pace and scale required.

5.5.2.2 Authority-led ground source prioritisation

Aside from planning policy and how it shaped the local selection environment for geoexchange development, the role of local authorities in actively undertaking or promoting ground-based heating approaches was emphasised by several interviewees. This suggests that local authorities may be acting to create and develop local niches where innovations including geoexchange can develop. It is not clear from the interview evidence whether they operated over all three phases of development proposed by Bush et al (2017), but they were potentially acting as a catalyst for new schemes.

In considering what was driving energy and climate action by local authorities, interviewees referenced the importance of local authority declarations of 'climate emergency,' and the impact of social movements such as the Fridays for Future youth strike pressure group. Considering how these landscape pressures affected the local regime for geoexchange, Bristol was cited as a good example of a location where a city is taking an active role in pursuing ground-based schemes in response to their declaration of climate emergency. Further to the findings of Tingey & Webb, who identified Bristol for its large in-house energy team, this suggests that the presence of such a team has enabled the local authority to respond proactively to landscape pressures in creating a local niche for geoexchange to flourish. Another interviewee noted how the increased social awareness of the climate emergency and the technology seemed to be leading towards geoexchange solutions. Through their experience at an event organised by a local authority in response to their climate emergency declaration, and interviewee described their interaction with a social housing tenant:

> *"…they came over to talk to us. What is the shared loop stuff? Will it work in this building? We are very concerned [about climate change]. Well, ask your landlord about it!" [INT1]*

Whilst the landscape factors such as heightened awareness of climate change and pressure on local authorities to act is outside of local control, how the institutions can respond, including having the skills and resources in place to do so, may therefore be a critical success factor at the early stage of the geoexchange journey.

5.5.3 Organisational and business case

The third main cluster of themes I identified from interview testimony surrounded internal issues of landlord organisations taking the decision to choose geoexchange (or otherwise). There were two distinct but related areas of focus, firstly to the business cases that investment decisions were based on and the business models that would achieve project viability, and secondly to considerations around what organisational characteristics appeared to facilitate the decision to take a geoexchange approach. I placed these findings as the third element of the *critical success factors framework* along from national and local factors, because they focus more closely on the process of organisations making an innovation-decision, which they do in the context of the broader national picture and specific local regime.

5.5.3.1 Business cases and business models

The interviewees revealed they were exploring a range of potentially fruitful opportunities to bolster the case for choosing geoexchange and novel ways of achieving project viability.

Several interviewees both in the domestic and commercial market referred to trialling heat-as-a-service business models to help with project viability, especially in light of the closure of the RHI scheme. In the case of a social landlord, they were implementing a geoexchange project to benefit tenants by replacing their expensive and hard-to-control electric night storage heaters. To enable project viability, they had simultaneously made a commitment to the tenants to deliver a certain and pre-agreed temperature to the dwelling, whilst *"everything behind the line again we control, so that allows us to exploit the asset for different sources of revenue" [RSL1]*. This suggests coevolutionary dynamics between *technologies, business strategies* and *user practices* were enabling client organisations to exploit some of the characteristics of geoexchange to help get the internal decision over the line. When asked about how residents would respond to this loss of control, the interviewee was confident their tenants would appreciate the predictable energy bills this new model would deliver.

One of the geoexchange technology developers reported they have been taking this approach throughout with their commercial clients – retaining full ownership and control of the system whilst delivering contractual requirements for heating and cooling in supermarket settings. They reported that whilst in their experience the ground energy storage and balancing mechanism was important, it was the more nuanced ability to understand and control the system more intelligently over time, made possible by this arrangement, which they felt made the most significant difference to delivering energy and carbon savings.

These point to critical success factors around organisational willingness to try and exploit the novel business models opened up by geoexchange technology to achieve viability. This may further include the ability of external change agents or internal champions to persuade colleagues or potential clients to take the risk. It also involves, in the case of a social landlord where any decision they make centrally affects potentially hundreds or even thousands of their residents, an ability and willingness to persuade and support users in accepting the new system.

Related to this I found evidence that social landlords were starting to change the way they viewed the heating systems from only being costs that must be met or breakdowns that must be repaired, to assets that could deliver a valuable service to the resident living at the property and other benefits to the organisation. This is a potentially important change of perspective for geoexchange, which can offer grid services and so earn ongoing revenue. As an example of this, one of the social landlord practitioners described how they were trialling an ESCo approach which took the capital costs for geoexchange aspects of new residential developments and separated them out to an independent business unit, which would then collect revenue over the long-term against them whilst delivering decarbonisation. This would suggest they are going through a redefining/restructuring process incorporating the novel geoexchange approach; a key part of the organisational innovation process (Rogers, 2003).

Whilst this novel approach was important to that organisation to tip the balance of a decision in favour of geoexchange, it appeared to be rooted in seeking straightforward financial returns. Guided by the EIBM framework I considered whether there was evidence of organisations seeking alternatives beyond traditional neoclassical concepts of value. A good example of this taking place was where a local authority landlord who had recently installed geoexchange to two blocks explained how they had made the decision that, rather than try to recover any costs from the tenants through bills, they would instead fund the whole cost of the installation from their own cash reserves. They built the internal business case for this by attempting to capture an array of non-traditional values for the benefit of their tenants, including social values inherent in reducing energy bills and tackling fuel poverty. As well as these non-traditional values, they reported the approach enabled other fiscal flows for the organisation including reducing the non-payment of rent from tenants struggling to pay both rent and heating bills. Both strategies suggest novel attempts to recognise and capture values, and that organisational willingness to do so may be a critical success factor for geoexchange deployment.

5.5.3.2 The importance of the counterfactual

Also rooted in traditional financial appraisal techniques of assessing project viability, seven interviewees brought up the concept of the counterfactual. Like the examples in 5.5.1 where a local champion was integral to making the case to colleagues based on national policies, this was in the context of the organisation having existing heating systems which needed to be replaced whether or not geoexchange was selected, and this enabled the champions to make the case that the cost of replacing the current system had to be borne regardless, and decision-makers should offset this against the cost of choosing geoexchange:

> *"So, I need to replace this, I am going to spend £200,000 [...] anyway, so what is the difference, what is the extra owed? [...] It is that kind of argument" [INT1]*

Several intermediary interviewees described how they struggled to support non-established organisations where there were no pre-existing assets and therefore no counterfactual. The example given was community organisations / community energy groups who were trying to branch out from solar PV projects to look at renewable heat using geoexchange. However, because their investment would be entirely new and there was no counterfactual to offset against, they were far more reliant on grant funding to achieve viability.

5.5.3.3 Organisational characteristics supporting geoexchange development

I found a second area of critical success factors within this *organisation and business case* element of the development process, focused on the organisational decision to invest in geoexchange. This was an important set of perspectives around organisational characteristics which tend to lead towards them making geoexchange or similar investments.

Single decision maker

Five interviewees raised the importance for a single point of decision, both in regard to this being a single organisation such as a landlord in control of many properties but was also applicable to different parts of a single organisation which could be aligned through the technology, or a process within an organisation whereby the decision regarding geoexchange would be made. For one of the technology developers focusing on the residential market, it was such a key concept that they had begun using the term specifically and directing their sales teams to "*go for what we call a 'single decision maker'" [CEC3]*. They reported it was an especially important consideration for retrofit geoexchange projects where, unlike in the case of new developments with their natural single point of decision being the organisation submitting the planning application, in the retrofit market there is no natural single decision maker for all the dwellings in a location. In retrofit scenarios, properties are typically inhabited, some may have been sold to leaseholders who may no longer live there having rented them out. Therefore, the identification of a single decision-maker, if one could be found, was more likely to lead to a geoexchange investment decision. This suggests a key role for social landlords who tend to retain ownership of the building fabric, even if some dwellings within a building have been sold to leaseholders.

The need to act as a single decision-maker was so important to one social landlord that they were willing to fund the capital cost of geoexchange for all tenants and leaseholders: *"we gave it them for nothing. Because there is no point in not doing. Because it makes the whole building on a single heating system" [RSL1]*. One of the local authority interviewees made the case for why they could not justify this approach, however:

> *"you could argue that the better way to do it is to say, 'You know what, it's free, just connect to it'. But, then we would have a duty of care to other residents, why are we giving away free heating systems to someone who is a leaseholder?" [LA1]*

This suggests that a critical success factor around creating a single decision-maker may be contentious when organisations have to weigh up their social remit and what impact this may have.

In a slightly different scenario, one of the geoexchange technology developers focused more on the commercial market noted how they had been able to align the previously separate heating and refrigeration aspects of supermarket customers. This synergy was made because their geoexchange technology was able to serve both needs, and the client had been able to connect and integrate the two. They claimed this alignment of heating and cooling had helped the decision step to choose geoexchange technology by the customer. In addition, because of the nature of their technology, which both serves and requires heating and cooling demand to function effectively, this alignment was key to project success and the delivered energy savings. These coevolutionary *technologies-business strategies* dynamics seen here appears to be a good example of where perceptions of an organisation's problem and the innovation come together through a redefining/restructuring process (Rogers, 2003). Geoexchange technology enabled a single decision maker to be created out of separate business units to deliver a geoexchange investment.

Importance of 'patient capital'

An organisational characteristic that interviewees felt was important to facilitating a decision to invest in geoexchange was the concept of 'patient capital'. This applies where the project developer maintains a long-term interest and stake in the investment or building and was contrasted with typical private financing where a much shorter timeframe for return is sought. The concept was summed up by:

> *"Social housing organisations such as this have an advantage…I would say we have patient capital…If you have private capital at the most you want to be in and out within 10 years with a return. Lots of these things aren't stacking up to do that." [RSL1]*

Because significant financial benefit is realisable through reduced long-term operating expenditures compared to a fossil-based option, this was helping to enable geoexchange approaches. This was noted as being an important aspect in the residential market, whilst in the commercial space it is already more likely for the business investor in a particular technology to see the value in longer-term benefits. Social landlords were seen as good examples of holding a long-term interest in the health and performance of their buildings, who sought financial benefits from long-term cost savings as well as a social remit to deliver other benefits to residents, such as reducing fuel poverty and providing warmth and comfort. Therefore, success factors centred around the type of organisation and its social purpose, as well as coevolutionary dynamics between the *technology* and *business strategies*, where geoexchange was fulfilling some of the needs to deliver a range of non-traditional values. Geoexchange developers expressed hope that they would be able to open up the residential market first via social landlords with their long-term view to bring about awareness and cost reductions required to draw in less amenable types of organisations. The approach taken was compared to private housing developers whose 'impatient capital' tended towards lowest cost options, even to the extent of removing other measures when they found out how big an impact a geoexchange type system would have on meeting their carbon targets.

> *"We've had developers tell us their policy is to pass the carbon target by 0.00001%. When you put a ground source heat pump in that slashes the carbon output of a building, their response then is to put less insulation and cheaper windows in so that they still pass by 0.00001% rather than deliver a building that is better' [CEC3]*

Aside from being an indictment of a particularly unscrupulous private developer in this case, these findings suggest the importance of considering deeper institutional structures which influence the transition process including how capitalism shapes the prevailing socio-political paradigm (Feola, 2020; Swilling et al., 2016).

The role of third-party consultants to the geoexchange development process was noted by interviewees representing technology developers highlighting that they frequently come up against resistant regime actors in the development of new housing schemes. They specifically cited traditional consultants whose singular focus on cost reduction blinded them to the bigger picture and long-term benefits that geoexchange could offer their client. A success factor in challenging the damaging impact of these consultants was described by one of the geoexchange developers, and this is linked back to *local policies and support*. Driven by requirements put in place by local planning authorities, they had experienced developers bringing their consultants to begrudgingly attend their presentations on geoexchange where they:

> *"…spent an hour talking to them about the benefits […] then they will say something like "well we're being forced to do it anyway so I'd better learn about it and we'd better get on board…"" [CEC2]*

These findings suggest the importance of considering organisations involved in the geoexchange decision process beyond just the technology developer and the client organisation, as well as further evidence as to the role of the local policy environment.

5.5.4 Technology aspects and system design

The fourth cluster of success factors concerned the following stage in the geoexchange development process around system design and technical challenges. Prominent themes here fell under two categories. Firstly, developers combined geoexchange approaches with ambient temperature heat networks to address challenges related to urban space constraints, serve multiple residential properties from a single ground heat exchanger, and tackle problems inherent with classic high temperature district heating. Secondly, there were technical challenges inherent in geoexchange which must be considered and addressed to facilitate successful deployment.

5.5.4.1 Benefits of combining geoexchange with ambient heat networks

Eight of the interview subjects highlighted synergies between geoexchange approaches combined with sharing heat between buildings through the concept of ambient heat networks. Whilst this approach went under various different names e.g. 'shared ground loops', key characteristics were the use of uninsulated pipework made possible by the ambient temperature, and the inclusion of multiple distributed heat pumps at the building or dwelling level to raise the temperature to the required level. Many interviewees had experience with this approach in both residential and commercial settings and claimed that it was a more efficient method than high temperature district heating. The main benefits were:

- ***Reduced heat loss, and environment-based heat gain***

Because of the ambient temperature of the water, one of the key benefits of this approach was the lack of heat losses. One of the interviewees described how their work to meter traditional district heating found a 70% heat loss from generation to the point of entering the residents' properties, and this inefficiency caused reputational damages for the organisation, and led to the residents complaining of overheating, as well as being hugely wasteful. Interviewees claimed the characteristics of ambient heat networks carried multiple associated benefits and these are set out here.

- ***Better system operation when dealing with low occupancy levels***

One of the technical challenges raised by interviewees which negatively affected operators of classic district heat networks was how to operate the system efficiently when residents are absent and not consuming heat. This issue was found to be especially acute in high-end developments in London:

> *"the interesting phenomenon of foreign investment in London, and the seemingly common situation where an apartment or a high end flat is bought by a foreign investor and they come and live there once a year for a couple of days and carry on with their international lives" [CEC4]*

This demonstrates coevolution between *technologies* and *user practices* but also connected to broader landscape trends of foreign ownership of housing in the UK, tied at higher order levels to the socio-political regime which has operated over decades to result in this situation. Participants explained that ambient heat networks comprise multiple distributed and independent heat pumps along with the ambient temperature network, meaning that low levels of occupancy did not compromise the rest of the system.

- ***Resident choice and lessening the heat metering, billing and administrative burden***

Interviewees highlighted the significant administrative and technical burden associated with traditional district heating, especially the heat metering and billing required by national regulations. They contrasted this to the approach made possible by the ambient heat network system with distributed heat pumps serving individual dwellings:

> *"They only pay for their electricity consumption off that heat pump [...] That basically means that resident is free to choose who their energy supplier is, and they are not locked into any particular energy scheme" [LA1]*

Because the local authority did not have to get involved in the 'messy' billing process, they saw this as a key selling point of the combined geoexchange and ambient network.

- ***Commercial model and the use of waste heat to reduce ground infrastructure costs***

Participants reported that the biggest cost in geoexchange projects is the ground installation element, typically a borehole field. Because ambient heat networks enabled the combination of a range of buildings of different types and functions on the same system who share heating and cooling between them, the system can serve the same development from a smaller borehole field, thus reducing capital costs. In addition, because of the ambient temperature operation of the heat sharing networks, they could bring in waste heat from a range of sources previously thought to be of too low grade to be useful, such as electricity transformers and substations.

Overall, the data suggested multiple benefits of combining geoexchange with another niche innovation, ambient heat networks. This double niche combination may become a critical success factor to wider deployment of both technologies especially in denser urban settings and when serving multiple dwellings.

5.5.4.2 Technical challenges and design constraints

The other main area of focus at this stage in the process was around the technical aspects of geoexchange deployment for which early consideration is important.

- ***Ground storage volume availability in urban areas***

There were differences of opinion in regard to the wider deployment of geoexchange, and one of the principal areas of contention surrounded the limits to surface and subsurface space availability, particularly in urban settings. Whilst the connection of dwellings via an ambient heat network was important, it did not completely ameliorate this issue. One of the interviewees was sceptical about the mass rollout of ground source heating in general, because:

"there's just too many people drawing heat out of too small a space." CEC1

They raised a concern that these issues could lead to rival ground heat extractors competing for a finite energy resource. It is important therefore for geoexchange developers to consider these *technology-ecosystem* dynamics when designing projects. Others noted that geoexchange was uniquely well suited to deal with this challenge, because of its ability to replenish rather than only drain energy from the ground. On top of this, they were exploring how they could bring in additional heating and cooling sources rather than just relying on the ground element, facilitated by the ambient temperature heat network. One of the developers further explained how their geoexchange system was suitable for constrained surface spaces because of their novel directional drilling approach, which obtained a large energy storage volume from a small surface footprint.

- ***Space in dwellings to install the equipment***

Because combining geoexchange with ambient heat networks requires a heat pump and thermal storage of some type to be installed within the dwellings, an issue was raised regarding suitable space in the properties, and in relation to the types of heat pump products on the market to meet this need. This is connected to the lack of an established market in heat pumps explored in 3.2.1.5 as well as the broader landscape trends for households to remove water tanks and use the space for other purposes. It is key for developers to consider how their system will operate in space-constrained dwellings.

- ***Dwelling energy efficiency standards***

Like any heating system, heat pumps work most efficiently in buildings which are well-insulated. Because most current heat pump models output at lower temperatures than gas boilers, I expected to find challenges for system designers and building owners around dwelling energy efficiency standards in retrofit settings. Interview subjects, however, claimed that they dealt with this through choosing larger radiators and engaging effectively with the residents to place these in suitable locations. This engagement also helped the developers deal with other behavioural aspects of how to use the heating and hot water following installation. Several noted the need for improved levels of insulation for heat pumps to operate effectively. However, one interviewee claimed they did not feel this was such a problem for social housing largely because of the 'Decent Homes standard', which required that by 2010, local authority and RP homes were provided at a certain minimum specification. These technical considerations however must still be considered at a sufficiently early stage in the geoexchange development process to identify suitable remedial actions or technological adaptions.

5.5.5 Installation and post-installation

In the final cluster was a set themes I grouped together around managing the installation process itself, and both short and long-term system and performance management and impact reporting.

5.5.5.1 Managing the installation process

An area that I expected participants to raise as an issue in retrofit projects was regarding the challenges of the installation process and dealing with physical disruption to residents. In fact, all the representatives of organisations who had installed retrofit systems reported this through positive comments such as:

> *"The actual project itself, went quite as smooth as clockwork really." [RSL3]*

One felt that the unusual nature of the project and technology lent itself to supporting the resident engagement and the installation process:

> *"People are interested because it's more interesting than more of the normal stuff we've that goes on…to see people drilling these holes. All the usual jokes about fracking…(chuckles)." [RSL1]*

Overall, the interviewees felt installation issues were like any other large project and were not a problem exclusive to geoexchange or ambient heat network approaches. All expressed the need for a careful resident engagement process however, which they undertake whether for a geoexchange or any other type of major works. This involves engaging with residents through public meetings, letter-writing, door-knocking, and then going to meet the residents in their home, to allow them to choose where the new radiators will go for example. In these visits they also described how the system would work and how the residents should operate it to minimise costs and deliver the heat they need. The need to manage the *technology-*

user practices dynamics was particularly acute because of how heat pumps are quite different to the gas boilers or electric night storage heaters residents were used to.

5.5.5.2 System monitoring, management and follow-up

The final area discussed was around post-installation management and monitoring of systems, both in terms of technical performance and user experience, and in terms of gathering evidence on energy, carbon and fuel bill reductions.

System performance management

Both technology developer and social landlord interviewees raised the challenge of managing systems after they have been installed, especially in the domestic market:

> *"The biggest problem you have is [...] these systems work very well until you put the human being into the picture [...] Not everyone will do what you want them to do or use the system how it's meant to be used" [RSL3]*

Developers reported they were working to address this with remote management systems, which will also develop the demand-response capabilities of their technology. Technology developers serving the commercial market however had quite different perspectives, noting how they and their customers had throughout maintained a clear emphasis on data-driven performance management.

Cost and carbon saving monitoring

The final coding hotspot was focused on the need to obtain evidence of impact both in carbon and fuel bill terms, and this needs to be considered well in advance of the installation. Interviewees reported they understood the value in doing this and a desire to do so, as the quotes show they felt this was not done to the standard they would have hoped.

> *"No. A missed opportunity I would say" [LA1]*

> *"What we weren't very good at on the first one was checking what they were all using and paying for on their existing heating system." [RSL3]*

In some cases, this was down to the different types of customers connected to different parts of the network, and in others because of the streamlined utility billing noted above meant that the landlord no longer had access to resident energy consumption data. Further complexities were due to comfort-taking by residents who made the most of the better system to have a warmer home. There was a keen sense of missed opportunity, with a desire to remedy this for future installations.

These issues suggest critical success factors in geoexchange deployment in the later stages of the process around good system management and monitoring practices to ensure efficient and low-cost operation. This has reputational impacts for the landlord organisations, as well as more broadly for the technology. The benefits of implementing geoexchange can be demonstrated far more readily if developers or landlords take steps to obtain pre-installation costs for later comparison and reporting.

5.6 Chapter discussion

In this chapter, I set out to explore some of the factors that have led to successful geoexchange deployment in UK cities. Through application of a combination of sociotechnical frameworks to interview data from geoexchange practitioners, I identified a set of insights through analysis of which I propose a critical success factors framework for geoexchange deployment. The emerging framework (shown in Figure 5.3 and full version at Appendix I) helped me to understand and classify how the success factors fitted together within a coherent framework overlaid with the project development process.

In terms of applying and contributing to theory, I applied several sociotechnical frameworks and found the multilevel perspective and coevolutionary frameworks were both useful in helping to focus my analysis and identify areas for deeper exploration. Taking a broadly abductive approach as outlined in 3.3.3, I alternated between the theory and the data to apply, test and develop the frameworks. Initially I attempted to base the analysis solely on the coevolutionary framework, but it was apparent that common themes and issues were evident in the data that were not well captured through consideration of the five coevolving systems. I introduced the MLP to explore where the data pointed to issues related to niche innovations and the broader sociotechnical landscape. Whilst both frameworks together drew attention to interesting aspects of the data, I believe however that my attempt to merge the two as hierarchy levels within a combined framework, as shown in Figure

3.4, was not particularly successful. This approach was partly driven by finding instances in the data around the effect of *regime - institutions*, such as effects of prevailing national policy, and partly by the hierarchical nature of template development within the template analysis methodology. On reflection both frameworks support a thorough sociotechnical analysis through focus on different aspects, but they don't fit together into a neat nested hierarchy.

In developing the geoexchange critical success factors framework, I attempted to draw together the sociotechnical insights into a useful and coherent tool for geoexchange practitioners and policymakers. At the broadest scale, the framework recognises the overarching policy landscape and national support mechanisms which impact on what funding was available, but also reflect more structural issues such as the shape of the market for non-fossil-based heating technologies, as well as confusion and uncertainty caused by the lack of a clear national direction for heat decarbonisation. As explored in Chapter 1, this is where the UK is clearly at odds with some of its European neighbours who have clear plans in place. The issues concerned the institutional aspects of national rules and policies set by central government as well as the beliefs held by policymakers about the impact of heat electrification on the grid, which participants felt were out of date and contributed to uncertainty over whether an electrification or hydrogen route was best.

The findings suggest that in addition to the physical infrastructure of the incumbent natural gas grid, the stability of the fossil-based heating regime in the UK is maintained via the prevailing socio-political regime. Participants were concerned a powerful lobby of incumbent actors was impacting the national discourse about the future of the grid towards a 'green gas' route, instead of decommission-electrification and this would jeopardise support for their technology. Prior work by Lowes et al (2020) in this area, the critiques of Feola (2020) and consideration of the socio-political regime of Swilling et al (2016) were helping in drawing attention to the effect of uneven power relations. Applying these together suggests that long-term success of geoexchange may require addressing higher order dimensions of *power dynamics* and *paradigm commitments*.

The introduction of the Future Homes Standard update to national building regulations was an important *regime* and *institutions* development because participants expected it would include a ban on gas boilers and therefore indirectly support project developers to seek alternative options, including geoexchange. There were also connections to the *landscape* layer of the MLP as some of these elements could be seen this as exogenous context, which can potentially put pressure on the existing regime. The importance of central government funding mechanisms for low carbon options such as geoexchange suggests that these technologies continue to demonstrate *niche* status, which require shielding from normal commercial pressures to compete in an open market. However, there were signs that organisations were starting to develop business models for geoexchange to attain viability in expectation of impending scheme closure, which may suggest tentative signs of transition.

The next element in the geoexchange development process affecting practitioners and decision-makers is around *local polices and support*. Within the broader national environment from where the overarching rules, structures and norms emanate, I created this element to identify what specific local situations, policies, and contexts are key to the development of geoexchange projects. The most prominent finding here was around the impact of the local planning system to support the adoption of geoexchange approaches. Whilst local planning authorities are governed by the National Planning Policy Framework (MHCLG, 2021a) and are limited as to what powers they can exert on developers, participants felt that in both the design and enforcement of local policies they were able to produce a significant impact through using what powers are available in different ways. Participants noted a few examples of cities of where this has been done, especially Bristol and London. In London, the 35 planning authorities within the Greater London Area operate to a set of devolved powers which means planners have more control over what they requirements they set (GLA, 2019; *Greater London Authority Act*, 1999). Bristol however operates under the same regulatory framework as other towns and cities in England, and participants felt they had achieved this through specific policies and practices which have had the effect of deprioritising gas in new developments. The data obtained from the interviews did not enable a more in-depth analysis and it is worth considering how and why some local planning authorities have been able to introduce such measures. Earlier research found that different local authorities such as Bristol are acting within their remit and powers to deliver energy action (Tingey and Webb, 2020). Noting the large energy team that Tingey & Webb (2020) had identified in Bristol, a deeper analysis through the intermediary roles framework developed by Bush et al (2017) may help to provide additional insights into how local authorities can develop local niches and create conditions for geoexchange and other niche technologies to flourish. This should be considered in the context of the broader situation faced by local authorities categorised by austerity and the loss of skills and resources (Chatterton et al., 2018; Harvey, 1989; Rose and Miller, 2010; Webb et al., 2016).

There were two issues raised regarding the role of local planning policies. Firstly, not all interviewees agreed with policies that aimed to reduce building emissions immediately, because they felt it would lead to an islanded approach which would jeopardise the wider business case for district heating. This suggests that geoexchange combined with ambient temperature heat networks is seen as a competing niche-innovation to larger district or city scale heat networks. Secondly, the inherent limits of the planning system given planning rules concentrate on new construction and buildings. The relevant context here is that over 80% of today's homes are likely to be still standing in 2050 (Kilip, 2008; Lipson, 2018). It is estimated that it would take 400 years to replace all UK homes at the current rate of replacement (Boardman et al., 2005). It is only in the process of a major refurbishment that the planning system would 'see' any of the existing building stock.

The themes in the *local policies and support* element of the success factors framework applied to the *institutions* node of the coevolutionary framework and the *regime* level of the MLP. However, I felt both frameworks lacked sufficient location-based analysis and decided that locational elements represented an important crosscutting theme. In the template development process, I created a separate top-level theme for this, which sat outside of the hierarchical framework. There were also local simultaneous *regime* impacts from local authority declarations of climate emergency with 2030 net-zero carbon targets, driven in part by exogenous *landscape* factors including climate change awareness, as well as being *location-specific* in their distribution and impact. Here I felt grouping these together under one *local polices and support* cluster within the success factors framework was helpful.

At the level of the organisation, it was useful to draw in concepts from the diffusion of innovations framework to consider how innovation-decisions come to be made, and the importance of key individuals acting as *champions*. The scale and complexity of geoexchange projects meant these involve organisational rather than individual decisions. For example, when a social housing landlord is considering replacing the heating systems in their housing blocks, and may be deciding between a conventional like-for-like system with which their staff and maintenance contractors are comfortable and familiar, or instead opt for a novel geoexchange system. Whilst recognising the importance of individuals acting as *champions* within organisations, Rogers (2003) says relatively little about the internal processes facilitated by the champion that the organisation must go through to reach a positive innovation-decision. Rogers noted that in general large organisations are likely to be more innovative, but for the benefit of this study, little was found about what is likely to make the difference in equivalent sizes and types of organisations between those likely to be open to innovations or not. Similarly, Rogers described some key characteristics likely to make a good innovation champion (e.g. interpersonal and negotiating skills) but little about the organisation-system, which is likely to allow champions to flourish, or how the role of *champion* is an internal mirror of an external *change agent* for which there is much more narrative.

Within a set of factors I identified as being around the fossil / non-fossil heating system decision point, the need for a viable business case, as well as some key organisational characteristics which participants felt would more likely to lead to a geoexchange decision were required. The coevolutionary framework was helpful here at drawing focus to this through the *business strategies* node. The coevolution of new types of business model along with the geoexchange technology and changing institutional situation was evident through the development of heat-as-a-service models. Instead of a tariff being set as a cost/kWh, these operate through an approach where quality of service is guaranteed (i.e., a certain agreed temperature in the property between agreed hours), and the operator takes on responsibility for reducing energy consumption and emissions. This arrangement was made possible by the technical ability to control the in-dwelling equipment remotely, and in light of the expected closure of the RHI mechanism, because participants felt it would help achieve financial viability.

I found it helpful to introduce additional nodes from the EIBM into the template analysis. These included the nodes relating to the attempt to capture *non-traditional values*, which included within the *fiscal* node the importance of a *counterfactual* case against which to offset some of the expenditure. This approach was noted by representatives from organisations such as local authorities with large housing stocks and corresponding capital asset budgets. However, it was recognised this is not the case of community groups investing in energy projects, where typically they get involved in an energy project by raising finance through a community share offer or similar, and earn a return through the RHI and selling heat to the customer. In the case of heating projects however, they are proposing to step into a new space where the lack of a counterfactual is an important consideration.

The *customer segments* node directed to the importance of considering leaseholders. Although a local organisational issue, it was linked to prior central government decisions, which since 1980 required local authorities and from 1997 Registered Providers to make dwellings available for sale to tenants through the 'right to buy' scheme (HM Government, 1997, 1980). National regulations also governed the need to consult the leasehold owners prior to undertaking works which affected them (HM Government, 2002). Leasehold ownership makes up around a third of dwellings, although in some buildings this proportion can be significantly higher with the majority dwellings now in private ownership (Wilson, 1999). These buildings tend to be the last ones considered for retrofit works to the heating systems. This organisational and institutional challenge supports the combination of geoexchange with the ambient heat network approach, because they can operate effectively without all dwellings connected and can accept additional dwellings onto the system later. Evidence suggested property owners were taking the decision to circumvent the issue by directly funding installation to all dwellings, although others challenged this approach. Whichever way it is tackled it is important for a successful geoexchange development that a strategy for dealing with leaseholders is considered.

I added a new node to the combined template regarding *organisational or financial structure*, which covered the approach by some landlords to separate heating assets off into an ESCo structure to finance the costs and capture the benefits without jeopardising the construction of new developments. This suggested coevolutionary dynamics in how actors responsible for the long-term management of the organisation's assets appeared willing to try new approaches, made possible by technological aspects of geoexchange such as the ability to earn income from grid balancing.

This node also included a prominent focus on the importance of patient capital to the likelihood of geoexchange style investments. Because this concept emphasises the benefit of long-term ownership, as a corollary it points to the negative impacts of a planning system which prioritises private developers especially volume housebuilders seeking short-term profits. These short-term profits come at the expense of both the subsequent inhabitants of the building who suffer in higher energy bills and lower comfort, and everyone who suffers the impact of avoidable carbon emissions. Whilst in the template I connected this to the landscape layer of the MLP as issues around the prevailing capitalist economic system, as discussed in Chapter 2, the challenge by Feola (2020) was helpful in considering how capitalism permeates the workings and logics of sociotechnical systems. Further evidence was reflected in the *technology aspects and system design* level in relation to ambient heat networks being able to address issues of low occupancy levels in residential developments, driven in London especially by international capital flows with foreign investors buying up luxury apartments and hardly living there.

Finally, I also added a new crosscutting theme relating to *actor decision-making* placed as an internal connecting node within the coevolutionary framework, because it was inherent within the connections between the nodes. Here I coded the important consideration of the *single decision maker* which was also connected to the *organisational or financial structure* node. This did not fit neatly into any of the other nodes of the coevolutionary framework, although it was related to some aspects of the *user practices* and *institutions* nodes. There was evidence of coevolution of actor decision-making with the *technology* node, where the geoexchange technology was facilitating previously separate parts of a business to come together and make joint decisions. This crosscutting node aligned closely to the organisation innovation-decision process described by Rogers (2003).

The primary finding from the *technology aspects and system design* element was the multiple benefits that developers could leverage by combining geoexchange with some type of ambient heat network. This was a straightforward technological consideration for transferring heat from the ground source to the end users, and technology developers saw the ambient approach as preferable to classic high temperature district heating. This also displayed the effects of coevolving *technological - institutional* factors, because national regulations around the need to meter and bill residents of classic district heating (and the technical and administrative burden involved in that) do not apply to ambient heat networks, leading developers to favour an ambient approach. An important consideration, which can be linked to *local policies and support* and the claim that a local planning system that supports geoexchange can jeopardise the case for city scale district heating, is whether such ambient systems could later connect to an external district heat network.

The second set of findings in the *technology aspects and system design* element were a series of technical considerations and potential future challenges. It is usually assumed that dwellings in the UK are not suitable for heat pump systems because of the poor levels of insulation especially compared to other European countries. However, connected to *institutions*, a central government programme from the 2000s had addressed this issue for social housing even though this was a by-product of the scheme. The issue about the need for (and general lack) of internal space for thermal storage is important, although an interviewee from a geoexchange technology developer alluded to a solution they were introducing of dwelling-based heat batteries with phase-change materials, which require much less internal space.

In the final set of findings that I grouped together as *installation and post-installation*, were a few key themes I felt should be incorporated into the framework. As noted in section 5.4.5, installation challenges were not particularly reported as a major issue in the findings. This may be due to the skill and experience of the organisations in managing large retrofit projects of this type, or that participants did not want to admit to problems in dealing with their own residents. However, key factors were evident around planning the works, and engaging with residents, and supporting them to use the new system. The emphasis on considering *user practices* in the coevolutionary framework was useful here. This level also included considerations around the control and management of geoexchange systems following completion of the installation. These were technical but also related to *institutional* and *business strategies* nodes of the coevolutionary framework, and *organisational and financial structure* node of the EIBM, because the technical issues of control and performance management are intertwined with the business model and enduring system ownership.

5.7 Chapter summary

In this chapter I applied a template analysis to a series of interviews with practitioners involved in various aspects of geoexchange development to explore a multilevel sociotechnical analysis of success factors for geoexchange deployment in UK cities. The findings suggest that geoexchange deployment involves an array of local and national contexts as well as organisational and technical factors and considerations. I drew together the insights to create a geoexchange critical success factors framework, which I propose can be applied to help geoexchange developers and other practitioners involved in geoexchange including organisational champions to navigate the development process and support wider deployment. I find particular importance of location-based impacts on geoexchange rollout, and further research is justified into the meso-level regime of municipal governance on the place-based selection environment for geoexchange especially in combination with ambient heat networks in urban settings.

Overall, the literature was helpful in drawing out some of the key insights from the interview data. The coevolutionary framework (Foxon, 2011) and multilevel perspective (Geels, 2002; Geels and Schot, 2007) were particularly useful especially when considered in light of the supporting literature which has helped develop the field. This included aspects of the prevailing socio-political regime (Chatterton et al., 2018; Feola, 2020; Geels and Schot, 2007; Harvey, 1989; Rose and Miller, 2010; Swilling et al., 2016), and the role of incumbents (Lowes et al., 2020). To conduct the analysis, I combined sociotechnical frameworks supplemented by some additional crosscutting themes supported by literature on local aspects of the energy transition (Tingey and Webb, 2020; Webb et al., 2016) and organisational innovation decisions (Rogers, 2003). The geoexchange critical success factors framework aims to bring these insights from the literature and empirical data together into a simplified and coherent whole for applied purposes.

6 Exploring city-based support for shared ground heat exchange

6.1 Introduction

Findings explored in Chapter 5 emphasised the importance of the local regime, institutional factors and location-based impacts on geoexchange deployment. The results suggested that developers of geoexchange projects faced a variable selection environment in different UK cities, despite city authorities operating under the same national legal and regulatory framework. Results also indicated that geoexchange combined with ambient temperature heat distribution through a combined shared ground heat exchange (SGHE) approach addresses some of the challenges associated with traditional high temperature district heating and opens up geoexchange applicability to dense urban and residential settings. Because of these findings, in this final empirical chapter and phase of research, I focused on issues of urban governance and particularly the policies and practices that local authorities can implement to impact the place-based selection environment on the development of SGHE and shape the local regime. I addressed this through the following research question:

> *RQ3. Within the same legal and planning framework, what actions are local authorities taking to support or constrain the deployment of shared ground heat exchange, and what effect is this having?*

I undertook the work presented in this chapter through a comparative case study of two UK cities, Leeds and Bristol, chosen for cross-case comparison partly based on results obtained in Chapter 5. The case study involved building a repository of documentary and interview evidence on thirty sub-cases of residential developments where developers chose SGHE or other approaches such as gas boilers, direct electric panel heaters, onsite communal heat networks, etc. I undertook this research from the position of an environmental campaigner in Leeds, including supporting the campaign to get the local authority to declare a climate emergency and pledge to reach net-zero carbon by 2030. I recognised that I am therefore embedded in the local regime which includes domestic heating in Leeds, and I used my local knowledge and connections to help shape the research. As a qualitative case study seeking to illuminate the real-world phenomenon of SGHE deployment I recognised that my proximity and involvement was, with careful techniques and protocols in place, an advantage to try to produce valuable applied research.

This work addresses gaps in the research into place-based transitions through a sociotechnical analysis of how local authorities can design and apply strategic and spatial planning policies in their locality, and how regime actors respond to the local policy environment. As well as examining the technical aspects of residential development subcases through a policy-adherence review process, I conducted a template analysis of documentary and interview evidence from local practitioners involved in urban spatial planning and residential development. As part of this work, I applied and developed the combined multi-level perspective and coevolutionary framework that was initially developed in Chapter 5, and this is set out in more detail in section 6.3. Through this research I aimed to address the real-world problem of continued reliance on carbon-based heating in favour of low carbon alternatives such as SGHE, and to generate applied knowledge on how cities can overcome the challenges of carbon lock-in and incumbency that will be useful for other cities in the UK and internationally.

6.2 Case city context

As broadly similar large UK cities subject to the same regulatory environment, I selected Leeds and Bristol for the comparative case study analysis. The set of regulations most relevant to the case studies is the English planning system, which is common for all planning authorities in England aside from those within the Greater London area where devolved powers mean planners have more control over what they requirements they set (GLA, 2019; *Greater London Authority Act*, 1999; Tomaney and Colomb, 2018). A different set of regulations also apply for the other nations of the UK (Adam et al., 2017).

Both cities are members of the Core Cities[3] network of major UK cities outside of London (Core Cities, 2021; Townsend and Champion, 2020). Current population

[3] The Core Cities is a non-statutory and self-selecting advocacy partnership between the major cities of the UK outside London (Taylor et al., 2010)

estimates are 465,866 for Bristol and 798,796 for Leeds (Bristol City Council, 2020; Leeds City Council, 2020; ONS, 2021). The limit of the case study was set as the planning authority boundary in each city. In Leeds the relevant planning authority is Leeds City Council (LCC), and in Bristol this is Bristol City Council (BCC). Both are large single-tier unitary authorities, of the type recognised by Tingey & Webb (2020) to more likely to be 'leaders' in energy engagement. BCC was cited by Tingey & Webb as particularly active, with activity less clear for LCC.

As identified by Tingey & Webb (2020), local authority scale was an important consideration. Particularly relevant to this investigation was the scale of the residential sector in both cities, and I measured this by the size of the planning function in each city. In the year to March 2021, the LCC planning department handled 4,321 planning applications compared to BCC's 2,556, but the majority of those in Leeds were small change-of-use or household applications, and both organisations processed around 850 planning applications for new developments (MHCLG, 2021b). It was not possible to ascertain the relative resource of the planning functions in each city.

I considered potentially relevant factors which may have an impact on technology choice: local land values and local authority housing delivery targets. The former because of the potential impact on viability calculations by housing developers which may affect how much they are willing to spend on other measures. The latter because whether the BCC and LCC authorities were meeting their nationally determined housing targets could affect the political pressure they may find themselves under from central government. I considered whether this could lead to attempts to boost housing numbers through accepting lower standards by developers. Leeds has a 33% lower average land value than Bristol which may have an impact on development financial viability (£2,150/ha in Leeds compared to £3,250/ha in Bristol) (HM Government, 2020b). To the year ending 31 December 2020, Leeds had over-delivered to its target for the previous three years, Bristol had consistently missed their target by around 28% (MCHLG, 2021).

Both cities have seen similarly significant cuts in central government funding of around 40% since 2015-16 (House of Commons Library, 2021) and so have both faced similar issues caused by the central government's neoliberal austerity programme (Huxley et al., 2019; Webb et al., 2016). In terms of progress towards reducing carbon emissions, Bristol has achieved a greater reduction than Leeds, cutting 43% since 2005 compared to 33% respectively (BEIS, 2021). Both cities made commitments to achieve net-zero emissions by 2030 as part of their declarations of Climate Emergency made in late 2018 in Bristol and 2019 in Leeds (Bristol City Council, 2018; Leeds City Council, 2019). Bristol's commitment includes both territorial production emissions and consumption emissions of the population unlike Leeds which covers only production emissions. Bristol features a strong history of local grassroots activism which has contributed to municipal initiatives on the environment including the establishment of Bristol City Council's Sustainable Cities Team in 1994 to coordinate sustainability-related activities from different departments and develop a strategic direction (Torrens et al., 2018). The role of this team is potentially key to Bristol's relative success and was an important consideration in the research (Tingey and Webb, 2020).

6.3 Data collection and analysis

The same data collection and analysis process was repeated for both case cities. To obtain a local authority perspective of each city, I first collected and analysed spatial planning and strategic documents and policies relevant to heat decarbonisation, and supplemented this with interviews of senior planning authority officers. This was to establish what local policies and plans were in force, how these had changed over time, and the direction of emerging policies.

To elicit some insights on how the local context impacted on the choices made by housing developers, for each of the thirty subcase residential developments, I collected and analysed documents for certain key information on the subcase related to the inquiry. For new build developments this included planning application submission documents related to carbon reduction, energy efficiency commitments, and information about the proposed heating system along with any other technologies to meet policy requirements. Documents also included correspondence between the developer / their appointed energy consultant and planning officers within the local authority, which were analysed to explore the types of support and enforcement activities taken in each case. For the retrofit developments which did not progress through the planning process, other primary data sources such as reports, minutes of meetings and public information from websites etc. were included. A full list of data sources is shown at Appendix J.

I supplemented the documentary analysis with interviews of practitioners involved in various aspects of the development process. This served two purposes. Firstly, to clarify uncertainties and fill in any information gaps in the documentary record. Secondly, to develop a deeper understanding of the situation behind why different innovation-decisions are made from a range of practitioner perspectives. The aim was to explore how developers and their consultants, as regime actors, responded to local regulation and the impact of the urban governance environment, as well as institutional responses and perspectives to developer proposals. I employed a template analysis of the interviews and a subset of documentary data using the combined *MLP / coevolutionary / EIBM / intermediary roles* framework developed in Chapter 5 and then conducted a hotspot analysis to highlight areas for further investigation. Figure 6.1 shows a diagrammatic representation of the hotspot analysis overlaid on the combined MLP and coevolutionary framework.

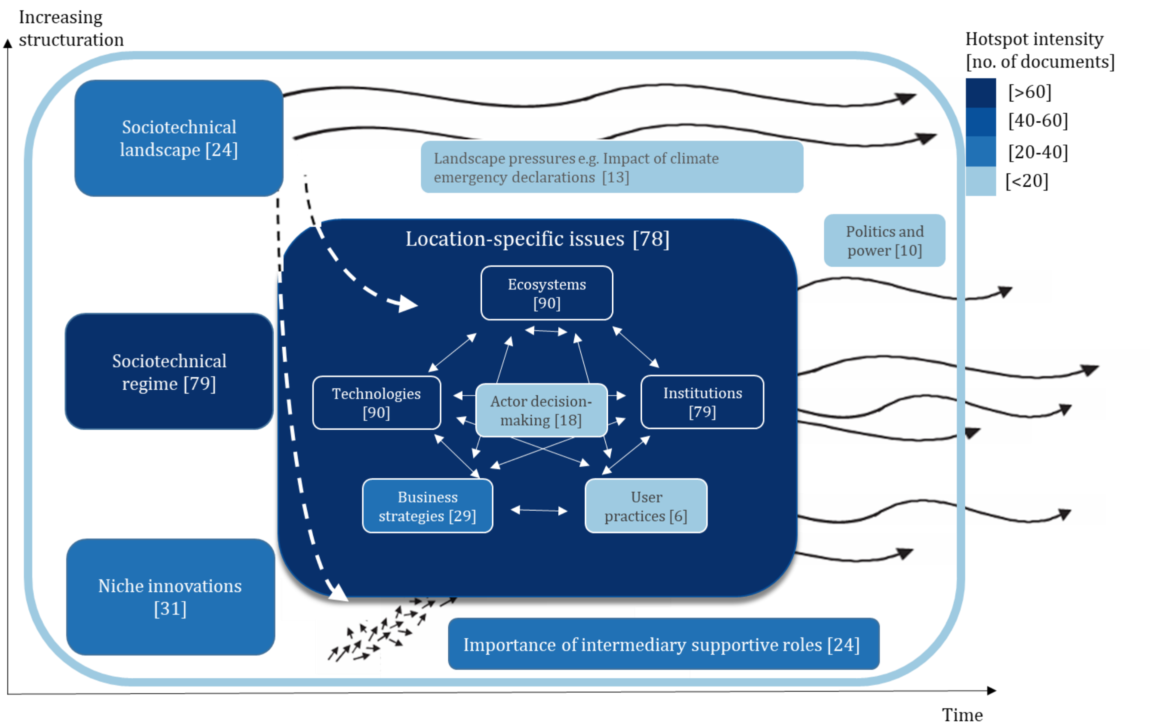


Figure 6.1 Diagrammatic representation of hotspot analysis overlaid on MLP (Geels and Schot, 2007) and coevolutionary frameworks (Bolton and Foxon, 2011). Hotspot intensity shown by colour (as per key), and number of interviews referring to theme [in square brackets].

The full results of this analysis are presented in section 6.5, but the strength of emphasis on the *regime* level of the MLP, the *institutions, technologies* and *ecosystems* nodes of the coevolutionary framework, and the *location-specific* crosscutting theme is clear. The hotpots of technologies and ecosystems were to be expected given that the policies and documents were produced as part of the process of technological measures to deliver carbon reduction. In light of some interesting dynamics in the results however, I added a *politics and power* element which encompasses the three levels of landscape, regime and niche, and the five nodes of the coevolutionary framework. To present the results of the thematic/hotspot and technical subcase analysis, I grouped together and simplified the findings around four key themes which are used to structure the presentation of results in section 6.5.

1. Design of heat-related planning polies
2. Support, intervention and enforcement of planning policies
3. Actor response to broader institutional and technological dynamics
4. Roles of developer and energy consultant actors in the heat transition

6.4 Subcase overview

In each case city, I included a range of residential development types where developers proposed different heating technologies. In Bristol, twelve subcases were new build and three were retrofit projects, whilst in Leeds thirteen were new build and two retrofit. In both case cities, I included all examples of residential schemes involving SGHE I could identify: six in Bristol sample, two in Leeds. Whilst in Bristol, most SGHE projects were new build, in Leeds I could not identify any new build SGHE schemes and included the two retrofit SGHE schemes I could find in the sample.

Table 6.1 provides a summary of subcases including the heating technology proposed and if it changed during the development process. The alphanumeric identifier reflects the primary heating technology, and this if this changed during the development process, this reflects the final / most recent technology specified. A more detailed narrative description of each subcase is provided in Appendix O.

Table 6.1 Overview of subcases by identifier, case city, heating technology and development type. Ind = individual, comm = communal, → = to change at a later date

Identifier	Case city	Heat source (initial)	Heat delivery (initial)	Heat source (final)	Heat delivery (final)	New build / retrofit
SGHE1	Bristol	Gas	Ind. + comm. boiler	Electricity + ground	SGHE	New build
SGHE2	Bristol	Electricity + air	ASHP + panel heaters	Electricity + ground	SGHE	New build
SGHE3	Bristol	Electricity + biomass	SGHE + comm. boiler	No change	No change	Retrofit
SGHE4	Bristol	Gas + biomass	Comm. CHP + boiler	Electricity + ground	SGHE	New build
SGHE5	Bristol	Electricity + air	ASHP	Electricity + ground	SGHE	New build
SGHE6	Bristol	Electricity + ground	SGHE	N/A planning refused	N/A	New build
SGHE7	Leeds	Electricity + ground	SGHE	No change	No change	Retrofit
SGHE8	Leeds	Electricity + ground + solar	SGHE + solar thermal	No change	No change	Retrofit
CITYDH1	Bristol	Gas	Comm. → city DH	No change	No change	New build
CITYDH2	Leeds	Gas → EfW	Comm. CHP → city DH	No change	No change	New build
ASHP COMM1	Bristol	Electricity + air	Comm + ind. ASHPs	No change	No change	New build
ASHPIND1	Bristol	Gas	Ind. boilers	Electricity + air	Ind. ASHPs	New build
DIRELEC1	Bristol	Electricity	Panel heaters	Electricity + air	Panel heaters + ASHPs	New build
DIRELEC2	Bristol	Electricity + air	Panel heaters + ASHPs	N/A planning refused	N/A	New build
DIRELEC3	Leeds	Gas	Comm. CHP	Electricity	Panel heaters	New build

Identifier	Case city	Heat source (initial)	Heat delivery (initial)	Heat source (final)	Heat delivery (final)	New build / retrofit
DIRELEC4	Leeds	Electricity	Panel heaters	No change	No change	New build
DIRELEC5	Leeds	Gas + electricity	Comm. CHP + panel heaters	No change	No change	New build
DIRELEC6	Leeds	Electricity + waste water	Heat recovery system	Electricity	Panel heaters	New build
DIRELEC7	Leeds	Electricity + gas	Panel heaters + ind. boilers	No change	No change	New build
DIRELEC8	Leeds	Unknown	Unknown	Electricity + air	Panel heaters + ASHP	New build
GASCOMM1	Bristol	Gas + biomass	CHP + comm. boilers	Awaiting submission	N/A	New build
GASCOMM2	Bristol	Gas	Ind. boilers	Gas	Gas comm. → city DH	Both
GASCOMM3	Bristol	Gas	Ind. + comm. boilers	No change	No change	New build
GASCOMM4	Leeds	Gas	Comm. CHP	No change	No change	New build
INDGAS1	Bristol	Gas	Ind. boilers	No change	No change	Both
INDGAS1	Leeds	Gas	Ind. boilers	No change	No change	New build
PASSIVE1	Leeds	Passive heat + electricity	MVHR + panel heaters	No change	No change	New build
PASSIVE2	Leeds	Passive heat + electricity	MVHR + panel heaters	No change	No change	New build
PASSIVE3	Leeds	Passive heat + gas	MVHR + ind. boilers	No change	No change	New build
UNKNOWN1	Leeds	Unknown	Unknown	No change	No change	New build

Aside from the six SGHE schemes in Bristol, several specified air source heat pumps (ASHPs). There were no ASHP schemes in Leeds. Both cities featured one subcase which was subject to a firm commitment to connect to a large external district heat network at a later date. There were also a range of subcases with site-wide communal networks served by either gas CHPs or communal gas boilers. The choice of direct electric panel heaters was a prominent feature of the Leeds sample, with six subcases of this type, compared to two in Bristol, reflecting the observed trend of technology proposals. Leeds also featured three Passivhaus-style schemes, where the level of fabric efficiency and design measures were such that only top-up or secondary heating was required. There were no equivalent schemes in Bristol. I included these to explore why such schemes were prominent in Leeds whilst SGHE was not.

In other non-technological characteristics, I identified two Bristol subcases as regeneration projects, where the new developments were being constructed in areas of existing housing subject to deprivation. This signified lower land values and provision of additional community facilities as part of the development, including medical centres, local shops, community centres etc. I included these to get the perspectives of developers facing challenges associated with regeneration projects. It was not clear how many schemes in Leeds fell into this category but as noted in section 6.2, land values are generally lower in Leeds so any issues are expected to be more pronounced.

Several different organisational models were included in the sample. In Bristol, eight developments were led solely by private housing developers, with the other seven subcases being undertaken by organisations with an explicit social purpose. These included three via partnership arrangements between the local authority and private developers, three by community organisations, and one by a Registered Provider social landlord. In Leeds ten of the schemes were undertaken by a private developer, although two of these used a model whereby collective ownership passes to the residents upon completion. Five schemes were constructed by organisations with an explicit social purpose, including SGHE7 by the local authority on its own social housing blocks and community-led PASSIVE3 involving elements of self-build.

6.5 Presentation of results

Here I present the results from the analysis of project, documentary and interview evidence. For each primary category, I first present results specific to each case in turn before comparing the two cases and discussing outcomes.

6.5.1 Design of planning policy

In the first stage of the analysis, for each case city I analysed the suite of planning policies that appeared to affect the choices applicants made about the heating system that they would install for each subcase. Then I explored whether and how in each subcase applicants attempted to meet or not meet the local policies.

6.5.1.1 Bristol

Three planning policies in Bristol appeared to be most relevant to how developers designed their residential schemes to account for climate change including the heating technology choice. They were introduced in 2011 and described as a *“suite of climate change policies which at the time were quite cutting edge but they’re getting a bit old now and some of the evidence has moved on” [PLANNING-1]*. The planning officer interviewee reported that an unrelated strategic issue has delayed the process of updating the policies to 2023.

Table 6.2 shows a summary of the policies with policy BCS14 separated into two sections to reflect its dual parallel elements.

Table 6.2 Bristol case overview of relevant planning policies, assessment of impact, and compliance. High policy compliance = green highlight; low policy compliance = red highlight

Key aspect of policy	BCS13	BCS14 (energy hierarchy)	BCS14 (heat hierarchy)	BCS15
Main focus of policy	Climate mitigation and adaptation	Energy and carbon reduction	Heating technology	Sustainable design and construction
Main impact	Requires submission of sustainability statements	Requires energy efficiency measures and 20% carbon reduction	Prescribes heating technology, excludes individual gas boilers and direct electric heaters.	Intended to prepare developers for (now defunct) Code for Sustainable Homes

Key aspect of policy	BCS13	BCS14 (energy hierarchy)	BCS14 (heat hierarchy)	BCS15
Impact on heating technology	No direct impact but requirement to provide sustainability statements enabled BCS14 assessment.	Little – could be satisfied with gas boilers or direct electric heat if combined with solar PV.	Significant – exclusion of conventional technologies led developers to choose options including SGHE	None
Compliance in sample (by applicable subcases)[4]	Complete (14/14)	Complete (14/14)	Almost complete (13/14)	Low (4/14)

The BCS13 policy requires applicants to *"demonstrate through Sustainability Statements" [LA1-4]* how they will mitigate and adapt to climate change. Applicants met this requirement in all fourteen applicable subcases, and this enabled a deeper analysis of how policies were enacted and the impact they had. In each subcase, energy consultancy companies on behalf of the developer client produced all sustainability statement documents. It was possible to see version history of the documents prior to submission in some cases. In one subcase, the document had evolved through seventeen versions between March 2017 and September 2018. However, BCS13 had little direct effect on the type of heating systems proposed.

The effect of BCS14 on the decisions of developers and their energy consultants was much more pronounced, and the evidence clearly suggests this policy has shaped the direction of heat decarbonisation in Bristol, including supporting deployment of SGHE. The policy is comprised of two parallel parts. Firstly, the energy hierarchy included a requirement for developers to demonstrate how they will reduce the carbon emissions of their development by at least 20% compared to a standard model of the development as set out in Building Regulations 2013 [LA1-14]. This requirement created an inherent link between the local and national institutional framework that the authority and developers operate in. The second part of the policy is a technology-specific heat hierarchy which sets out a list of heating options and specifically does not include individual gas boilers and direct electric heating.

[4] One subcase progressed through planning process prior to current policy enactment

The energy hierarchy required developers to demonstrate how they would meet a set of three criteria:

> *"Developments must reduce carbon emissions according to an energy hierarchy*
>
> *- 1. Minimising energy requirements;*
>
> *2. Incorporating renewable energy sources (sufficient to reduce residual in-use carbon emissions by at least 20%);*
>
> *3. Incorporating low-carbon energy sources." [LA1-4]*

To investigate the impact of the energy hierarchy I first analysed each subcase to ascertain what measurable carbon reduction commitments were made against levels 1, 2 and 3 of the policy at initial and (if applicable) revised submissions of planning documents. The results of this are displayed in Table 6.3, which shows carbon reduction against the three levels of the energy hierarchy.

Table 6.3. Carbon reduction commitments by subcase. Ordered by level of total commitment (final submission). N/P = Not Provided; N/R = Not required; requirements fully met = green highlight; requirements partially met = orange highlight

	Initial submission				Final submission			
Hierarchy level	**Level 1**	**Level 2**	**Level 3**	**Total**	**Level 1**	**Level 2**	**Level 3**	**Total**
SGHE5	-12%	-48%	N/R	-54%	-7%	-25%	-75%	-83%
ASHPIND1	-7%	-21%	N/R	-26%	+37%	-76%	N/R	-67%
CITYDH1	-42%	-20%	N/R	-64%	-42%	-20%	N/R	-64%
GASCOMM2	-34%	-20%	0%	-47%	-34%	-20%	0%	-47%
GASCOMM1	-22%	-20%	N/P	-35%	-28%	-20%	N/R	-42%
SGHE2	-20%	-20%	N/R	-36%	-20%	-20%	N/R	-36%
SGHE6	-7%	-28%	N/R	-36%	-7%	-28%	N/R	-36%
ASHPCOMM1	-11%	-24%	N/R	-32%	-10%	-26%	N/R	-33%
SGHE1	-2%	-23%	N/R	-24%	-7%	-21%	N/R	-28%
SGHE4	0%	-22%	N/R	-22%	-3%	-22%	N/R	-24%
GASCOMM3	0%	-23%	N/R	-23%	0%	-23%	N/R	-23%
INDGAS1	-2%	-20%	N/R	-22%	-2%	-20%	N/R	-22%
DIRELEC1	+19%	-32%	N/R	-20%	+39%	-42%	N/R	-20%
DIRELEC2	-5% to -9%	-20%	N/R	N/R	-5 to -9%	-20%	N/R	N/R
SGHE3	N/R	N/R	N/R	N/R	N/R	N/R	N/R	N/R

The lack of a specific minimum requirement against some of the levels of the hierarchy limited the impact of the policy. For example, as can be seen in Table 6.3, commitments against level 1 of the energy hierarchy ranged from zero % to over 30%. In the DIRELEC1 and ASHPIND1 instances, applicants predicted an increase in carbon emissions against level 1, although the total carbon reduction after measures in the levels 2 and 3 satisfied the overall 20% reduction requirement. The applicant in the DIRELEC1 subcase explained that this quirk was caused by out-of-date carbon factors for grid electricity, which they were required to use by Part L of the Building Regulations 2013. This caused their choice of direct electric panel heaters to appear to increase carbon emissions, but that with an up-to-date carbon factor, the same heating system choice would lead to a significant saving in carbon emissions. This suggests coevolutionary dynamics between *institutions - technologies* where a national regulatory/institutional issue was having an impact on how different technologies appeared able to satisfy local institutional policy requirements. The lack of measurable target also affected the level 3 requirement to incorporate low carbon energy sources, with applicants in one subcase explaining how they would comply. No challenge was made during the planning process implying that planning officers were satisfied the carbon target in level 3 had been fulfilled at other levels.

The impact of level 2 of the energy hierarchy was clearer, with all subcases demonstrating what measures they proposed to reduce carbon emissions by at least 20%. This link demonstrated a clear connection between the national and local regimes, with the 20% carbon reduction set by national government as the maximum that local planning authorities could demand. Whilst the level 2 policy was effective at requiring carbon reduction measures, it did not necessarily affect the type of heating technology chosen. I analysed this further to assess whether the carbon reduction modelled under hierarchy level 2 was through heating technology or by other measures. Table 6.4 shows the results, with the type of heating technology against whether this delivered level 2 carbon savings or not.

Table 6.4 Heating technology measures assessed by contribution to carbon reduction savings. Ordered by whether heating delivery technology did or did not contribute. Savings through heating = green highlight; other technology = orange highlight

Subcase identifier	Heating delivery technology chosen (final submission)	20% carbon reduction attributed to	Carbon reduction %
SGHE6	SGHE	Heating (SGHE)	-28%
ASHPCOMM1	ASHP with communal heat network	Heating (ASHP element of chosen system)	-26%
SGHE5	SGHE	Heating (SGHE)	-25%
SGHE4	SGHE	Heating (SGHE)	-22%
SGHE1	SGHE	Heating (SGHE)	-21%

Subcase identifier	Heating delivery technology chosen (final submission)	20% carbon reduction attributed to	Carbon reduction %
GASCOMM1	Communal heat network with gas CHP and biomass boiler	Heating system (biomass element of heating system)	-20%
ASHPIND1	Direct electric panel heaters, ASHPs	Non-heating (solar PV)	-76%
DIRELEC1	Direct electric panel heaters plus hot water heat pumps	Non-heating (solar PV)	-42%
GASCOMM3	Communal heat network with central gas boiler for apartments	Non-heating (solar PV)	-23%
SGHE2	SGHE + ASHPs	Non-heating (solar PV). Non-final version	-20%
CITYDH1	Site-wide network, future connection to city DH scheme	Non-heating (solar PV)	-20%
GASCOMM2	Communal heat network, central gas boiler, future connection to city DH	Non-heating (solar PV)	-20%
DIRELEC2	Direct electric panel heaters with 25x ASHPs	Non-heating (solar PV)	-20%
INDGAS1	Individual gas boilers	Non-heating (solar PV)	-20%
SGHE3	SGHE	N/A prior to policy	N/A

Table 6.4 shows that six schemes satisfied the local 20% carbon reduction policy through the type of heating technology, with four of these being SGHE. In eight other subcases however, the carbon reduction requirements were satisfied through non-heating measures such as the addition of solar PV panels. This suggests this *institutions - business strategies - technologies* dynamic on its own did not cause applicants to choose SGHE or other heating technologies. Some schemes such as ASHPIND1 proposed a much greater carbon reduction than the minimum 20%, so the data in Table 6.4 also suggests that it is technically and economically possible to do so. This suggests that developer organisations, in collaboration with their energy consultants, are making an active decision to propose less ambitious reductions, regardless of what type of heating system they use. Although it is not clear whether the barriers from the developers' side is technical or economic, this quote within a planning submission illustrates attitudes towards going further than the policy requires them to:

> *"Passing […] 2013 Part L is already demanding […] we would not expect there to be significant additional savings that could be made"* [GASCOMM1-6].

The perspective of one of the interviewees representing an energy consultancy which prepares energy strategy submissions for private housing developers emphasised how their clients approached the idea of doing more than the minimum:

> *"I think most developers just want to tick the box for planning so if the planning condition says 20%, their question to us is, "How do we get to 20.01%", that's the mindset of most builders."* [CON-1]

The relationship between the energy consultants and developers is explored further in 6.5.4, however this supports the key role of the local institutional environment in setting higher minimum standards.

The second half of the policy, the heat hierarchy element, had a more significant impact in terms of guiding applicants to choose certain low carbon heating options including SGHE. This was primarily because it set out a list of technical options that included SGHE but did not include conventional technologies such as individual gas boilers and direct electric panel heaters. The heat hierarchy requires that developers select one of six technical options for the dwelling heating provision:

> *"Developments should demonstrate that heating and cooling systems have been selected according to a heat hierarchy:*
>
> > *1. Connection to existing CHP/CCHP distribution networks*
> > *2. Site-wide renewable CHP/CCHP*
> > *3. Site-wide gas-fired CHP/CCHP*
> > *4. Site-wide renewable community heating/cooling*
> > *5. Site-wide gas-fired community heating/cooling*
> > *6. Individual building renewable heating" [LA1-4]*

It was emphasised in other planning policy documents that the options did not include direct electric panel heaters and individual gas boilers [LA1-2]. The planning officer interviewee outlined that direct electric was not a viable option because it was relatively inefficient, would case a strain on the grid, and would rule out later connection to district heat networks [PLANNING-1]. To assess what impact the policy was having on SGHE deployment, Table 6.5 presents an analysis of heating technology choice against the heat hierarchy policy, including whether the proposal met the heat hierarchy at initial and revised stages, and an assessment of the heat hierarchy level that the solution would achieve.

Table 6.5 Analysis of heat hierarchy compliance at initial and revised stages. Ordered by heat hierarchy position. Fully complaint = green highlight, partially complaint = orange highlight, not compliant = red highlight, planning permission refused = greyed out

Subcase identifier	Initial heating delivery technology	Heat hierarchy (# no.)	Final heating delivery technology	Heat hierarchy (# no.)
CITYDH1	Site-wide network, future connection to city DH scheme	Yes (1)	Site-wide network, future connection to city DH scheme	Yes (1)
GASCOMM1	Communal heat network with gas CHP and biomass boiler	Yes (2/3)	Communal heat network with gas CHP and biomass boiler	Yes (2/3)
SGHE3	SGHE	Yes (4) (prior to policy)	SGHE	Yes (4) (prior to policy)
ASHPCOMM1	ASHP with communal heat network	Yes (4)	ASHP with communal heat network	Yes (4)
GASCOMM2	Individual gas boilers	No	Communal heat network, central gas boiler, future connection to city DH	Yes (5 / 1)
GASCOMM3	Individual gas boilers	No	Communal heat network with central gas boiler	Yes (5)
SGHE4	Communal heat with gas and biomass CHP	Yes (2/3)	SGHE	Yes (4)
SGHE5	Site-wide communal network from ASHP	Yes (4)	SGHE	Yes (4)
SGHE6	SGHE	Yes (4)	Not applicable, planning permission refused	N/A
SGHE1	Individual gas boilers	No	SGHE	Yes (4)
SGHE2	Direct electric panel heaters	No	SGHE + ASHPs	Yes (4 / 6)
ASHPIND1	Individual gas boilers	No	ASHPs, direct electric panel heaters	Yes (6 / NA)
DIRELEC1	Direct electric panel heaters	No	Direct electric panel heaters plus hot water heat pumps	No (N/A / 6)
DIRELEC2	Direct electric panel heaters + ASHPs	No (N/A / 6)	Not applicable, planning permission refused	N/A
INDGAS1	Individual gas boilers	No	Approved at initial submission	No

Table 6.5 shows how the heat hierarchy requirement affected the type of heating system and suggests that the policy led applicants to choose low carbon heating options including SGHE. At initial submission stage, seven subcases met the heat hierarchy with the proposed solution, of which two were SGHE. Eight subcases had

selected individual gas boilers or direct electric panel heaters at initial submission, which did not meet the heat hierarchy. By the time of the final submission however, two of these had been changed to SGHE, two to communal heat networks, and one to include ASHPs. One subcase, DIRELEC2, proposed direct electric panel heaters and had planning permission refused based on failure to meet the heat hierarchy. It was also notable that in some subcases such as SGHE4 and SGHE5, the applicant changed from an already heat hierarchy-compliant solution to SGHE. Some of the impacts are due to officer intervention, and this is explored further in section 6.5.2. However, in terms of the policy design, the evidence suggests the technical options policy which ruled out conventional fossil-based heating was impacting the innovation-decisions of developers and supporting the heat transition towards SGHE. Instances like this emphasised the importance of the *actor decision-making* node of the combined framework through which I attempted to capture factors around how actors within developers made innovation-decisions in light of the local institutional environment. The impact of this technical options policy was not universal however, with one subcase, INDGAS1, granted planning permission with non-compliant individual gas boilers.

I found no evidence that in their review of applications, planning authority officers treated the heat hierarchy as a priority list of options in which applicants must aim for the highest possible number. Indeed, the evidence suggested support for lower-ranked approaches, and this benefited the deployment of SGHE which the following quote suggests was considered by officers to be at hierarchy level 4:

> "*Following discussion with Bristol City Council Sustainability officers, it has been established that micro-district approaches to the provision of heat meets the definition of* [level 4] *site-wide renewable heating within the heat hierarchy and are therefore supported by policy BCS14" [SGHE4-5]*.

It was not clear from the evidence available whether this was an institutional decision or whether it was left to officer discretion to take a position on particular technologies. Additionally, whilst the planning policy document outlines that applicants must select the *"lowest carbon solution feasible for the development" [LA1-4]*, this aspect was not actively implemented by officers. Most applications in the sample did not assess carbon impacts of the different options, and because this was not a barrier to planning approval, suggesting this policy requirement was not enforced. Both of these circumstances supported SGHE deployment and suggest that individual actors may be able to use institutional levers within their power to shape the local regime.

Another issue which the data suggested was an important factor in applicants choosing SGHE over other options were doubts about the reality of external district heat networks actually being constructed. Through interviews and documents the evidence suggests that issues of risk and costs of future-proofing for this approach, combined with negative past experiences of district heating, was leading applicants to favour other options. This was typified by quotes such as:

> *"…we don't think it [district heating] is ever going to come to that area […] it doesn't really make sense to allow for a connection that's never going to happen"* [CON-2]

I found five subcases in the Bristol sample where these reservations and doubts affected the chosen approach. These issues led applicants to pursue alternative solutions including SGHE and in some subcases direct electric panel heaters (although the latter was challenged through enforcement activities). This suggests coevolutionary dynamics in play where scepticism about local authority (*institutional*) commitment to district heating (*technology*), combined with bad experiences (*user practices*) was leading to developers choosing to implement other approaches in their scheme (*business strategies, actors decision-making*), both of conventional or niche-innovation types.

Overall, the evidence presented here suggests that the design and implementation of the heat hierarchy made SGHE selection more likely for two reasons:

1. Because it ruled out the installation of gas boilers or direct electric panel heaters and so promoting alternative solutions such as SGHE.

2. Because SGHE was defined as an eligible technology, and the policy as implemented did not require applicants to choose the highest ranked option.

The impact of these two aspects of the local institutional environment were supported by the high levels of compliance in the Bristol sample, and this is explored further in 6.5.2. Finally, the other climate-related policy, BCS15, appeared to have little impact on heating technology choice. I found no examples of this policy being applied to challenge an application apart from ensuring the provision of high-speed broadband and implementing measures to limit water consumption.

6.5.1.2 Leeds

Most relevant to the type of heating system were policies EN1, EN2 and EN4 of the Core Strategy, which came into force in 2014 [LA2-12]. The planning authority updated some Core Strategy policies in 2019 but this did not include climate change policies, and a major update to climate change aspects of planning policy is underway at the time of writing [PLANNING-2, LA2-15]. Prior to the 2014 implementation, a voluntary standard was in place since 2011 which encouraged developments of 10 dwellings or more to meet a 20% carbon reduction and 10% onsite energy generation which would later become formal Policy EN1 [LA2-34]. Table 6.6 presents a summary of the policies and assessment of their impact, with the two aspects of policy EN1 dealt with separately.

Table 6.6 Leeds case overview of relevant planning policies, assessment of impact, and compliance. Partial policy compliance = orange highlight; low policy compliance = red highlight

Key aspect of policy	EN1(i)	EN1 (ii)	EN2	EN4
Main focus	Energy and carbon reduction	Renewable energy generation	Sustainable design and construction	Heating technology
Main impact	Requires energy efficiency measures and 20% carbon reduction over Building regulations Part L 2013	Requires 10% of energy needs to be generated through low carbon energy	Reduce water consumption and prepare for (now defunct) Code for Sustainable Homes	Prescribes heating technology, excludes individual gas boilers and direct electric panel heaters.
Impact on heating technology	Some, although could be satisfied with gas boilers or direct electric heat if combined with solar PV.	Little evidence of impact	None	Potentially significant – but not enforced
Compliance in sample (by	Partial (8/12)	Partial (6/12)	Partial (5/12)	Low (2/12)

Key aspect of policy	EN1(i)	EN1 (ii)	EN2	EN4
applicable subcases)[5]				

Policy EN1 was described as "*the main policy" [PLANNING-2]* intended to bring about carbon reduction in new developments through the planning system. The policy is in two parts (i) and (ii), and states that:

> *"All developments of 10 dwellings or more, or over 1,000 square metres of floorspace, (including conversion) where feasible, will be required to:*
>
> *(i) Provide a 20% reduction in CO2 emissions over Part L Building Regulations requirements (2013) until such time as the energy performance requirement in Building Regulations is set at a level equivalent to that in Code Level 4 of the Sustainable Homes.*
> *(ii) Provide a minimum of 10% of the predicted energy needs of the development from low carbon energy." [LA2-10]*

To assess what impact this appeared to be having, Table 6.7 shows the analysis of commitments against the two elements of the policy.

Table 6.7 Carbon reduction commitments by subcase. Ordered by level of EN(1) commitment (final submission). N/P = Not Provided; N/R = Not required; requirements fully met = green highlight; requirements partially met = orange highlight, requirements not met = red highlight

	Initial submission		Revised / final submission	
Hierarchy level	**EN1 (i)**	**EN1 (ii)**	**EN1 (i)**	**EN1 (ii)**
PASSIVE1	N/P	N/P	-58%	N/P
PASSIVE2	N/P	N/P	-43%	11%
CITYDH2	-48% / -33%	N/P	-48% / -33%	N/P
DIRELEC4	-12%	5%	-22%	11%
DIRELEC5	-35%	N/P	-21%	14%
DIRELEC6	N/P	N/P	-21%	15%
INDGAS2	-20%	12%	-20%	14%
DIRELEC8	N/P	N/P	-20%	N/P
UNKNOWN1	-20%	10%	-20%	10%
DIRELEC3	-20%	20%	N/P	N/P
DIRELEC7	N/R	N/R	-14% (SAP10.1=-72%)	17%
GASCOMM4	N/P	N/P	N/P	N/P

[5] The policies applied to twelve subcases because two completed the planning process prior to EN1-4 or the voluntary standard coming into force and one was a retrofit project that did not require a planning application.

	Initial submission		Revised / final submission	
Hierarchy level	**EN1 (i)**	**EN1 (ii)**	**EN1 (i)**	**EN1 (ii)**
PASSIVE3	-35% (N/R)	N/R	-35% (N/R)	N/R
SGHE8	N/R	N/R	N/R	N/R
SGHE7	-77% (N/R)	N/R	-77% (N/R)	N/R

Overall Table 6.7 shows incomplete EN1 compliance in the sample, although there was a clear improvement between initial and revised submission stage. Eight applicable schemes demonstrated EN1(i) compliance at revised or final stage, with four schemes going substantially further than the 20% carbon reduction over a standard model of the development using Building Regulations Part L 2013 required by the planning policy. Six applicable schemes demonstrated EN(ii) compliance at final stage. Of the four schemes which did not demonstrate compliance with EN1(i) and six with EN1(ii), all achieved planning permission, suggesting the policy was not enforced rigorously, and this is discussed further in 6.5.2. Taking the issue of compliance aside, to explore in more detail whether the EN1 policy as intended was leading developers to choose SGHE and other low carbon options in favour of conventional technologies, I conducted a closer inspection of final stage planning application submissions. Table 6.8 shows this analysis, including where it was possible to identify carbon savings from fabric efficiency measures separately to the addition of technology.

Table 6.8 Heating delivery technology measures assessed by contribution to meeting EN(i) and EN(ii) policy requirements. Ordered by whether heating technology did or did not contribute. Savings through heating = green highlight; other technology = orange highlight, information not available = red highlight, policy not applicable = no highlight.

Subcase identifier	EN1(i) Design & fabric measures	EN1(i) Savings from technology	-%	EN1(ii) Onsite generation	+%
CITYDH2	Design & fabric measures (-14%)	Heating technology	-48%	Heating approach	?%
DIRELEC3	Design & fabric measures	Heating technology *(not installed)*	-20%	Heating technology	20%
DIRELEC7	None specified	Heating technology (-14% SAP2012 / -72% SAP10.1)	-14%	Comm. ASHP	17%
GASCOMM4	Unknown	Heating technology	?%	CHP, solar PV	?%
PASSIVE1	Passive design & fabric efficiency	Heating technology	-58%	Solar PV	?%
PASSIVE2	Passive design & fabric efficiency	Heating technology	-43%	Solar PV	?%
DIRELEC4	Fabric efficiency measures	Solar PV	-22%	Solar PV	11%

Subcase identifier	EN1(i) Design & fabric measures	EN1(i) Savings from technology	-%	EN1(ii) Onsite generation	+%
DIRELEC5	Design & fabric measures (-9%)	Solar PV (-14%)	-21%	Solar PV	14%
DIRELEC6	Design & fabric measures	Solar PV	-21%	Solar PV	15%
INDGAS2	Fabric efficiency measures (-5%)	Solar PV (-16%)	-20%	Solar PV	14%
DIRELEC8	Design & fabric measures	Solar PV (-20%)	-20%	Unknown	?%
UNKNOWN1	Unknown	Unknown	?%	Unknown	?%
SGHE7	No fabric efficiency measures	Heating technology. (-77%)	-77%	N/R	N/R
PASSIVE3	Passive design & fabric efficiency	Heating technology and solar PV	-35%	Solar PV, Solar thermal	?%
SGHE8	Insulation triple glazing	SGHE, solar thermal, wind turbines	N/R	N/R	N/R

Table 6.8 shows that in four of the twelve applicable subcases, heating delivery technology contributed to meeting both EN(i) carbon reduction targets and EN(ii) onsite low carbon generation. Two further subcases where the heating combination of passive design with MVHR heating contributed to the carbon reduction savings, but solar PV was used to deliver onsite generation. Following this were five subcases where heating technology was not used to meet either policy, suggesting they did not necessarily lead developers to choose certain heating technologies. In all five subcases, the addition of solar PV was proposed to meet the local policy requirement, and planning approval was granted. This suggests existence of an *institutions - business strategies - technologies* dynamic but this was not exerting pressure on *actor-decision making* towards SGHE or other heating technologies. This was emphasised in seven of the twelve applicable subcases where the 20% carbon reduction was to be satisfied through solar PV whilst proposing individual gas boilers or direct electric panel heaters. Finally, despite the policy stating, "*We would expect developers to take a 'fabric first' approach" [LA2-4]*, the evidence suggests the lack of a measurable target for carbon savings from fabric efficiency measures was affecting the approach taken by developers. Six subcases described fabric efficiency measures in narrative form but with no carbon reduction figure, and three subcases did not include any reference to fabric efficiency and were granted planning permission.

As noted in Table 6.6, policy EN2 was not particularly relevant to heating technology. I analysed compliance against the policy and found that five of the twelve applicable subcases outlined how they would address it. Policy EN4 was however directly related to heating technology. It appeared to be designed to prioritise connection of developments to existing district heat networks, and if that was not possible, to be, "*future-proofed so it's ready to connect to a heat network or to create a new heat network" [LA2-8]*. The policy applied to all developments over 1,000 sqm or 10 dwellings (applicable to all subcases), and set out a list of four hierarchy options:

> *"(i) Connection to existing District heating networks,*
>
> *(ii) Construction of a site wide District heating network served by a new low carbon heat source,*
>
> *(iii) Collaboration with neighbouring development sites or existing heat loads/sources to develop a viable shared District heating network,*
>
> *(iv) In areas where District heating is currently not viable, but there is potential for future District heating networks, all development proposals will need to demonstrate how sites have been designed to allow for connection to a future District heating network." [LA2-4]*

The policy gave three heating technology options that developers are able to choose from, based around site-wide heating, and one requiring the ability to connect in the future, which in effect means site-wide communal heating must be installed. The policy does not specify how heat must be generated, but the need to choose district or communal approaches means that individual heating technologies such as direct electric panel heaters or gas boilers are not available options. This suggests that the intuitional framework is in place in the city to support the deployment of niche-innovation heating technologies, potentially including SGHE. To assess what impact the policy was having on the choice of heating approach, I explored in each subcase whether the applicant referred to policy EN4 and whether the proposed heating technology solution was one of the four options. Table 6.9 sets out the results of the analysis.

Table 6.9 Leeds subcase reference and compliance with policy EN4. If proposed heating was compliant, position in hierarchy shown. Compliant = green highlight; partial compliance or justification for noncompliance = orange highlight, noncompliant = red highlight, policy not applicable = no highlight

Subcase identifier	Reference to EN4	Compliance with EN4	Narrative	Hierarchy position
GASCOMM4	Yes	Yes	Site-wide heat network chosen	(ii)
CITYDH2	Yes	Yes	Connection to main city network	(i)
DIRELEC7	Yes	Partial	Mixture of approaches with direct electric panel heaters for apartments, gas boilers for houses, a limited network for hot water from communal ASHP	N/A / (ii) blocks E/F
PASSIVE2	Yes	No	Reasons given as low heat demand leading to poor economics, location	N/A
DIRELEC5	Yes	No	Reasons given as dist. losses, overheating, grid carbon reductions	N/A
PASSIVE1	No	No	No reference or compliance	N/A
DIRELEC6	No	No	No reference or compliance	N/A
UNKNOWN1	No	No	No reference or compliance	N/A
DIRELEC8	No	No	No reference or compliance	N/A
DIRELEC3	No	No	No reference or compliance	N/A
DIRELEC4	No	No	No reference or compliance	N/A
INDGAS2	No	No	No reference or compliance	N/A
SGHE8	N/A	N/A	Prior to policy enactment	(ii)
PASSIVE3	N/A	N/A	Prior to policy enactment	N/A
SGHE7	N/A	N/A	Planning permission not required	N/A

Of the twelve applicable subcases, the table shows that two fully met the policy requirement and one partially. Three further subcases provided justification for noncompliance including the distribution losses associated with district heating and the reducing carbon content of the electricity grid making direct electric heating favourable. This suggests coevolutionary dynamics between *technologies*, *business strategies*, *institutions*, *user practices* and *actor decision-making* where previous poor experiences with district heating, combined with national policies to decarbonise grid electricity, were leading developers to choose to challenge the local institutional framework rather than make the decision to adopt the district heating niche-innovation.

Beyond this, seven subcases did not refer to the policy or justify not meeting it in their submissions. Because of the low levels of policy compliance and enforcement, it was not clear that the policy was having any particular impact. Whether SGHE was a potential option in the hierarchy was unclear as it was not tested by applications in the sample. Neither of the SGHE schemes in Leeds progressed through the planning system under the current institutional framework, so no evidence was available to assess how officers viewed the technology in satisfaction of the policy requirements. Analysis of the two SGHE schemes suggests that SGHE8 would be eligible as it featured SGHE comprising boreholes as part of a site-wide network. SGHE7 however employed a micro-network configuration with a handful of dwellings connected to each borehole, and so may not be compliant.

Overall, the situation in the Leeds case suggests an institutional framework in place which may support deployment of SGHE and other low carbon niche-innovations, but little evidence that this is causing developers to make the innovation-decision necessary to see SGHE deployment. The role of institutional actors in supporting developers and enforcing policies is explored further in section 6.5.2.

6.5.1.3 Cross-case comparison and discussion

Overall, it appears that both cities feature a broadly similar institutional environment which affects the innovation-decisions made by developers of residential schemes. However, there are key differences which together add up to significantly divergent local regimes shaping the prospects for SGHE deployment.

The evidence that both planning authorities operate within a common framework was clear in several ways. Firstly, that when seeking carbon emissions reductions from developers, both planning authorities were required to do so against the same national building standards, which are out of date in regard to the carbon content of grid electricity. Secondly, both cities require a 20% carbon reduction against those standards which is the maximum allowed outside of London under the current National Planning Policy Guidance [GOV1-3]. This shared national-local regime dynamic is a key factor in defining and curtailing the ability for the two local authorities to seek more transformative climate policies and support low carbon niche-innovations. This was illustrated by policies in both cities continuing to refer to an expected 2016 national government policy which would have required zero carbon residential development, but which was abandoned through a written ministerial statement in March 2015 [GOV-3]. Referring to the impact on home builders, the wording of the statement and later analysis suggests the power of private housebuilder incumbents to resist regime change (Greenwood et al., 2017; O'Neill and Gibbs, 2020). This backs up other work which emphasised the importance of considering power and politics, and the effects of capitalism permeating throughout sociotechnical systems (Feola, 2020; Lowes et al., 2020, 15 May 20148; Swilling et al., 2016; Unruh, 2000).

Despite the commonalities and the common governance framework both cities operate in, the findings indicate that the local authorities clearly did have some power to shape the local regime for domestic heating. Table 6.10 shows a comparison of the policies in the two case cities.

Table 6.10 Comparison of case city policies in carbon reduction and heating technology

Bristol	**Policy detail**	**Leeds**
20% reduction in residual operational emissions over Part L, after energy efficiency measures	***Carbon reduction target***	20% reduction in operational emissions over Part L
All developments	***Applicable to***	Residential developments over 10 dwellings
Building regulations Part L 2013	***Current baseline for carbon reduction***	Building regulations Part L 2013
Range of technologies inc. non-heating e.g., solar PV	***Carbon reduction can be met with***	Range of technologies inc. non-heating e.g., solar PV
Yes, but no % target	***Fabric efficiency requirement***	Yes, but no % target
Yes, but no % target	***Energy generation requirement***	Yes, 10% of onsite needs
Yes, heat hierarchy within BCS14	***Heating technology policy***	Yes, heat hierarchy as separate policy EN4
Eligible at hierarchy level four, defined by officers	***SGHE eligibility***	Unclear, potentially eligible when connected to site-wide network
Level 1-5 with connection to existing network top priority	***District heating eligibility***	All levels with connection to existing network top priority
Not eligible	***Individual gas boilers eligibility***	Not eligible, but policy unenforced
Not eligible	***Direct electric panel heaters eligibility***	Not eligible, but policy unenforced

Table 6.10 shows that the relevant spatial policies in place in Leeds and Bristol share more similarities than differences. In terms of how these impacted the innovation-decisions made by developers, in both case cities the data suggested that the carbon reduction requirement did not direct developers towards SGHE or other low carbon heating options. This was primarily because the policy could be satisfied through conventional individual gas boilers or direct electric panel heaters, provided these were combined with other measures such as solar PV and/or fabric efficiency measures. It was notable that in both cities some developers proposed carbon reductions far more than the 20% requirement demonstrating that such an approach was technically and economically viable. This further suggested that the minimum standards approach taken was an active choice by private developers without policy to compel them to do otherwise. This was backed up by energy consultants with experience of working for multiple private developers.

More important for the deployment of SGHE, especially in the Bristol case, was the heat technology eligibility policies which made certain conventional heating options including individual gas boilers and direct electric panel heaters ineligible. In the Bristol case, the heat hierarchy had a clear impact on the heating technology chosen by developers with all but one adopting hierarchy-compliant systems, and six of those opting to use SGHE. Achieving compliant systems did involve significant intervention and enforcement by officers from the Bristol planning authority and this is explored further in section 6.5.2. In Leeds, EN4 also ruled out gas boilers and direct electric panel heaters but the impact was far less evident because of low compliance. In Bristol the planning authority made it clear that direct electric heating was not a compliant option and gave a justification for this position. In Leeds it was made less explicit that developers should not adopt direct electric heating, and this may have contributed to the lower levels of compliance along with lower enforcement activity.

In both cities, the intention to compel developers to connect to city district heat networks was evident through policy design, and this had the potential to rule out SGHE in certain formulations. In Bristol, whilst the micro-network SGHE systems proposed in five of the six subcases did not permit later connection to an external district heat network and so were outside of levels 1-5 of the hierarchy, evidence showed officers considered SGHE as level 4 and that they supported its consideration. Additionally, there was no evidence of hierarchy ranking by planning officers and this enabled SGHE to be considered alongside other options ranked higher in the hierarchy. In the Leeds case, all four options in the heat hierarchy policy involved connection to a district heat network or being connection-ready. This had the potential to rule out SGHE when not combined with a site-wide heat network, although the potential was not tested by any of the subcases. Overall, these findings suggest that policies intended to promote niche-innovations by excluding conventional technologies may inadvertently disadvantage certain innovations if they don't fit neatly within the terms of the policy wording. However, this can be managed through local actor discretion in implementation of institutional commitments.

Given the markedly different outcomes in terms of the numbers of SGHE schemes, the primary finding is that the Bristol case demonstrates successful SGHE deployment supported by local spatial planning policies. This backs up findings from Chapter 5. Whilst the ability of local authorities to shape the local regime for residential heat decarbonisation are clearly limited by the national regime subject to the pervasive effects of lock-in and incumbency, with careful policy design considering unintended consequences, local authorities can lay the foundations for niche-innovations to flourish. Considering the apparent institutional similarities in the two city regimes, the difference in terms of SGHE deployment between Bristol and Leeds was striking. Therefore, whilst the findings suggest that within the same legal and regulatory framework, planning authorities can design local policies that support the deployment of low carbon technologies including SGHE in their area, this is only part of the story. The next section 6.5.2 considers how the local authorities supported developers and enforced policies to deliver their objectives.

6.5.2 Support, intervention and enforcement of planning policy

Beyond the design of the policies, the data from the documentary and interview analysis emphasised the role of local support, guidance and enforcement activities to outcomes of SGHE deployment. Here I consider the different approaches taken in the two case cities, their likely impacts, and what may be the underlying causes behind these.

6.5.2.1 Bristol

In the Bristol case, I found considerable evidence of the impact of a team of officers within the planning authority, the Sustainable Cities Team, which appeared to create positive outcomes for SGHE deployment through a range of activities. These may indicate empowering intermediary action to 'stretch and transform' the incumbent regime. The representative from the authority described how the team's role is to provide *"expert advice" [LA1-7]*, but more importantly for the impact on heating system decision is that *"they are a consultee to our planning officers dealing with planning applications" [LA1-7].* To assess the impact of the Sustainable Cities Team on SGHE deployment, I analysed the planning documents and interviews to develop timelines for each subcase and trace interventions through to their likely impact. A summary of this analysis is shown in Table 6.11.

Table 6.11 Analysis of local authority intervention in subcases, ordered by level of intervention severity. Colour-coded by impact: Intervention appeared to change heating type = green highlight; intervention did not appear to change heating type = red highlight, no intervention = no highlight.

Subcase identifier	Initial heating technology	Intervention detail	Final heating
SGHE6	SGHE	Planning permission refused, partly due to applicant not explaining how 20% carbon saving would be met	N/A Planning permission refused
DIRELEC2	Direct electric panel heaters with 25x ASHPs	Significant intervention. Recommended planning refusal for failure to meet heat hierarchy	N/A, planning permission refused
GASCOMM2	Individual gas boilers	Threat to refuse permission for failure to meet heat hierarchy. Preference for city DH connection	Communal heat network, central gas boiler, future connection to city DH
GASCOMM3	Individual gas boilers	Challenge case for gas boilers employed in initial submission	Communal heat network, central gas boiler
ASHPIND1	Individual gas boilers	Confirm no gas on site, preference for ASHPs	Direct electric panel heaters, ASHPs
SGHE1	Individual gas boilers	Instruct to meet heat hierarchy, suggested communal system + ASHPs	SGHE
GASCOMM1	Communal heat network with gas CHP and biomass boiler	Emphasise the need to meet heat hierarchy, require consideration of SGHE.	Not applicable, condition discharge

Subcase identifier	Initial heating technology	Intervention detail	Final heating
			application not yet received
SGHE2	Direct electric panel heaters	Guidance and support. Recommend SGHE, offered to fund O&M costs	SGHE + ASHPs
SGHE4	Communal heat with gas and biomass CHP	Guidance and support. Recommended SGHE	SGHE
DIRELEC1	Direct electric panel heaters	Guidance and support. Recommend SGHE	Direct electric panel heaters, hot water heat pumps
CITYDH1	Site-wide network, future connection to city DH scheme	Approval of proposed strategy to connect to city DH contractual agreement for DH connection, provision of energy centre	No change
SGHE5	Site-wide communal network, ASHP	No intervention. Option changed due to 'costing exercise and identification of funding streams'	SGHE
SGHE3	SGHE	No intervention	No change
ASHPCOMM1	ASHP with communal heat network	No intervention, approved at initial submission	No change
INDGAS1	Individual gas boilers	No intervention, approved at initial submission	No change

Table 6.11 shows a range of intervention types undertaken by the Sustainable Cities Team. I identified active intervention in eleven of the fifteen subcases, with the most stringent being actual or threatened planning refusal for failure to meet the relevant planning policies. In two subcases (SGHE6, DIRELEC2), this threat was carried out and planning permission refused based on failure to demonstrate policy compliance. In the GASCOMM2 subcase the threat of refusal resulted in the chosen heating approach being changed from noncompliant to compliant approach. There were four lower-level interventions where the Sustainable Cities Team required changes or consideration of certain approaches including SGHE. In three subcases, this led to applicants amending noncompliant individual gas boiler solutions to compliant ones, including to SGHE. There were also four subcases that suggested more supportive activities where the team provided guidance for how applicants could meet the policies. In three of those four subcases, the team specifically recommended that applicants consider SGHE. In two of those subcases, the final technology chosen was SGHE.

To illustrate intervention activities, in the SGHE4 subcase, written dialogue between the Sustainable Cities Team and developer in May 2018 noted that a potential solution was *"micro-heat networks using ground source heat pumps" [SGHE4-4]*. I considered the activities of the Sustainable Cities Team in light of the niche-nurturing intermediary roles frameworks (Bush et al., 2017; Kivimaa, 2014). The type of activity seen in the SGHE4 subcase suggests both *awareness raising* and *provision of advice and support*. Other types of niche nurturing roles were also evident in the data, with interviews relating to SGHE2 detailing how officers from the team offered local authority provision of lifetime financial support for operations and maintenance if they were to choose SGHE *[SGHE2-9, SGHE2-10]*. A significant aspect of the role was clearly *technology assessment and evaluation* whereby the officers assessed the different technological solutions proposed by developers and combined this with *policy implementation* to enforce the local planning policies.

Consideration of power and politics in the operation of the niche empowerment activities recognised where incumbent developers were attempting to invoke the stability of the socio-political regime to resist pressure to choose niche innovations. They did this through direct lobbying to elected councillors in their position as having seniority and power over officers, to attempt to secure waivers of the local planning rules. In the SGHE2 subcase for example, the developer reported how they had approached ward councillors to try and get an exception to the heat hierarchy because of the other community benefits the scheme would bring such as affordable housing, a new doctor's surgery and other community facilities. Therefore, the importance of political backing for officers to stand up to developers, which was also evident, was clear. In that subcase, the representative of the developer explained how the councillors responded to their lobbying with, *"that ain't changing […] you're going to have to find another solution" [DEV-4]*.

Whilst the approach taken by Bristol authority officers was having a clear positive effect on the deployment of low carbon heating especially SGHE, it appeared this came with certain risks and challenges. There was resentment amongst developers when their proposals were challenged, emphasised by:

> *"So, that was going swimmingly through planning, they were happy with it […] And, on the eleventh hour in planning, somebody put their hand up and said,*

> *"We're not going to grant you planning anymore on that [...] We need you to actually adhere to our heating priority" [DEV-2]*

A representative from a developer described how they felt the team did not consider other benefits from their schemes and the heat hierarchy was, "*like the trump card, it trumps everything, even the provision of affordable housing" [DEV-4]*. A local builder felt the unwillingness to negotiate and strict adherence to the heat hierarchy was having negative effect on the city, *"it's my feeling that developers are switching off from the Bristol residential development because of the policy requirements" [BUILD-1]*. This suggests local incumbent regime actors attempting to invoke the national regime to resist change. As part of the analysis, I checked the city's progress against national housing delivery targets and found that Bristol had consistently missed their annual target for the previous three years, which may back up this claim (MCHLG, 2021). Anecdotal contact with actors involved in residential development in Bristol challenges this assertion however. An associated risk with the focus on SGHE above other heat technologies is connected to issues raised in Chapter 5 regarding overarching issues around the lack of an established market with a variety of options available. Five of the six SGHE subcases proposed the same micro ambient heat network approach which is currently only provided by one company in the UK. This carries certain risks of technical/maintenance problems if the company ceased trading for example, and the subsequent impacts on residents as well as reputational damage to the local authority.

The evidence suggested that the institutional arrangements in Bristol imbued the Sustainable Cities Team with significant ability to shape the local regime and this was enabling SGHE deployment in the city. Because the team are a consultee on planning applications, they have the power to propose rejection if they believe developers are failing to meet the local policies especially the heat hierarchy without sufficient justification. As well as this punitive role, they undertook a range of niche empowering intermediary activities including advice and support, awareness raising about SGHE, offering to provide local authority resource to improve SGHE viability, as well as acting as a catalyst through the use of planning powers.

6.5.2.2 Leeds

Developments in the Leeds case demonstrated a low level of compliance with planning policies. From the analysis of compliance with policy measures shown in tables 6.7 and 6.9 in section 6.5.1, developments were able to achieve planning permission without meeting with carbon reduction or technical heating requirements in many instances. I analysed the data for evidence of intervention and enforcement activities in the Leeds sample to address the low compliance levels. For each subcase, I explored the initial heating type, the final heating type, whether an intervention could be identified which appeared to have an impact on the final heating system, and whether the final heating approach was policy compliant. Table 6.12 provides a summary of this analysis.

Table 6.12 Analysis of local authority intervention in subcases. Colour-coded by impact: Intervention appeared to change heating to compliant technology = green highlight; intervention appeared to change heating to noncompliant technology = orange highlight; intervention did not appear to change heating type = red highlight, no intervention = no highlight.

Subcase identifier	Initial heating technology	Intervention detail	Final heating technology	Impact, yes / no	Policy compliant (if no, policy)
DIRELEC7	Unknown system or carbon saving, prior to policy start date	Reserved matters application required for each phase	ASHP, dir. electric panel heaters, ind. gas	Yes	Yes (partial)
DIRELEC6	Unknown heating, hot water heat recovery	Planning condition to show EN1 compliance	Direct electric panel heaters	Yes	No, EN4
DIRELEC8	Unknown system or carbon saving	Planning condition to show EN1 compliance	Direct electric panel heaters	Yes	No, EN4
INDGAS2	Individual gas boilers	Planning condition to submit ES for each phase	No change	No	No (EN4)
DIRELEC5	Direct electric heat, gas CHP for communal hot water	Reserved matters application	No change	No	No (EN4)
PASSIVE1	Passive with MVHR & direct electric panel heaters	Planning condition to submit ES for each phase	No change	No	Yes
PASSIVE2	Passive with MVHR & direct electric panel heaters	Planning condition to submit ES for each phase	No change	No	Yes
DIRELEC4	Direct electric panel heaters	Discussion and negotiation to	No change	Yes	No, EN4

Subcase identifier	Initial heating technology	Intervention detail	Final heating technology	Impact, yes / no	Policy compliant (if no, policy)
		show EN1 compliance			
DIRELEC3	Gas CHP communal system with 20% carbon saving	Planning condition to show compliance (no submission received)	Direct electric panel heaters	No	No, EN4
PASSIVE3	Passive heat with MVHR & gas boiler top-up	Meetings held to discuss application, initial resistance expressed.	No change	N/A	N/A
CITYDH2	Gas CHP communal with future connection to city district heat	None	No change	N/A	Yes
GASCOMM4	Potential options given but further work needed	None	No change	N/A	No
UNKNOWN1	Unknown heating system	None	No change	N/A	No
SGHE8	SGHE, solar thermal, communal heat network	Not applicable, prior to policy	No change	N/A	N/A
SGHE7	SGHE with micro ambient heat network	Not applicable, retrofit project	No change	N/A	N/A

The primary finding shown in Table 6.12 is that of the eleven identified interventions, in only one subcase did this play a role in a change in developer decision, with the DIRELEC7 indicating a change from a non-complaint to partially compliant heat technology. Interventions were mostly bureaucratic and process-based rather than showing evidence of direct contact between planning authority officers and developers or their consultants. Nine of the eleven interventions involved placing of planning conditions on applicants to demonstrate compliance at a later stage. There was little evidence of intermediary activities beyond indirect policy implementation through the planning process.

I analysed more closely the two subcases where there was evidence of direct interaction between officers and applicants, DIRELEC4 and PASSIVE3. In the DIRELEC4 subcase the applicant maintained that cost, noise, and space limitations meant that direct electric panel heating was the only viable approach. A report from officers to the planning committee stated "*Through discussions and negotiations with* *the developer the scheme is now considered to be compliant with Policy" [DIRELEC4-6].* This suggests that local authority officers were engaging with applicants to try to get them to meet policy requirements. However, this was to meet the 20% carbon reduction only rather than heating technology policy requirements. There was no evidence in the sample of attempts to engage with applicants to meet the EN4 heat hierarchy policy.

The other subcase where direct contact could be established indicated a reversal where the community-led developer was challenging the established regime of traditional approaches to planning as a niche actor. The PASSIVE3 subcase interviewee described meetings with planning officers to try to persuade them to allow their Passivhaus concept with its low car and unusual design. After significant resistance from regime actors, they persuaded the senior planning officers of the value of treating the scheme as a pilot and it was approved. I found considerable later evidence the planning authority now treats the PASSSIVE3 scheme as an exemplar development and routinely cites it as an example for other developers to follow. The niche actor in this subcase had brought about a change in approach such that the regime actors were then acting as intermediaries to promote the niche innovation.

Three subcases, UNKNONW1, GASCOMM4, and DIRELEC3 were notable by the low level of information provision or divergence from approved specification which did not appear to negatively affect the local authority decision to award planning permission. The DIRELEC3 subcase, where construction-stage evidence suggested the proposed heating technology of gas CHP with communal heat network became direct electric panel heaters at the point of installation. The potential situation was backed up by an interviewee who commented, *"Yeah, but who checks?" [CON-3]*. This suggests a potential issue of technology verification which may affect other schemes.

Overall, the Leeds case evidence suggests little attempt by the local authority to empower niche-innovation heating technologies through the institutional framework of the planning process. Mostly process-based compliance activities were visible, but these were not universal and did not lead developers to choose non-conventional heating approaches. There were some early signs that officers may be starting to take a more robust enforcement approach since the authority's declaration of climate emergency in 2019:

> *"…in the light of the Climate Emergency declaration in March 2019, the minimum figures as adopted by Full Council in the Core Strategy were insisted upon." [DIRELEC4-6]*

However, evidence suggested that despite the support for district heating deployment through policy EN4, there remained a general commitment to a technology-agnosticism to developer innovation-decisions by the local authority:

> *"'Policy EN1(i) is highly flexible, allowing developers to choose the most appropriate and cost effective carbon reduction solution for their site" [LA2-4]*

The potential conflict between the different attitudes expressed may suggest the lack of a shared vision amongst institutional actors (Bush et al., 2016). A developer with experience of operating in Leeds and other cities felt Leeds was constrained by scale of the planning authority and resource available, *"The fact of the matter in Leeds is they're struggling to process applications. The planning team seems to be under quite a lot of pressure" [PASSIVE2-12]*. This may indicate effects of the broader national socio-political regime shaped by austerity and the draining of skills and resources from local authorities (Chatterton et al., 2018; Harvey, 1989; Webb et al., 2016).

6.5.2.3 Cross-case comparison and discussion

There were significantly different approaches in Bristol and Leeds in the types of activities undertaken to support niche-innovation heating technologies especially SGHE, leading to markedly different outcomes. In Bristol, the outcome of enforcement along with a range of other supportive activities was clear, with all applicable planning applications in the sample meeting the carbon reduction requirement, and only one subcase achieving planning permission without meeting the heat hierarchy. There was clear support for SGHE with the niche-innovation being directly recommended in four subcases. It appears that this direct support, along with the implementation of the technical policy outlined in section 6.5.1 which ruled out conventional gas boilers and direct electric panel heaters, worked together to deliver SGHE deployment. In Leeds, there was much less evidence of direct intervention, although there was improvement in policy compliance between initial and final submissions. This suggests some process was in place to liaise with developers to improve submissions. However, three subcases were approved without meeting the carbon reduction policy requirements, and five were approved without meeting the onsite energy generation requirements of EN1. Policy EN4 was only fully met by two applicable subcases.

The findings suggest Bristol's Sustainable Cities Team were implicated in a range of supportive and enforcement activities which resulted in SGHE deployment in five subcases. Considering the activities described in this section in light of the two approaches to niche empowerment, *fit and conform* vs *stretch and transform* (Bush et al., 2017; Smith and Raven, 2012) the evidence suggests that niche actors within the Bristol local authority may be "seeking to transform the incumbent regime to the extent that it becomes possible for an innovation to diffuse" (Bush et al., 2017, p. 138). They were doing this through a range of activities within the three broad intermediary roles categories shown in Table 2.2, and they appeared to primarily act at *pre-feasibility* and *feasibility* stage when developers and energy consultants were exploring what technology might be the best solution. Whilst Bush et al placed the *acting as a catalyst for new schemes and expansion using planning powers* within the *delivery* stage, there was evidence of this function supporting SGHE at earlier stages, for example in early meetings between developers and the team where they recommend considering SGHE. The evidence also suggested the team, and by extension SGHE technology, benefitted from political backing by elected councillors against incumbent developers seeking exceptions against the heat hierarchy. This may indicate a supportive coevolving process whereby the Sustainable Cities Team has been able to create and benefit from a shared institutional vision of the local authority's role in shaping the local regime and nurturing niches (Bush et al., 2016). This was absent in Leeds where there was a lack of clarity and agreement about the local authority's role in supporting niche-innovations.

Considering the origins and development of the Sustainable Cities Team within the city, Torrens et al (2018) explored how through co-evolution between urban experimentation and governance, Bristol has developed across four 'settlements' since the 1970s involving grassroots organisations, local government, intermediaries and social entrepreneurs underpinned by a history of strong local green countercultural movements. Starting in the early 1990s, BCC brought together the dedicated multidisciplinary Sustainable Cities Team to work across local authority departments, and intermediate between the city's environmental groups and the council. Diverging from national trends, and through support of the local universities and participation in specialist networks, expertise, capacities and capabilities were developed and retained in-house. This reinforced the development of a new approach to urban governance from 'enabling' to 'leveraging' involving a political-led integration of climate change response across multiple municipal agendas, amplified within the new mayoral system established in 2012. Considering the regime resistance to interventions by incumbent actors identified, the political support across levels of governance for the team and for taking potentially unpopular actions to tackle climate change was key. The approach taken in Bristol did carry some risks and consequences, including threatening scheme viability, which would deliver other local benefits such as affordable housing, as well as the city becoming overly reliant on one technology provider.

6.5.3 Actor response to broader institutional and technological dynamics

There was considerable evidence that current and future central government policies were affecting the technology decisions made by developers and energy consultants as they went through the decision process. Recognising the consequences of this is an important consideration for future SGHE deployment.

6.5.3.1 Bristol

Local planning policy in the Bristol case was linked to the national institutional spatial planning framework, the National Planning Policy Framework (NPPF). Applicants in every Bristol subcase referred to the NPPF aside from the SGHE3 scheme that progressed through the planning process prior to the enactment in 2012. National building regulations had a specific impact on carbon reduction because of the requirement that developers *"[use] the methodology in the current Building Regulations Part L as a baseline" [LA1-2]*. Part L 2013 requires that applicants must use the Standard Assessment Procedure 2012 (SAP2012) methodology [GOV-5, GOV-6], despite this having been updated to SAP10 in 2018 and then 10.1 in 2019 [GOV-3, GOV-7]. To explore what effect this had on developer technology decisions, Table 6.13 shows analysis of the data on the methodology used and whether the developer / energy consultant used this to justify why their proposal was complaint or whether they attempted to challenge the local policy and use the modelled figures to justify why a noncompliant proposed approach should be accepted.

Table 6.13 Applicant use of SAP2012/10/10.1 to meet or challenge local planning policy. SAP2012, challenge local policy = orange highlight; SAP2012, meet local policy = pale green highlight; SAP10/10.1, challenge local policy = red highlight; SAP10/10.1, meet local policy = dark green highlight.

Subcase identifier	Calculations based on	Purpose and impact	Used to meet policy or challenge
ASHPIND1	SAP2012	Justify initial proposal of ind. gas boilers	Challenge policy
GASCOMM2	SAP2012	Justify initial proposal of ind. gas boilers	Challenge policy
SGHE2	SAP2012	Justify initial proposal of panel heaters	Challenge policy
SGHE1	SAP2012	Justify initial proposal ind. gas boilers	Challenge policy
GASCOMM3	SAP2012	Justify initial proposal of ind. gas boilers	Challenge policy
INDGAS1	SAP2012	Justify proposal for ind. gas boilers	Challenge policy
CITYDH1	SAP2012	Justify proposal to connect to district heat network	Meet policy
SGHE5	SAP2012	Justify the proposal of communal ASHP	Meet policy
GASCOMM1	SAP2012	Justify proposal for part-renewable heat network	Meet policy
SGHE6	SAP2012	Justify proposal for SGHE with micro ambient DH	Meet policy
ASHPCOMM1	SAP10 vs SAP 2012	Emphasise that grid carbon intensity is decreasing.	Meet policy
SGHE4	SAP10 vs SAP 2012	To justify not choosing communal heating, based on SAP10 losses reflected in communal heating	Challenge policy
DIRELEC1	SAP10.1 vs SAP2012	To justify use of direct electric panel heaters	Challenge policy
DIRELEC2	SAP10 vs SAP2012	To justify use of dir. electric panel heaters, based on SAP10 losses in communal heating	Challenge policy
SGHE3	No reference to SAP	N/A, prior to SAP2012	N/A

Table 6.13 shows that applicants used both the older and more up-to-date national regulations to challenge the local heat hierarchy policy and make the case for non-compliant heating technologies. The SAP2012 methodology was invoked to justify individual gas boilers, citing the proportionally higher carbon content of grid electricity compared to natural gas. More recent versions of SAP were used to justify direct electric panel heating over communal heating. The DIRELEC1 subcase illustrates how the applicant justified the choice of direct electric panel heating

because electricity grid had become much lower carbon than was reflected in SAP2012, *"from 0.519kgCO2/kWh to 0.136kgCO2/kWh, representing a -74% reduction in the carbon intensity" [DIRELEC1-1]*. The applicant claimed that if SAP10.1 carbon factors were allowed, this would recognise that the amount of carbon emitted by direct electric heating would be far lower.

Overall, the evidence suggests two things. Firstly, that regime actors will routinely invoke the national institutional framework which is embedded in the broader sociocultural regime against local attempts to support niche-innovations. Secondly, that as the lower carbon content of grid electricity and the higher losses inherent in communal network approaches comes to be recognised in the national governance framework, this resistance is likely to shift increasingly towards favouring direct electric heating in the form of panel heaters.

6.5.3.2 Leeds

In the Leeds case, local technology decisions by developers and their energy consultants were linked to the national planning framework through the wording of the EN1 policy, which requires developers to "*Provide a 20% reduction in CO2 emissions over Part L Building Regulations requirements (2013)" [LA2-10].* To analyse what impact this requirement was having on technology choices in the Leeds case I analysed each submission to identify the version of building regulations and inherent SAP methodology used. The results of this analysis are shown in Table 6.14.

Table 6.14 Analysis of applicant use of SAP2012/10/10.1 to meet or challenge local planning policy. SAP2012, meet local policy = green highlight; SAP10/10.1, challenge local policy = red highlight.

Subcase identifier	Calculations based on	Purpose and impact	Used to meet policy or challenge
PASSIVE3	SAP2012	Justify passive approach	Meet policy
INDGAS2	SAP2012	Justify proposal for ind. gas boilers	Meet policy
DIRELEC5	SAP2012	Justify proposal for mixed dir. electric panel heaters and communal CHP for hot water	Meet policy
DIRELEC4	SAP2012	Justify proposal for dir. electric panel heaters	Meet policy
DIRELEC8	SAP2012	Justify proposal for dir. electric panel heaters	Meet policy
DIRELEC3	SAP2012	Justify initial proposal for communal network with CHP and central gas boiler	Meet policy
CITYDH2	SAP2012	Justify connection to district heat network	Meet policy
DIRELEC7	SAP10 vs SAP 2012	Justify not meeting carbon reduction under SAP2012	Challenge policy
GASCOMM4	SAP10 vs SAP 2012	Flag up that proposed solution will look less favourable under new carbon factors	Challenge policy
PASSIVE1	No reference	N/A	N/A

Subcase identifier	Calculations based on	Purpose and impact	Used to meet policy or challenge
PASSIVE2	No reference	N/A	N/A
DIRELEC6	No reference	N/A	N/A
UNKNOWN1	No reference	N/A	N/A
SGHE8	No reference	N/A	N/A
SGHE7	Not required	N/A	N/A

Table 6.14 shows that nine subcases made it clear which version of SAP they were using to carry out their carbon reduction modelling. There was no evidence of developers attempting to challenge local policy using current SAP2012 methodology. This may have happened more if local policy was enforced. The two subcases that did so referred to the lower carbon factors in SAP10. In the GASCOMM4 subcase, the applicant noted that although their proposed solution was policy complaint under current local and national regulations, they wanted to flag up that the latest version of SAP will *"strengthen the case for specifying electric heating and heat pumps" [GASCOMM4-3]*. The applicant in DIRELEC7 challenged the current policy and used SAP10 to justify their proposal which failed to meet the 20% carbon reduction under Part L (2013) but, *"Using SAP10 carbon factors, the development achieves a 57.3% betterment over the gas boiler/Part L baseline" [DIRELEC7-4]*. It is difficult to assess further how developers in Leeds are likely to respond to an updated national governance framework because of the low levels of local policy compliance.

6.5.3.3 Cross-case comparison

The evidence shows that when challenged by local niche-empowering activities, incumbent regime actors will invoke the institutional effects of the broader national socio-political regime to resist change. The data suggests impacts of broader national policy and direction were being felt in both case cities, although the developer response was different, likely driven by the varying level of policy compliance and intervention activities which sought to transform the local regime in Bristol. Through evidence of coevolutionary dynamics between *technologies, institutions,* and *business strategies*, the carbon factors recognised in the governance framework was having a clear impact on the choice of heating technology. In Bristol, there was considerable evidence that developers used the carbon content of grid electricity in both the older and newer regulations to challenge local policy and justify installing conventional heating technologies over niche innovations. This was less evident in Leeds but that may be due to lower levels of enforcement of the heating technology policy. Expecting the coevolutionary effects to continue as the reducing carbon content of grid electricity is recognised in national policy, the evidence suggests that developers will increasingly opt for direct electric heating in the form of panel heaters and invoke the institutional framework as justification for resisting regime change towards less conventional choices. With the much higher power consumption of direct electric heating compared to heat pump-based approaches such as SGHE, this carries challenges and risks for the electricity grid especially when combined with the adoption of electric cars (Rees and Curtis, 2014). Challenges for district and communal heating may be exacerbated by recognition in the new SAP methodology that heat losses are significantly higher the previously recognised (BRE, 2018). Therefore, if local planning authorities want to prioritise SGHE and other more efficient niche-innovations as new building regulations come into force, the evidence suggests that implementation and enforcement of heat technology policies will be required.

6.5.4 Roles of developer and energy consultant actors in the transition

To further assess the role of different actors in the innovation-decision process, I considered the relationship between developers, energy consultants and technology decisions in both case cities.

6.5.4.1 Bristol

From the evidence gathered, it appears that both energy consultants and developers played a key role in the deployment of SGHE as actors both in regime and niche levels. In all Bristol subcases an energy consultant was employed to prepare an energy strategy. To explore the impact of consultants on the innovation-decision, I analysed each subcase in terms of the company involved and the technology choice. A graphic representation of these connections is shown in Figure 6.2, with subcases colour-coded by technology type.

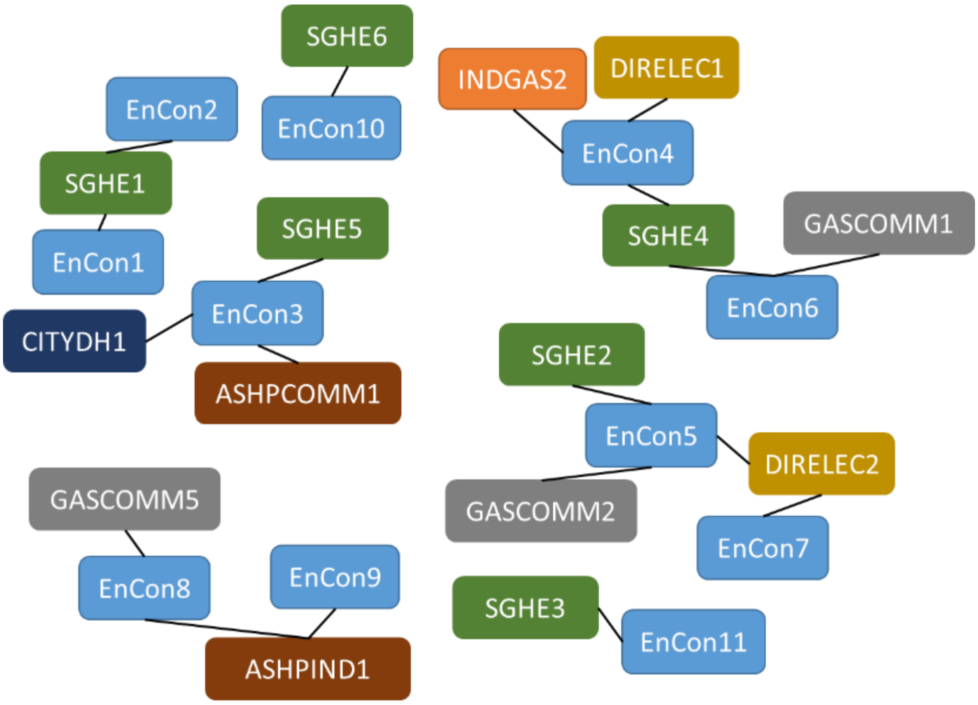


Figure 6.2 Graphic representation of energy consultants and colour-coded subcases in Bristol sample. SGHE = green, direct electric resistive = mustard, ASHP = brown, gas communal = grey, individual gas boilers = orange, connecting to district heat network = dark blue

Figure 6.2 shows there was some crossover in consultants across the subcases, represented by single consultancies to multiple developer connections such as can be seen with EnCon5. However, as is made clear by the distributed colours of the developer-technology combinations, the figure suggests little correlation between energy consultant and technology type. Because each SGHE subcase involved a different energy consultant, this suggests the success of SGHE deployment in Bristol does not arise from specific energy consultants acting as niche actors to promote the innovation to their developer clients.

To explore the consultant/client relationship and its impact on technologies, I conducted interviews with representatives both from the client-developer side and energy consultancies and attempted to establish whether they took an active niche-supportive role or tended to operate passively according to developer preferences. Differing viewpoints were expressed with some taking a more passive view of their role where, *'we will take our lead from the developer because the developer will, nine times out of ten, have an idea about what they want to do' [CON-1]*. Others suggested a more active role where consultants, *"hear about the interesting technologies, we speak to the manufacturers, we understand you know how they work and how they* *could be implemented and then we've got to try and sort of speak to our client about them and convince them it's a good idea" [CON-2]*. This suggests some tentative niche empowerment activities, however "*we don't see ourselves as the green police" [CON-1]* would indicate that consultants are not willing to challenge the regime resistance of incumbent developers.

I found conflicting viewpoints of the same innovation-decisions, with different actors keen to take credit for proposing the niche-innovation. In the SGHE1 subcase both the local authority developer [DEV-1] and the private developer partner [DEV-2] described how when the original gas boiler proposal was challenged by the Sustainable Cities Team, it was they who developed the SGHE idea and not the other. The attitude from the local authority compared to the private developer of the requirement to meet the heat hierarchy was markedly different, with DEV-1 seeming happy to acknowledge the need to meet the best standards whilst DEV-2 described how it was spring on them unexpectedly and that what they were being required to do was unreasonable. It appears from both sources that the revised SGHE proposal came from the developers themselves rather than from the energy consultants. This is backed up by a representative from the consultancy supporting SGHE1, "*For ground source, it probably is that the builder has come to us and said, "we want to use ground source." It's not the most viable solution quite often purely because of the financial implications" [CON-1].*

The general perspective from energy consultants interviewed in the Bristol case was that housing developers are driven by simple cost / profit drivers and want to go for the lowest cost and lowest hassle option. Therefore, the role of the energy consultant was to acknowledge the preference of their client and inform them of the consequences of that choice. This suggests that energy consultants choose not to, or given the constraints of their business model do not feel able to, lobby for niche-innovations over conventional technologies.

6.5.4.2 Leeds

In the Leeds sample, I identified thirteen energy consultant companies working across the fifteen subcases, and one situation where the developer conducted this work-in house. Figure 6.3 shows a graphic representation of energy consultants to subcases.

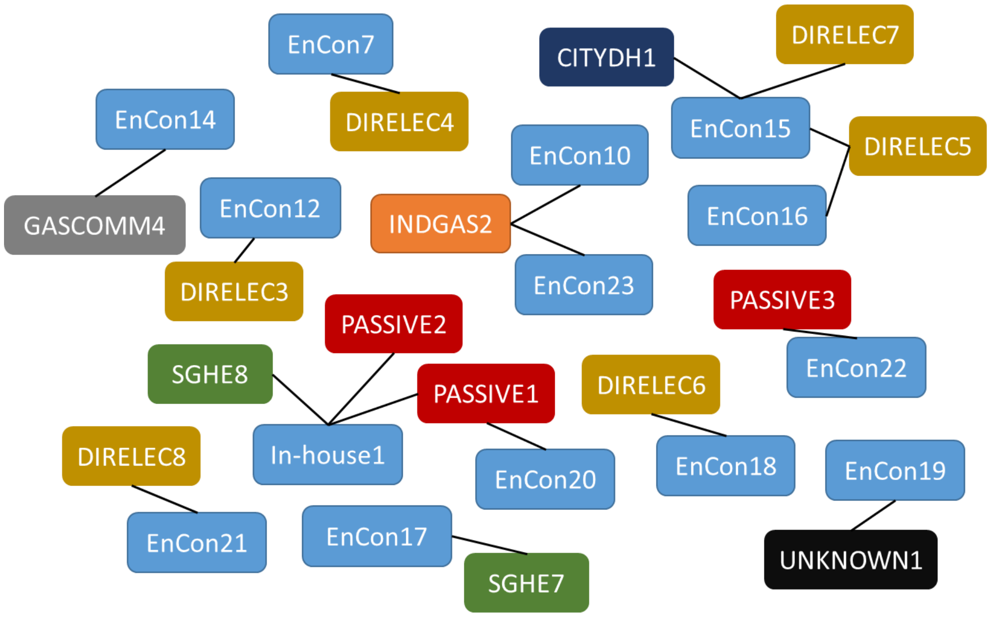


Figure 6.3 Graphic representation of energy consultants and colour-coded subcases in Leeds sample. SGHE = green, direct electric resistive = mustard, gas communal = grey, individual gas boilers = orange, connecting to district heat network = dark blue, Passivhaus approach = red, unknown = black

From Figure 6.3 there was little correlation between energy consultants and the heating approach specified, with no pattern of colour-clustering to indicate the involvement of certain consultants being more likely to result in particular technologies. The most prevalent heating approach in the sample was direct electric panel heaters, and the six subcases used five different energy consultants, with only the DIRELEC5 and DIRELEC7 sharing the same energy consultant. The passive schemes were slightly different because the PASSIVE1 and PASSIVE2 developer brought energy consultancy services in house. The most projects served by any single energy consultant were the three schemes that employed EnCon15, including two direct electric heating schemes and one which would be connected to the city DH network.

A representative from a local energy consultancy described how they tend to work through an intermediary such as an architect or another consultant, with sometimes many layers in between them and the developer client. They reported that developers *"want easiest and cheapest, they always want cheapest!" [GASCOMM4-6]*.

Their approach was driven by their need to earn their fee and because of this, they had no choice but to put forward a proposal that the developer would accept. They were finding this was increasingly to be direct electric panel heaters because, *"it's just a panel on the wall, they don't want to bother with a wet system in the apartments, so they want electric panels and they think that's going to be easy and cheap and they, well cheap basically!" [GASCOMM4-6]*. This suggests that energy consultancies in Leeds are embedded in, and not able to shape, the prevailing socio-political regime based around powerful private housing developers, who prioritise profit maximisation over providing optimal solutions.

6.5.4.3 Cross-case comparison

From the results it appeared that consultants were important actors in the development process because they deliver the energy strategies that developers rely on to meet local institutional requirements of the planning system. However, they did not play a particularly key role in supporting certain niche-innovations and the innovation-decision rested largely with developers. Comparing the patterns shown Figure 6.2 and Figure 6.3, beyond the weight of green-SGHE in Bristol compared to mustard-direct electric in Leeds, both are characterised by high decentralisation indicating that energy consultants are not associated with particular heating technologies. This was backed up by interview evidence suggesting consultants can undertake some awareness raising of different technological options in some circumstances, but generally they take a passive approach in which they see their role as prioritising their developer-client's preferred technology. The evidence suggested that consultants see the decision-process made by most private developers to be rooted in neoclassical profit-maximisation appraisal of different technologies, and this emphasises the prevailing socio-political regime in which the actors operate. Overall, this suggests that consultants are not likely to be act as empowering niche actors to support deployment of SGHE and emphasises the need for other niche-empowering processes explored in sections 6.5.1-6.5.3.

6.6 Chapter discussion

Earlier work suggested niche-innovation heating technologies faced different local regimes and this was affecting deployment. There was evidence that local authorities were able to use powers through the spatial planning system to shape the local regime in their area. In this chapter I explored what actions local authorities in two UK cities each taking to support or constrain the deployment of SGHE and what effect this appeared to be having. The results presented in section 6.5 find that whilst operating under the same national regulatory framework embedded in a wider socio-political regime, local authorities can take certain key actions that are likely to lead to greater niche-innovation deployment in favour of conventional heating technologies. This study looked specifically at SGHE, but the findings are not limited to a single technology.

Overall, the case study revealed a coevolving but stable regime for residential heating based around conventional heating technologies. The evidence shows that residential developers seeking profit-maximisation tend to prioritise lowest cost, lowest hassle technologies such as individual gas boilers and direct electric panel heaters. Through analysis of coevolving *technological – institutional - business strategies* dynamics, carbon factors inherent in national building regulations have in the past led developers to favour individual gas boilers. Supported by energy consultants who tend to propose technologies favoured by their clients rather than pursuing niche-innovations, developers have attempted to leverage the national institutional framework to resist efforts by local authorities to empower niche-innovation technologies such as SGHE. The data suggests that as national regulations are updated to more accurately reflect the UK's relative success in electricity grid decarbonisation, the conventional technology preferred by developers is likely to shift from gas boilers to direct electric in the form of panel heaters. Due to the impact on the electricity grid of increased direct electric heating deployment, combined with other electrification such as the shift to electric cars, local authorities seeking to promote other technologies can take policy and practice measures to support niche-innovation heating technologies.

From the findings, the two case study authorities were limited in their ability to shape the local regime by the national institutional framework. Covering all local planning authorities across England and Wales outside of London, this restricts the maximum carbon reduction that they could require of housing developers to 20% better than same standard methodology (*Greater London Authority Act*, 1999; MHCLG, 2021a, 2019, 2018, 2015). Both authorities have sought to implement the maximum permitted carbon reduction under this framework, although in both cases this had relatively minor impact on developer innovation-decisions around heating technologies such as SGHE because it could be met by non-heating technologies such as solar PV.

Both Leeds and Bristol city authorities sought to influence developer innovation-decisions and promote niche-innovation heating technologies through technical options policies which restricted the range of heating technology options, excluding individual gas boilers and direct electric panel heaters. Building on earlier work around local authority support for district heating (Bush et al., 2017, 2016; Bush and Bale, 2019; Foxon et al., 2015; Karvonen and Guy, 2018; Webb, 2015), the case study evidence suggested both were attempting to prioritise district heating through 'heat hierarchy' technical options policies which were permitted under national planning rules. This was either for immediate connection or through the ability to connect in future, requiring the inclusion of site-wide communal networks at the time of construction. Because SGHE can be designed on a site-wide or small-scale 'micro network' approach, the heating options policies could potentially exclude the technology. There was no evidence of this in the case study, however, and it appeared that officers had the autonomy to apply the policy in a balanced fashion such as not to inadvertently rule out SGHE, but the potential unintended consequences of heat hierarchy policies are important to recognise.

Despite superficially similar attempts to shape the incumbent regime for residential heating systems and create opportunities for niche innovations to break through, the outcome in the two cities was markedly different. Further to indications in Chapter 5, there is considerable evidence presented in section 6.5 that Bristol City Council (BCC) has been successful in supporting SGHE deployment by residential developers. Through the results presented in section 6.5.2, the success of BCC can be traced back to several supportive niche-nurturing activities undertaken by the multidisciplinary Sustainable Cities Team. There was evidence for 'stretch and transform' activities involving direct support for SGHE approaches, including financial through offering to fund operations and maintenance costs, combined with more typical 'fit and confirm' approaches of requiring consideration in new developments through planning policy (Bush et al., 2017; Smith and Raven, 2012). The lack of political commitments and resources was found by Bush et al (2017) to be a key limiting factor in embedding a new regime locally, and in the Bristol case there was evidence of political commitment to back up the sometimes-unpopular work of the Sustainable Cities Team against incumbent lobbying by established regime actors. Exploring the history and evolution of the Sustainable Cities Team highlighted that their development has coevolved closely with the socio-political regime of the city over the last quarter of a century (Torrens et al., 2018). Whilst this indicates challenges to direct replication of Sustainable City Team roles and activities in other cities, there are certain policies and practices which can be learned from the success in Bristol and implemented in other cities to support the deployment of SGHE and other low carbon heating niche-innovations. These are explored in section 6.7.

A key technical difference between the SGHE technology supported through empowerment activities in Bristol and the traditional high temperature district heat networks explored by Bush et al (2017) is the single-site nature of SGHE. This was proposed by practitioners in Chapter 5 as a key benefit of the technology which they claimed remains economic down to single-building scale. Thus, whilst Bush et al found that a key 'stretch and transform' empowerment activity was strategic local authority ownership of district heating infrastructure, the evidence suggests such an activity is not necessary for SGHE deployment.

In exploring the positive impact of the niche nurturing activities of Bristol it was helpful to compare to a base case of Leeds. There were indications of some good intentions and attempts by city actors to undertake 'fit and conform' empowerment for niche-innovations using planning powers. However, the lack of robust enforcement of planning policies and lack of evidence of stretch and transform type activities resulted in a stable local regime based around conventional direct electric heating. Considering the causes behind the lack of enforcement activity, this may be a consequence of the loss of resources and associated drain of internal skills and expertise which might be expected under the broader neoliberal socio-political context of austerity and huge local government budget cuts (Chatterton et al., 2018; Gray and Barford, 2018; Rose and Miller, 2010; Webb et al., 2016). There was some evidence to support this impact. However, along with a lack of resources was a question of priorities and commitment which in the Leeds case appeared to shape the institutional response.

There was some evidence of support for niche-innovations in Leeds through the development of Passivhaus style low energy developments. Whilst it appeared initially that the local authority planning officers were acting as resistant regime actors, later evidence suggested they were now actively supporting and encouraging this approach. There was also evidence of active local authority support for deploying SGHE in retrofit schemes through the local authority's function as a social housing landlord, with a large programme to upgrade the old electric night storage heating in housing blocks with SGHE getting underway.

6.7 Development of the SGHE-friendly city framework

Based on the findings presented in Section 6.5 and discussed in Section 6.6 suggests there are applied lessons for other local authorities seeking to change the local regime for residential heating and promote niche-innovations such as SGHE. Drawing out the insights from the comparative case study and supported by the strategic niche management literature (Bush et al., 2017; Kivimaa, 2014; Smith and Raven, 2012), there are four key niche empowerment approaches which can be applied.

- 'Fit and conform' – support the niche-innovation to compete within the selection environment.
    - Put in place a heat technology planning policy which excludes conventional technologies of gas boilers and direct electric heating.
    - Commit institutional resources and empower local authority actors to enforce the heat technology policy.
- 'Stretch and transform' - transform the incumbent regime to the extent that it becomes possible for an innovation to diffuse.

- Provide the political commitment to challenge incumbent lobbying and clarify institutional priorities to support niche-innovations.
- Empower local actors to support the niche technology in developer innovation-decision processes through awareness raising, providing advice and support and require consideration.

Figure 6.4 shows a visual representation of the four conditions that local authorities can put in place to shape the local regime and empower niche-innovations such as SGHE.

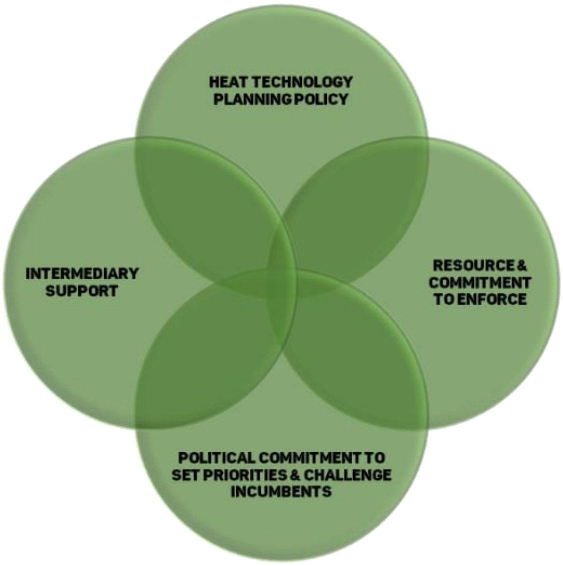


Figure 6.4 Framework of conditions for a 'niche-friendly city'

The framework represents a series of overlapping conditions which local authorities can undertake to empower niche-innovations such as SGHE. Recognising that not every local authority will have the unique history and local socio-political regime of Bristol, the framework proposes that through embedding a series of overlapping conditions, they can create local conditions for niche-innovations to diffuse. Whilst each condition on its own supports the niche-innovations, when combined they amplify each other and work together shape the local regime.

6.7.1 Testing the SGHE-friendly city framework

I tested the framework through a series of analyses of subcases, assessing for each what elements of the framework were present or absent in the data, and what effect this appeared to have. These are presented below with brief discussion for each.

DIRELEC3

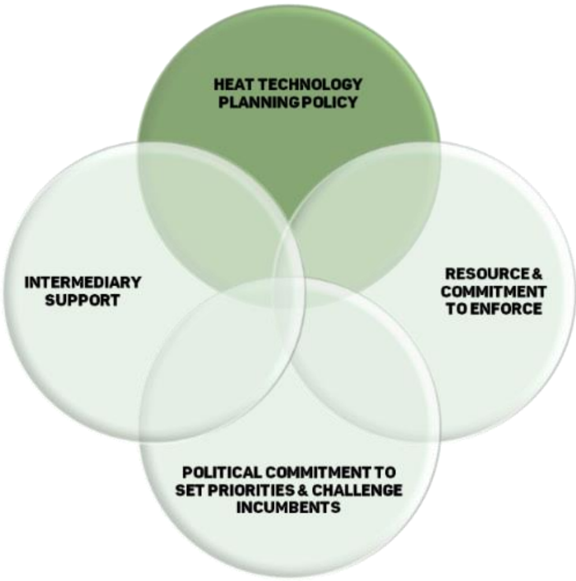


Figure 6.5 DIRELEC3 conditions analysis. Outcome: SGHE-unfriendly

In the conditions analysis for the DIRLEC3 subcase, summarised in Figure 6.5, the technical options policy that excluded direct electric heating and individual gas boilers was in place. The technology proposed by the developer would have met the heat hierarchy policy, but the condition placed on the developer to verify the proposed approach in a later submission was not fulfilled and there was no evidence of enforcement to ensure the condition was satisfied. Political backing to support officers to challenge a non-compliant proposal was not required because of the earlier lack of enforcement activity. There was no evidence of institutional support to consider SGHE or any other niche-innovation heating technologies. The result of the approach taken in the DIRELEC3 subcase was a noncompliant direct electric panel heaters.

SGHE1

In the SGHE1 subcase summarised in Figure 6.6, the institutional challenge to the developer proposal to install individual gas boilers was made possible by the technical options policy which permitted SGHE but ruled out conventional gas boilers and direct electric heating.

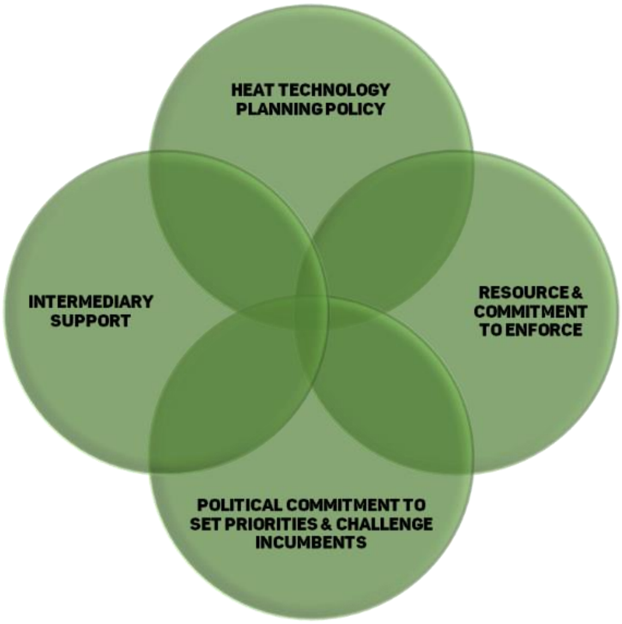


Figure 6.6 SGHE1 conditions analysis. Outcome: SGHE-friendly

There was clear evidence of strong enforcement by the Sustainable Cities Team to require the developer to meet the heat hierarchy. Political backing was implicit rather than explicit because the scheme was local authority-led and the development manager described how they felt they had no choice but to accept the planning policy, *"because politically that wouldn't go down very well" [SGHE1-17]*. There was anecdotal evidence of specific SGHE technology-supportive activity, with officers recommending the applicant consider single-building communal heating systems with ASHPs for the houses, but interview data suggested it was through dialogue with the Sustainable Cities Team which led to the eventual SGHE proposal. The result was the eventual installation a SGHE system using a 'micro-network' approach.

INDGAS1

The INDGAS1 subcase conditions review shown in Figure 6.7 provides an interesting example of a conventional individual gas boiler heating decision in Bristol. The heating technology policy was in force at the time of the planning application, however whilst the resource was in place there was no evidence of enforcement activities to ensure compliance. Because the noncompliant solution was not challenged, there was subsequently no political backing required to support the challenge. There was no evidence of supportive intermediary activities through the subcase history. The application received approval at initial submission stage with the noncompliant fossil-based solution.

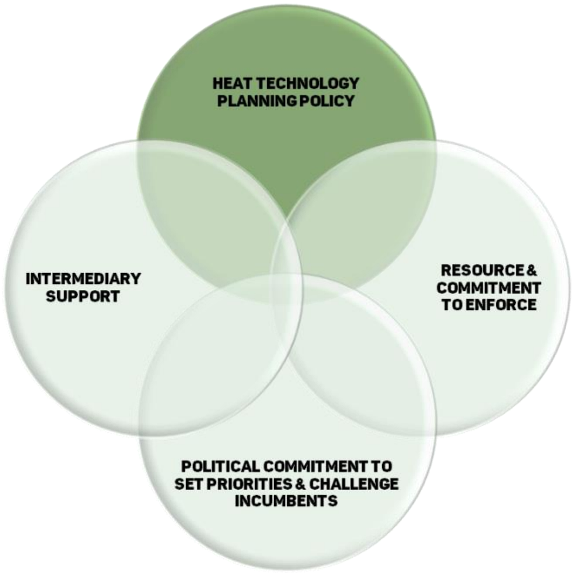


Figure 6.7 INDGAS1 conditions analysis. Outcome: SGHE-unfriendly

SGHE4

The SGHE4 subcase demonstrates that not all conditions are necessary for a SGHE-friendly outcome, as shown in Figure 6.8.

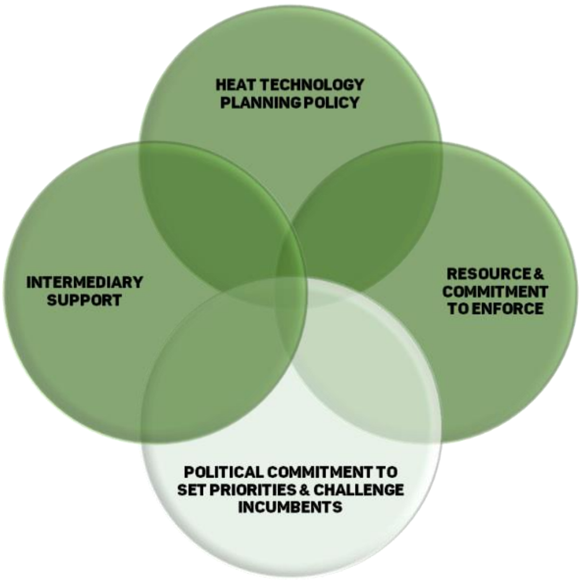


Figure 6.8 SGHE4 conditions analysis. Outcome: SGHE-friendly

In the SGHE4 subcase, the reasons for the positive innovation-decision were more based on the activities from the Sustainable Cities Team who provided significant intermediary support. The evidence suggested that officers actively encouraged the developer to consider SGHE in their innovation-decision in face-to-face meetings. This was followed up with the placing of a planning condition specifically to make sure SGHE was considered. An important consideration in this subcase was the applicant's own scepticism of district heating based on technical and consumer protection issues, as well as how they felt the lower carbon factors in grid electricity would favour a heat-pump based solution. However, whilst this is important, it is not an active policy or practice local authorities can pursue and so I decided not to include in the framework. There was no evidence of political support of the Sustainable Cities Team being required in this subcase although the team were operating in an environment where such support was implicit. The result was the decision to install a SGHE system.

Overall, the framework testing suggests that whilst not all elements of the framework are necessary to enable SGHE, having three or more conditions in place is a decent indicator of a SGHE-friendly city where deployment is more likely.

6.8 Chapter conclusions

In this chapter, I set out to explore what actions local authorities can take which support or constrain the deployment of SGHE and what effect this is having on the local domestic heating regime. Through the comparative case study, I found two markedly different approaches and through extensive analysis of documentary and interview data, composed a framework of conditions that local authorities can put in place to create a 'SGHE-friendly city.' Whilst not all conditions are required to deliver SGHE deployment, the framework is a useful predictor of the likelihood of developer innovation-decisions resulting in SGHE. When most conditions are absent however, conventional technologies tend to displace SGHE. The findings are not confined only to SGHE but can also apply to other low carbon niche technologies. Developers tend to default to the conventional options of individual gas boilers, and driven by landscape and national regime factors, increasingly towards direct electric panel heaters. Therefore, if local authorities want to prioritise low carbon options this framework may offer a useful template to support them in efforts to shape the local regime and support heat decarbonisation.

7 Thesis discussion, further work and conclusions

7.1 Introduction

This thesis set out to explore the role of thermal energy storage (TES) in supporting the transition to low carbon energy systems. A review of existing literature demonstrated that while TES has the potential to support energy system operation with high renewable penetration, the technology has received little focus beyond techno-economic analysis. Ground thermal storage in various forms was identified as offering distinct benefits but deployment is limited in the UK. The review explored how a sociotechnical approach can help to generate insights into the transition to low carbon heat provision, and what a focus on cities as sites of transition might mean for the study.

The thesis comprised three chapters of empirical research. Chapter 4 examined the current state of UK TES deployment and considered how sociotechnical factors are shaping deployment prospects. This provided a solid foundation for later work in Chapters 5 and 6 which focused on configurations of ground-based TES. These chapters explored the sociotechnical transition for geoexchange and shared ground heat exchange (SGHE) from different perspectives. Chapter 5 considered critical success factors in geoexchange development from the perspective of project developers or practitioners within organisations attempting to obtain positive geoexchange investment decisions. Chapter 6 investigated issues of urban governance and explored SGHE development from the perspective of local authorities and how they might create the conditions for SGHE to flourish in their area.

This chapter draws together findings from the empirical research and positions them in the context of previous work. Firstly, the remainder of Section 7.1 considers how the work has addressed the three research sub-questions RQ1-RQ3. In Section 7.2 I consider the contributions of the work within the context of the theoretical frameworks and discuss practice and policy implications of the thesis. In Section 7.3 I explore the limitations of the thesis method and findings, and in Section 7.4 propose areas that would benefit from further research. Finally in Section 7.5 I consider the overall conclusions of the work through analysis of how it has contributed to answering the overarching research question:

> *How can cities unlock the potential for thermal energy storage to support the UK's net-zero transition?*

7.1.1 Sociotechnical factors in thermal energy storage deployment

> *RQ1. What is the current state of UK thermal storage deployment and how do sociotechnical characteristics shape deployment prospects?*

This question was primarily addressed by empirical Chapter 4, but supplemented by the findings from Chapters 5 and 6. The initial study found a multiplicity of TES approaches, but little convergence around dominant designs or combinations along with other signs of continued niche-innovation status. The findings backed up earlier work suggesting the UK continues to face technological lock-in of fossil gas heating through an incumbent natural gas grid. Considering coevolutionary dynamics suggested signs of positive coevolution of business models with technologies to exploit the grid balancing characteristics of TES which can support project viability whilst enabling the progress of carbon reduction in other parts of the energy system. The role of national policy and the relationship between national and local policy is paramount to the prospects of TES, and the results indicate that greater local control of planning policy and the ability to set tougher building standards would support greater TES deployment.

Considering the overall research findings in the context of the four transition pathways suggested by Geels & Schot (2007) suggests little evidence of dominant design stabilisation. Heat pump based systems were found to align with TES but the very low current deployment suggests embryonic niche status even of this broader niche-innovation. Further, the disruptive nature of interactions between the various TES approaches explored in the thesis against conventional heat technologies suggests a transformation pathway most likely. The *transformation* pathway typology typically involves moderate landscape pressure with a key role for outsiders such as social pressure groups to highlight the negative externalities of the regime. There was evidence of such landscape pressure involving outside actors from social movements both at a national and local level to move away from fossil gas for heating, driven by heightened climate change awareness. This was characterised in the study by campaigns for local authority declarations of climate emergency. An unfolding transformation pathway would be more likely lead to reorientation and survival of regime actors, where they use their adaptive capacities to reorient their activities and development trajectories. The outcome for niche-innovations in the *transformation* path is gloomy, whereby some gradual adjustments in the niche take place but they do not break through (Geels, 2011). Where the UK situation may challenge the pathway typology however is due to the extensive natural gas grid, which because of its physical reach to most households serves to stabilise the dominant regime and is a significant factor in technological lock-in. This may create something of an all-or-nothing tipping point with regards to a future gas or electrified heating pathway. Therefore future government decisions may act as a major landscape pressure to either stabilise the regime around gas and then hydrogen boilers or disrupt to the extent that a range of electrically based solutions including TES are given the opportunity to flourish.

Further evidence emphasised the role of incumbents and their ability to shape the socio-political regime. This may impact the deployment prospects for TES especially if the outcome of incumbent lobbying is for the UK to pursue a hydrogen-based future for home heating. Because of the importance of central government decisions on the future heat decarbonisation, the findings emphasise the importance of how such a decisions are to be made. Here the literature on the socio-political regime (Swilling et al., 2016) and the techno-institutional complex (Unruh, 2000) helped focus attention on the apparent coalition of policymakers and resistant regime actors. Further to earlier work which found a vigorous incumbent coalition comprised of gas networks, hydrogen generation and CCUS developers attempting to resist the electrification pathway for domestic heating in the UK (Lowes et al., 2020, 2019), there was some evidence of this in Chapter 5 where concern about the effect of this on policy decisions was expressed amongst geoexchange developers. Evidence in Chapter 6 also suggested that housing developers were attempting to use their incumbent positions to resist the transition to lower carbon forms of heating on a local level. Considering incumbent regime resistance through the four strategies proposed by Geels (2014), there was some evidence that natural gas / hydrogen industry incumbents were attempting to leverage instrumental power through their access to national government decision-makers. Through this access, interviewees believed incumbents were seeking to frame a 'green gas' approach to the heat transition. There was evidence of the effects of broader institutional power in residential development based around a prevailing liberalised market ideology, and this appeared especially so in the case of Leeds. This also had an effect at a national level where the central government drive for greater house building and the power of volume housebuilders was manifested through Housing Delivery Targets for local authorities. This feedback into local institutional dynamics around the balancing act local authorities must play between viability and high environmental standards.

The importance of city-based contexts and local governance and institutional arrangements to TES deployment was established. A proposed set of critical success factors included organisational characteristics which can assist landlord organisations when deciding whether to pursue conventional heating or novel TES approaches such as geoexchange. The importance of considering organisational decision processes and the role of *champions* in the residential development sector was identified. There was further evidence of supportive coevolutionary dynamics shaping deployment prospects through the development of novel business models that can exploit the technological characteristics of ground-based TES.

New national building standards may support TES deployment through implementation of updated carbon factors and prevention of new homes being connected to the gas network. However, findings showed that expected changes may lead to developers choosing direct electric panel heaters to the detriment of more complex ground-based TES / heat pump approaches. Results indicate that despite the constraints of the national regulatory framework, deployment prospects for TES could be shaped by local authorities through implementing certain local policy and practice measures. These issues are explored further in Sections 7.1.2 and 7.1.3.

7.1.2 Urban geoexchange deployment success factors

RQ2. What are the factors that have led to successful geoexchange deployment in UK cities?

Whilst this question was primarily addressed through the study detailed in Chapter 5, findings from Chapters 4 and 6 also provide some insights to help answer the research question. The study established that centralised TES systems such as geoexchange are suitable for urban settings where they can potentially exploit a range of heat sources and users, but suggest that geoexchange is one of a wide array of potential heating technology options that developers have to choose between. The research found little to suggest geoexchange will emerge as the dominant alternative to conventional gas heating in urban settings.

Considering the research in light of the prior coevolutionary study of TES in the UK (Taylor et al., 2013), the evidence suggests that geoexchange straddles the micro-scale (aligned with a *user-led* pathway) and the meso-scale (more aligned with a *decentralised* pathway). Geoexchange was found to be suitable for single commercial sites (micro), and when combined with low temperature distribution through SGHE, was able to serve multi-residential developments (meso), although many of the SGHE systems were of the 'micro-network' design (micro-meso). There was no evidence of geoexchange or SGHE being deployed as part of larger district or city scale systems in the UK. There are small signs of *user-led* or *decentralised* pathway features, although these are primarily in recognition of what is not happening: e.g. civil society recognition that central government / market actors are not delivering change at the speed required, and heat pump deployment is way behind where it needs to be (CCC, 2021; HM Government, 2020a; Rosenow et al., 2020a). There are many signs to suggest the UK is set on a continuing *centralised* pathway with central government providing the framework for private companies to compete in a liberalised market. There is little to suggest bottom-up community leadership is supporting a flourishing of diverse solutions as part of a successful user-led pathway, or signs that local authorities can best deliver the transition through city-scale district heating in a decentralised pathway.

Within this broader context, results showed the likely importance of novel business models which can exploit the temporal displacement characteristics of geoexchange to stack fiscal flows and help achieve project viability. This may involve organisational restructuring to make the most of the functionality of geoexchange. Some evidence of project developers considering a range of non-traditional values in their decision-making was found, but have not superseded financial viability in heat technology decision-making. Other organisational success factors included being able to offset counterfactual like-for-like costs when heating systems were being replaced in retrofit settings, and that maintaining a long-term interest in the building and its residents is likely to support geoexchange deployment. This suggests organisations such as social landlords may be key to geoexchange deployment, but such an approach is not typical of the wider residential sector development sector.

Results across the empirical chapters found that the overall national institutional environment shapes local contexts which have an impact on geoexchange project success, especially around the availability of funding to close the viability gap, and the limits placed on local authorities in setting carbon reduction targets through the spatial planning system. Local authorities were identified as key local energy actors to consider in the deployment of urban geoexchange. Results suggest that through certain local policy and practice measures, it is possible for local authorities to shape the local conditions for niche-innovation heating technologies including geoexchange, and this has a significant impact on the likelihood of deployment success. These issues were addressed more explicitly through RQ3 and discussed further in Section 7.1.3.

The combination of geoexchange with heat networks was found to be key in opening up the residential sector to serve multiple households from shared geoexchange installations. Ambient temperature heat networks were shown to be particularly suitable for this purpose whilst addressing some of the challenges inherent in traditional high temperature district heating. Early consideration of the installation process was found to be an important success factor, along with developer organisations supporting evidence-based analysis of the impact of geoexchange. This involves collection of pre-installation energy and cost data which can be challenging, but is likely to be key to longer-term reputational success.

A novel framework to support geoexchange practitioners, organisational champions and policymakers was proposed shown in Figure 5.3 and Appendix I, which addresses RQ2 over five levels: *national direction and policy*, *local policies and* *support*, *organisational and business case*, *technology aspects and system design*, and *installation and post-installation*.

7.1.3 Creating a SGHE-friendly city

> *RQ3. Within the same legal and planning framework, what actions are local authorities taking to support or constrain the deployment of shared ground heat exchange, and what effect is this having?*

Evidence across all three empirical chapters suggests that, whilst limited by the national spatial planning framework and in the context of austerity budget cuts, local authority policy and practice can shape the local regime for niche-innovation heating technologies including ground-based TES. The analysis of residential developments in comparable cities showed that city actors have the power to design and enact local policies and practices which lead developers to choose lower carbon options including SGHE, and these approaches could be applied in other cities. The exclusion of conventional heating technologies such as gas boilers and direct electric panel heaters as options in new developments was found to be possible and enforceable within the current national framework, and likely to have most significant impact on heat technology choice. The results suggested however that implementing such policies without associated support and enforcement activities was likely to have only a limited effect on deployment.

Once spatial planning policies were in place, the evidence showed that change happens when a local authority commits institutional resources, and empowers officers to take necessary action to enforce policies. The political commitment to the shift away from conventional heating technologies and the willingness to challenge incumbent lobbying were shown to increase the likelihood of successful SGHE deployment. Supportive activities such as technology awareness-raising were found to have a positive impact on developer decision-making processes. A set of measures were proposed in Figure 6.4 in the context of strategic niche creation, and the results suggested that within a common legal framework, local authorities which implement these policies and practices are able to support deployment of SGHE and other niche-innovation heat technologies.

The results also showed that local policies and practices are likely to continue to be important even as national building regulations are strengthened, because these may lead towards greater direct electric heating deployment in favour of less conventional technologies such as SGHE. Because of impacts in other parts of the energy system, there remains a valid justification for local authorities to want to take an active role in shaping the direction of heat technology deployment in their area. This indicates the importance of the practice and policy implications of the thesis, explored in Section 7.2.

7.2 Theoretical, applied and policy implications of the thesis

7.2.1 Implications for theory

This research has contributed to theory in the following ways:

(a) Development and application of a synthesised theoretical framework to analyse deployment prospects for niche-innovation technologies at a local level.
(b) Recognising the importance of considering location-based aspects of transitions including conditions of local lock-in and local agency to shape regimes.
(c) Recognising the need to explicitly consider politics and power in sociotechnical analysis of how new infrastructure systems can be brought forward.

A key contribution of this work was through development and application of a synthesised theoretical framework which combined and built on aspects of various pre-existing sociotechnical theories to explore how structural factors and local agency shapes the implementation of niche-innovation TES technologies at a local level. Through the abductive approach set out in Chapter 3, this was developed iteratively through application of empirical data to develop and refine the framework. New themes were added to help make sense of the data. This section discusses the development and implications of the framework for understanding the urban energy transition for heat.

Central to this work is a recognition that TES technologies in their various configurations are part of wider systems which also include human interactions and social relations, power structures, companies and communities, rules and underlying political and economic narratives, and so on (Arthur, 1989b; Geels, 2002; Kemp, 1994; Raven et al., 2016; Rip and Kemp, 1998; Unruh, 2000). The empirical evidence presented in the thesis indicates a stable regime for domestic heating in the UK based around gas boilers and an incumbent natural gas grid. There was some evidence that of any technology, direct electric panel heaters may be the most likely to replace gas boilers and there are valid reasons for challenging this in favour of more efficient alternatives. Thus, the main issue under consideration in this thesis is how such a stable regime can be displaced by alternative technologies such as TES to facilitate low carbon heat delivery.

I first applied the template analysis approach set out in Section 3.3.3 to a subset of data from using the *a priori* themes of the coevolutionary framework (Foxon, 2011). Finding important themes which were not adequately captured, as I developed the template through the various stages, I brought in the multilevel perspective (Geels, 2002; Geels and Schot, 2007), intermediary roles framework (Bush et al., 2017; Kivimaa, 2014; Smith and Raven, 2012), extended infrastructure business model canvas (Foxon et al., 2015) and diffusion of innovations (Rogers, 2003) to help make sense of the data (see Figure 5.2 for diagrammatic representation). In Chapter 6 the synthesised framework was developed further to support the analysis of measures that local authorities are able to take to shape the local regime for heat (Figure 6.1).

I found that existing sociotechnical frameworks do not lend themselves to a closer analysis of organisational decision processes. Important aspects from the data emphasised internal decision process of organisations considering whether to make conventional fossil-based replacements to heating systems or opt for niche-innovations such as geoexchange. The empirical data in Chapter 5 suggested a key role for information sharing, persuasion and decision-supportive activities within landlord organisations which were critical to seeking a geoexchange-positive decision. The diffusion of innovations framework (Rogers, 2003) places a particular emphasis on the role of *change agents* in communicating, persuading and influencing in support of innovation-decisions. As noted in Chapter 2, the typical focus of change agent activity in diffusion is external and directed more towards, for example, a business seeking to promote their innovation to a client. In this study however, the important consideration is how internal organisational resistance to what may be seen as a risky venture may be overcome. Figure 2.4 set out five stages of an organisational decision but these are fairly high level and whilst highlighting the role of champions within organisations Rogers (2003) says little about how such individuals emerge, operate, are supported or challenged, for example. To address the prominent issues in the data, support analysis of organisational decisions and the role of individuals within the process, I added an *actor decision-making* connection to the combined sociotechnical framework. The importance of organisational decision-making was evident throughout Chapter 6, and the addition of this element to the framework helped to recognise, for example, that whilst consultants play a key role in the organisational decision process this is not one which supports niche-innovation approaches. There was little useful empirical data generated to enable a deeper analysis of how organisations can nurture champions or more niche-innovation friendly decision processes, and this would benefit from further study.

Considering issues of place and the role of cities in the energy transition, this was clearly supported by the data which emphasised the importance of locational aspects in TES deployment. The study findings saw cities as both local regimes and as geographical containers for issue-based regimes, such as the local regime for domestic heating in Leeds and Bristol. The analysis suggested that stable city regimes were leading to local lock-in of conventional heating technologies, as was the case in Leeds. However, the study also suggests that city actors such as local authorities do have local level agency to shape the regime through the implementation of certain policies and practices. This was evident in Bristol where policies to exclude conventional heating technologies were enforced and combined with active support for SGHE by a dedicated team of local authority officers. The work by Hodson & Marvin (2010), Kivimaa (2014), Smith & Raven (2012) and Bush et al (2017) were helpful at drawing attention to the role of intermediaries in city-based transitions. These works supported the analysis of the Sustainable Cities Team in Chapter 6 and helped to identify and classify types of supportive intermediary activities seen in the data. However, the research did not delve into deeper questions of the shared creation of city visions or the types of structural changes which might be required to deliver transformational local change.

Finally, the importance of national government decisions around the future of heat decarbonisation and the impact this may have as a landscape pressure on the stable regime for residential heating were keenly felt. These factors were closely connected to embedded issues of power, politics, and the overarching neoliberal ideology which shapes the UK's socio-political regime. The study findings also suggest the value of considering power and politics at a local level, where the local regime was shaped by underlying socio-political dynamics around the power of housing developers within a system tilted towards development, overt expressions of power to challenge support for niche-innovations, and the political commitment by local authority actors to implement regime change. Due to important findings related to pervasive issues of political ideology and power relations, I added *politics and power* as an underlying element to the combined framework, as shown in Figure 6.1. This is an admittedly crude and simplistic way of recognising the morass of complex issues that such a node includes. As shown by Bolton & Foxon (2011), the coevolutionary framework can facilitate consideration through the *institutions* node and in the coevolving dynamics between systems. However, I propose there are clear benefits to including a focus on these issues in any sociotechnical analysis.

The work presented in this thesis has benefitted hugely from the array of sociotechnical, innovations and institutions literature and attempted to make some useful contributions to the field through the development of a synthesised theoretical framework to support analysis of the transition for heat at a local level. Taken together, the theoretical implications of the work provide a useful addendum to existing analyses of power, incumbency, lock-in and transition which tend to consider such issues at a national scale.

7.2.2 Implications for practice

This research has implications for urban planning practice in the following ways:

(a) Local authorities should establish a clear position towards supporting niche-innovation heat technologies and ensure a level playing field amongst developers by making it clear to all that policies will be enforced.

(b) Planning officers should be empowered to enforce policy compliance and have the political backing to challenge developers attempting to circumvent policies.

(c) Officers should apply planning policies in a way which doesn't inadvertently rule out emerging low carbon niche-innovations yet to be formally recognised.

(d) Support should be given to developers and their energy consultants to consider niche-innovation heat technologies, including information and awareness raising and requiring inclusion in technology appraisals.

The research has implications for organisational practice within residential landlords / developers:

(a) Recognition of a range of values beyond simple financial returns can help in the creation of a viable business case for investment in niche-innovation heat technology.

(b) The role of organisational champions in achieving innovation-decisions should be recognised and supported.

(c) In existing residential settings where heating retrofit is under consideration, the approach to cost recovery and connection of private leaseholders must be addressed.

(d) Innovative business and organisational models, such as the creation of separate business unit to invest in heat technology assets, as well as long-term interest in buildings and the welfare of inhabitants can support deployment.

(e) In retrofit settings, pre-installation data collection for later impact assessment should be undertaken wherever possible.

Application of the theoretical frameworks helped to draw out useful insights to understanding and supporting the urban energy transition for heat. This section considers outcomes from the theoretical perspectives which helped shape some applied practice contributions.

The survey results in Chapter 4 revealed a range of technology types involved in providing heat storage, suggesting that whether TES can be considered a niche-innovation or not depends on the attributes of TES technology in question. Applying the definition noted in Section 7.2.1 suggests that electric night storage heating TES for example would not be considered as such. Figure 1.4 shows that electric night storage heating represents the most ubiquitous alterative to gas boilers in the UK, even if its share is only 6% of the domestic heat market, but with a long history of UK deployment implying non-niche-innovation status. TES through domestic hot water tanks also remains ubiquitous in the UK despite a steady decline (HM Government, 2016a; Palmer and Cooper, 2013). However, there was evidence that novel approaches such as the advanced electric night storage heaters and domestic hot water tanks were being developed to operate in novel ways e.g. to offer grid-balancing services, and these combined technology packages exhibited niche-innovation characteristics such as shielding from normal commercial pressures supported by government or research funding.

Further to the findings discussed in section 7.2.1 which suggests the UK retains a stable fossil-based regime for domestic heating, there is evidence in Chapters 5 and 6 to suggest that the stable regime based on individual gas boilers is shifting towards direct electric panel heaters. Whilst direct electric heating will effectively decarbonise in line with electricity grid, it is acknowledged in prior work (Chaudry et al., 2015; Rees and Curtis, 2014) and in the empirical research presented here, that widespread deployment will result in significantly higher energy consumption and will cause other problems for managing competing demands on the national grid. Interestingly studies which consider technical or policy implications of future demands on the national grid from heat and other system electrification tend to consider only heat pump adoption rather than widespread shift to direct electric heating (Baruah et al., 2014; Broad et al., 2020; Chaudry et al., 2015; Eyre and Baruah, 2015; Love et al., 2017; Watson et al., 2019). The findings in Chapter 6 suggestive of potential widespread adoption of direct electric heating without national or local policy intervention make credible earlier concerns by Wilson et al (2013) about the significantly challenging impact of mass adoption on the energy system. This was especially the case given that the types of system being installed appeared to be purely ‘direct’ resistive rather than feature any kind of storage which would enable load shifting to reduce peak demand and ramp rate impacts. Wilson et al (2013) found that moving just 30% of current UK heating demand to direct electric resistive heating would result in a doubling of demand in winter months.

Given the potential impacts of a mass transition to direct electric heating, it is no surprise that it does not feature in UK government scenarios or that of their climate advisors (CCC, 2020b; HM Government, 2021b). The study findings suggest that coevolving institutional-technological dynamics may lead developer decision-makers to naturally drift towards this approach. An important applied implication of the study is therefore that without measures to support niche-innovation TES alternatives, there is a risk of an unplanned widespread deployment of direct electric panel heaters. In the creation of three applied outputs, this thesis attempts to address this challenge, through: an understanding of the current state of TES the UK and the sociotechnical factors shaping deployment, a critical success factors framework to support developers and actors within organisations such as the *champions* described in 7.2.1 and others seeking to scale-up geoexchange deployment, and a framework of policy and practice measures for local authorities seeking to support niche-innovations such as SGHE in favour of gas and direct-electric conventional alternatives.

The intention behind the geoexchange critical success factors framework as shown in Figure 5.3 is that it can help practitioners as well as local and national policymakers to consider prominent issues across the five levels of context for successful delivery within the broad parameters of a geoexchange project timeline. Some of the aspects are beyond the ability of local actors to shape, such as whether there is a counterfactual case the higher cost of the geoexchange project can be offset against, although knowledge of the advantages that such a situation confers may support the development of creative local solutions. Whilst many of the factors are likely to be familiar to experienced champions in this field, the intention is that through bringing them together into a concise framework, others new to the technology or who are for the first time attempting to build internal momentum within an organisation to take the innovation-decision may also benefit.

7.2.3 Implications for policy

Whilst the intention is for the practice proposals and frameworks to be a useful tool in support of niche-innovation heating technologies, they can only do so much because some of the key issues cannot be addressed at a local scale. Alongside the implications for practice, the research has produced several policy proposals which can help to support the transition to low carbon heat:

National policy implications

(a) Because of the connection between national regulations and local innovation-decisions, electricity carbon factors inherent within national building regulations should be updated regularly to reflect true grid carbon intensity.

(b) The policy of preventing of new connections to the gas grid should be implemented to build experience and capacity in alternative technologies in new build settings, and drive down technology and installation costs.

(c) National policy which levies carbon reduction taxes onto electricity but not gas bills to be addressed, with levies moved into general taxation. This will eliminate an artificial barrier to adoption of electrified options whilst tackling energy bills for customers.

(d) Current carbon reduction limitations placed on local authorities through the national spatial planning framework to be removed. The evidence shows that where planning authorities can set higher minimum standards, developers are able to meet the requirement and choose lower carbon heating technologies.

(e) Decisions about the future of the gas grid should be made as soon as possible, with the best available evidence regarding impacts of different heat technologies.

(f) Policies should support the development of a vibrant market for geoexchange, SGHE and other TES technologies. Currently progress is hampered by low levels of awareness and expertise remains in the hands of a small number of companies.

Local policy implications

(a) Within the current national planning framework, a local planning policy which offers a range of heat technology options but rules out conventional gas boilers or direct electric panel heaters can support the shift to niche-innovation heat technologies.

(b) Local authorities should consider their strategic position in supporting large district or city scale district heating networks in light of the findings around the potential for SGHE to offer an alternative solution that can overcome many of the challenges inherent in traditional district heating.

(c) In light of (b), local planning policies which emphasise district heating development or connection should be reviewed to ensure they don't inadvertently prevent deployment of low carbon solutions such as geoexchange / SGHE, and other future innovations.

The study findings suggest a stable regime based around an incumbent natural gas grid which is shifting towards direct electric panel heaters. The findings indicate where national and local policy can shape the regime, and based on the results discussed throughout the thesis suggest the above policy proposals are the most likely to support the net-zero transition for residential heating.

As seen in Chapter 5, central government decisions about the future of the gas grid are eagerly awaited by practitioners. These decisions may mean the gas grid is either wholly or partially abandoned or converted to hydrogen or biomethane (Dodds and McDowall, 2013; Lowes and Woodman, 2020; Speirs et al., 2018). This is likely to act as a major landscape pressure on the current regime for residential heating. National decision-makers should consider these with the best evidence available of the different technical options. The UK government's Heat & Buildings Strategy was released in October 2021 signalling that gas boilers are to be phased out by 2035, with no new connections to the natural gas grid from 2025 (HM Government, 2021b). The strategy primarily considers three approaches to heat decarbonisation: heat pumps, district heating and hydrogen. However, broadly the types of heat pumps considered are for individual, low density settings, and heat networks are of the city or district scale type requiring a long-term strategic local approach e.g., through zoning areas of a city where all developments would be required to connect. There is no direct recognition of the SGHE approach which is characterised by distributed heat pumps connected through an ambient heat network. This suggests the technology is not yet on the radar of national policymakers and there is a risk of the technology being overlooked as national goals around the decarbonisation of heat and buildings are translated into local and regional plans and policies.

In the UK, the significant challenge to electrically based niche-innovations continues to be exacerbated by central government policy which results in electricity bills significantly higher than gas bills (CCC, 2016; Gross and Hanna, 2019; Ofgem, 2021a; Wolf et al., 2021). This creates an artificial 'spark gap' which penalises those served by electric heating options and means that heat pump based solutions must be at least 400% efficient to deliver heat at cost parity for users. There are early signs this issue is beginning to get some attention (HM Government, 2021b), although this is currently only through a proposed consultation. Shifting the levies into general taxation will not only remove this artificial barrier to the adoption of electrified options, it would share the costs of energy system decarbonisation in a progressive, rather than regressive, fashion.

Another of the key national challenges for the UK, identified especially with regard to the deployment of geoexchange and SGHE, is the very low number of operators in the market. This backs up earlier work which recognised this as a main challenge to wider adoption (Buffa et al., 2019a). This simultaneously hampers deployment through low levels of awareness whilst carrying risks associated with near monopoly status of technology developers. This niche characteristic is a concern on a local level, as found in Chapter 6, when city support for a technological alternative means they can inadvertently support a single provider. This issue has recently been recognised by national policymakers (HM Government, 2020c), but represents a key challenge which must be addressed to enable widespread deployment.

The evidence from the current situation in Leeds and Bristol as identified in Chapter 6, and experience of other cities, suggests that following earlier declaration of climate emergency and pledges to achieve net-zero by 2030, local planning authorities are currently or soon to be developing net-zero compatible planning policies. Therefore, there is currently a window of opportunity to put into place policies which will create positive local conditions for niche-innovation alternatives such as geoexchange and SGHE. The SGHE-friendly city framework proposed in Chapter 6 is aimed at supporting local authorities to create the conditions for niche-innovations to flourish. The policy element of the framework emphasises that within the currently limited powers available to local planning authorities, the adoption of local policies which rule out conventional heating technologies can drive developers to choose lower carbon niche alternatives. This has been found to be permissible and effective in supporting deployment of SGHE.

As has been found in this work, SGHE can provide an alternative to conventional fossil-based heating technologies which is applicable for multi-residential settings where it is not feasible for each home to have a ground heat exchanger. It also addresses some of the challenges inherent in traditional district heating. Earlier work and the findings in this thesis suggest local authorities continue to support widespread district heating deployment, with policies designed to prioritise this over other technological approaches. Because of the advances that SGHE can offer, it is appropriate for local authorities to consider this technology in their strategic plans and policies, whilst ensuring policies currently in force do not rule out low carbon niche alternatives which may be suitable in different settings.

7.3 Limitations of the thesis

This section discusses the limitations of the research presented in the thesis and considers the implications for overall findings.

Accepting the limitations of a desk-based survey based on secondary data, Chapter 4 provided a useful overview of the current state of TES in the UK which has helped to fill a research gap in this area. A broader sample with specific attention to include projects from all parts of the UK such as Northern Ireland may have helped facilitate a more thorough regional analysis to consider why TES technologies are able to flourish more in some parts of the UK than others. Limited by access to privileged company information, the inclusion of primary data may have helped to generate more detailed insights into organisational decision-making around TES development.

In Chapter 5 I gathered a rich set of data through a series of semi-structured interviews with practitioners. Accepting the limitations of qualitative research design, I attempted to achieve a broadly representative sample in terms of a range of different perspectives. However, time limitations resulted in a smaller sample size which did not enable inclusion of perspectives such as those of private housing developers. I attempted to address this limitation in Chapter 6 through a concerted effort to include the perspective of housing developers. Chapter 5 included only interview data and accepting a critical realist perspective that individuals may have different and entirely justified perspectives on situations, it would be interesting to triangulate data from other sources to support or challenge interviewee perspectives.

In Chapter 6, the housing development subcases included in the sample broadly reflected the types of development and heating systems being undertaken in each city, within the time and resource limit available. This resulted in lower focus on retrofit-style developments than initially planned. The study was adapted to focus more on new build developments on this basis, leading to a remaining research gap specifically focused on SGHE deployment in retrofit developments which will hopefully be filled by further work. The onset of the COVID-19 pandemic made securing interview candidates challenging during this phase of work, and there are more fascinating and relevant perspectives that could be included. However the substantial dataset of written material provided ample documentary evidence on which to draw the conclusions presented here.

Some personal frustrations about the nature of detached social science research and the potentially limited value of postgraduate study in an era of climate breakdown have remained ongoing concerns throughout the study. I attempted to address this through actively seeking to engage with key city actors in Leeds during the course of study, leading to some findings being incorporated into the city's new spatial planning policies, and a more active approach to enforcement. Work is underway to take findings from this study along with other research on ground-based TES to a national and local policy audience to support wider adoption.

7.4 Suggestions for further applied work

Based on the theoretical and applied implications, and the limitations of the research design, there are several areas that would benefit from future research.

The study has gone some way to address the lack of up-to-date knowledge on UK TES deployment but accepting the limited scope of the initial study set out in Chapter 4, a more detailed and regional analysis of current UK TES deployment incorporating a range of sociotechnical characteristics and access to primary data would support the research, practitioner and policy community to better understand the value of TES to support the transition to fully renewable energy.

Given the study findings around the potential widespread shift to direct electric heating, which may already be underway, research is justified on how this unplanned transition can be best managed and the negative impacts on grid stability may be ameliorated.

Further work around the application of geoexchange and SGHE to retrofit settings is justified. There was evidence that some local authorities are beginning to consider the approach as a suitable means to provide low carbon, low-cost heating to tenants previously served by night storage heaters. There are questions about how this transition is managed and because of the lack of widespread adoption, there may be challenges in ensuring best outcomes for residents whilst reducing carbon emissions.

The lack of a vibrant UK market in ground-based heat storage was recognised as a key challenge facing the industry and city governments who take an active role in supporting deployment. The challenge of company failure in the geoexchange / SHGE technology market should be recognised and considered.

As noted in Section 7.2, there was a key role for organisational *champions* in building the case for internal TES decisions. The study presented some initial but limited findings around support for internal change agents, but a broader study would consider how individuals within organisations are empowered to bring about internal change.

Given the two-city scope of the comparative case study presented in Chapter 6, a broader review incorporating other types and scales of local authority, potentially using the empirical framework of Tingey & Webb, would develop interesting insights into how rural authorities for example are addressing similar challenges.

7.5 Conclusions

This thesis set out to explore the role of TES in supporting the transition to decarbonised urban energy systems. To undertake this task an overarching research question was posed which set out the overall aim of the study:

> *How can cities unlock the potential for thermal energy storage to support the UK's net-zero transition?*

Overall, this work has revealed that as a low carbon alternative to conventional heat technologies, in the UK, TES faces a stable fossil-based regime characterised by an incumbent natural gas grid. Early signs suggest a transition towards the less-efficient direct electric panel heaters shaped by broader technological and institutional factors. An array of technical arrangements and the lack of a clear winner suggests TES niche-innovations are not generally able to displace conventional heating technologies. Importantly, however, through a three-part sociotechnical analysis of TES, the study finds significant agency for city actors to shape the local sociotechnical regime for heat which can create the opportunities for niche-innovation technologies to flourish, and this has implications beyond TES. Several theoretical, applied and policy contributions are made which can support the wider net-zero transition.

A synthesised theoretical framework is provided which combines and develops several pre-existing sociotechnical frameworks to support analyses of local regimes and niche-innovation technology deployment at a local level. This was based on findings which emphasised that consideration of location-based aspects of the urban energy transition, the importance of organisational decision-making, and the role of internal champions, can help to understand local implementation of sustainable heat technologies such as geoexchange or its networked counterpart shared ground heat exchange. This includes key consideration of underlying issues of power and politics which shape the local regime.

A set of practice proposals for local authorities and landlord organisations are provided. The empirical analysis showed that despite common assumptions, there are clear measures that actors can take at a local level which can help create city or organisational friendly conditions for niche-innovations to flourish. Within local authorities, this begins with organisational priorities and political commitment to support niche-innovation heat technologies against local incumbent resistance, and ensuring spatial planning policies are applied robustly and consistently to support this. Within developer and landlord organisations faced with the choice between conventional or less conventional heating technology options, recognition of the role of organisational champions and their ability to demonstrate a viable business model to more risk-averse colleagues was identified. Proposals for attaining financial and non-financial viability included specific recommendations such as counterfactual cost offsetting, novel business models which stack fiscal flows made possible by technological capabilities of TES, and consideration of non-traditional values in organisational decision-making.

These measures are synthesised into a set of proposals which are applicable to various types of TES including the ground-based technologies explored in the work, but are also applicable more broadly to similar technologies facing issues of technological lock-in and a stable regime based around high carbon conventional technologies. Two novel frameworks are provided to support developers and others seeking to understand issues facing niche-innovations like TES and how a supportive local regime can be shaped.

To supplement the theoretical and practice proposals, a set of national and local policy recommendations are provided to support the energy transition for heat. Study findings indicate that changes to national policy which bring carbon factors of different energy sources into line with current carbon intensity, and address the environmental levy structure which creates an artificial 'spark gap' between electricity and gas, are likely to support niche-innovation electrified heating technologies. Low levels of awareness and higher costs resulting from market immaturity are holding back wider deployment TES technologies, and national policies which support the development a vibrant marketplace are required.

Locally, findings suggest that local authorities can implement spatial planning policies which support deployment of shared ground heat exchange and other low carbon heat technologies. This can be done effectively through policies which restrict conventional options such as gas boilers and direct electric panel heaters when developers are considering heating strategies for developments. Whilst local authorities have traditionally been highly constrained in their ability to set ambitious decarbonisation targets by national regulations, the study found this particular approach is however permitted and effective when enforced robustly.

The study finds that cities and TES technologies make a powerful combination which can unlock energy system decarbonisation. Success is not guaranteed and TES deployment is intertwined with a complex set of institutional and governance arrangements in a prevailing socio-political regime which is rooted in the principles of liberalised markets and centralised power. This regime is not delivering change at the speed required. However, considering the work in this context, the findings and theoretical, practice and policy proposals set out in this thesis can go some way to enabling TES deployment and supporting the net-zero transition. The urgent and drastic need to cut carbon emissions in the shortest possible timeframe is the challenge of all our lifetimes, and this work is intended to go some small way to supporting this endeavour.

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9 Appendices

Appendix A Chapter 4 project descriptions

Project identifier	**Description**
ELECSTOR1	Decentralised heat storage through new smart equipment attached to traditional electric storage heaters and hot water tanks across dwellings in seven tower blocks. Remote control to enable grid balancing service.
SOLAR1	Large heat network serving new housing and commercial development, powered from solar thermal array with high temperature heat pump and central thermal storage tank for evening heat.
HEATBATT1	Decentralised storage through phase-change material 'heat batteries' retrofitted to 766 dwellings to provide on-demand heat and hot water. Charged with excess electricity from roof-mounted solar PV in 426 homes.
GEOX1	Geoexchange approach employed at several supermarket sites across the UK to balance heating and refrigeration needs. Directional drilling to achieve large storage volume from car park borehole site.
TANK1	Large town centre heat network with integrated tank thermal storage serving civic and commercial buildings and social housing dwellings.
AQUIFER1	Aquifer thermal storage used to provide heating and cooling to new housing development.
CRYO1	Clean energy hub combining a range of innovative technologies. Cryogenic energy storage to serve liquid air network for electricity generation and connected to heat network.
MINE1	Demonstrator project exploring the use of abandoned coal mines under city for heat source and potential thermal storage.
TANK2	Demonstrator project featuring energy recovery from sewage water to provide heating and cooling to a museum and art gallery, with tank storage for pre-heat hot of water supply.
TANK3	Large mixed development as part of city regeneration scheme served by trigeneration heating, cooling and electricity networks from central combined heat and power (CHP) plant with thermal storage tanks.
NETWORK1	Mixed development featuring a river source heat pump with site-wide energy sharing and balancing between hotel and social housing through 'energy loop' ambient network & distributed heat pumps.
TANK4	City-scale high temperature district heat network serving local authority homes and municipal buildings. Powered by energy from waste (EfW) CHP plant with thermal storage tanks to maximise heat recovery.
TANK5	Low temperature heat network powered by sewage water energy recovery serving new commercial development.
GEOX2	University development of geoexchange using boreholes and shared heating and cooling between university buildings through ambient network.

Project identifier	**Description**
TANK6	Waste heat recovered from underground rail network with air source heat pump. Part of expansion of large established heat network with thermal storage tank integrated to support system operation.
GEOX3	Large local authority community facility using geoexchange approach through 'thermal bank' ground storage recharged with waste heat from summer cooling demand.
AQUIFER2	Aquifer thermal storage for new wing of national museum with active seasonal recharge through waste heat and coolth.
TANKCRYO1	Decentralised hot and cold storage employed in homes and businesses for research project to limit peak export of local renewables generation.
TANK7	CHP district heat network with thermal storage tanks serving new science and research hub along with commercial and residential buildings.
AQUIFER4	Aquifer storage providing heating and cooling provided to new residential development and commercial spaces.
TANK8	Oldest district heat network in the UK with large tank thermal storage serving 3,256 homes, 50 commercial premises and 3 schools.
TANK9	Large scale district heat network covering legacy Olympic site, residential developments and shopping complex. Powered by trigeneration CHP and biomass boilers with thermal storage tanks.
CRYO2	Established district heat, chilled water and electricity network serving residential, commercial and municipal users from geothermal heat. Ice storage employed to meet peak daytime cooling demands.
TANK10	New deep geothermal powered city heat network incorporating thermal storage tanks in energy centre housing directional drill site.
AQUIFER5	Large mixed residential and commercial development using underlying aquifer storage and CHP.
ELECSTOR2	Smart controls retrofitted to electric storage heaters in social housing dwellings as part of national fuel poverty technology fund.
MINE2	Demonstrator district heat scheme serving 700 dwellings, school and church connected to abandoned mine working thermal energy store.
AQUIFER6	City centre hotel development employing aquifer thermal storage for summer cooling and winter heating.
GEOX4	Community-owned geoexchange project serving community centre and small heat network using summer air capture to recharge ground.
TANK11	Trigeneration CHP with large thermal storage tank serving extensive mixed district heat network.
ELECSTOR3	Decentralised storage through retrofitted 'cyclo-control' remote switching to electric storage heaters and tanks in social housing tower blocks. Smart meters combined in each block to access industrial electricity tariff.

Project identifier	Description
TANK12	City centre heat network with biomass boiler, gas CHP and thermal storage tank serving thirteen social housing blocks. Long-term aim to connect to city-wide heat network.
TANK13	City scale district heat network fired from EfW plant initially serving range of civic buildings and cathedral. Prominent thermal storage tank seen as landmark feature with mounted carbon saving counter.

Appendix B Chapter 4 matrix of TES project attributes

	Storage Type									Storage horizon		Storage approach		Location of storage			Grid balancing		Main heat generation source											Heating / cooling		Heating system type					Heat network type			Customer / end-user type				Ownership model							Operational model								Business strategy			Devolved powers involvement					
Project identifier	Aquifer	Borehole	Electric storage heater	Phase-change material	Tank	Heat sharing network	Cryogenic	Abandoned mine shafts	Underground mass transit	Seasonal	Day / Intra-day	Sensible	Latent	Centralised within network	Distributed throughout network	Within end-user property	Yes	No	Balancing heating and cooling	Air source heat pump	CHP/CCHP	Grid electricity	Locally-generated electricity	Energy from Waste	Geothermal	Sewerage	Solar thermal	Water source heat pump	Waste heat	Heating only	Both heating and cooling	Domestic	Communal (one building)	District (several buildings)	District (neighbourhood)	District (city-scale)	High temperature	Low/ambient temperature	Unknown/NA	Commercial only	Mixed (small scale)	Mixed (large scale)	Residential only	Community energy group	Local authority	Private landlord	Private heating system developer	Public sector - non-housing	Registered Provider	Utility company	Community energy group	Local authority	Private landlord	Private ESCo	Public-private ESCo	Public sector - non-housing	Registered social landlord	Utility company	Commercial basis	non-commercial basis	Experimental / demonstrator	City Deal	Devolved government support	Both City Deal and Devolved government	Not Applicable	Strategic regional authority	Local Growth Fund
AQUIFER6	■									■		■		■				■										■			■			■					■			■				■					■			■					■			
CRYO1							■			■			■	■				■						■						■			■					■	■						■							■					■		■	■					
TANK12					■							■	■		■			■				■										■						■		■					■				■							■								■		■				
TANK6					■				■		■	■		■				■	■									■		■						■		■					■				■							■								■							■	
MINE2								■		■		■		■				■						■				■							■		■						■								■						■					■		
GEOX4		■							■		■		■			■		■	■										■				■				■	■								■											■			■	
TANK11					■							■	■		■			■				■											■						■		■					■				■										■					■							■	
ELECSTOR3				■									■	■				■	■					■									■		■									■					■						■								■	■					■		
TANK13					■							■	■		■					■						■			■				■					■				■							■									■		■		■					
SOLAR1					■							■	■		■										■				■			■					■					■			■											■							■			■			
HEATBATT1				■								■		■			■	■							■								■		■								■					■						■								■	■					■		
GEOX1		■							■	■	■		■			■		■										■		■					■		■									■							■					■					■		
TANK1					■							■	■		■			■				■										■						■		■					■				■							■								■		■				
TANK5					■							■	■		■				■								■			■		■				■	■				■								■						■				■				■				
MINE1								■		■		■		■				■						■				■								■				■		■											■				■				■			
TANK2					■							■	■		■				■								■	■			■					■			■									■									■		■					■		
TANK3					■							■	■		■				■										■				■			■				■							■									■					■								■	
NETWORK1						■						■	■			■		■	■									■	■	■				■				■			■		■							■							■				■		■		
TANK4					■							■	■		■			■						■					■				■					■				■								■									■			■		■					
GEOX2	■					■					■	■		■	■		■	■										■		■					■			■		■									■									■				■			■		
GEOX3		■							■		■		■			■		■													■		■					■			■		■									■							■						■				■		
AQUIFER2	■									■	■	■		■				■	■										■		■					■			■		■										■								■					■				■		
TANKCRYO1					■		■						■	■				■	■				■							■		■								■				■						■								■			■					■		
TANK7					■							■	■		■				■				■											■				■			■			■										■		■					■							■					■
TANK8					■							■	■		■			■				■										■						■		■					■				■												■		■		■					■	
TANK9					■							■	■		■				■				■										■				■			■					■				■									■				■							■	
AQUIFER5	■									■		■		■				■									■			■			■					■			■				■					■			■				■			
CRYO2							■				■	■		■				■						■				■				■	■		■			■				■									■				■		■				■		
TANK10					■						■		■		■				■						■					■				■			■		■						■						■							■		■					
ELECSTOR1				■									■	■				■	■					■							■		■									■					■						■								■				■			
AQUIFER4	■									■		■		■				■									■			■			■			■				■				■					■			■				■			
AQUIFER1	■									■		■		■				■									■			■			■					■			■				■					■			■				■			
ELECSTOR2				■									■	■				■	■					■							■		■									■					■						■								■		■				■		

Appendix C Chapter 4 list of empirical data sources

Project	Reference Type	Access Date	Producing organisation
AQUIFER6	News Article	08/05/2018	Birmingham Post
AQUIFER6	Planning	10/05/2018	Energy & Marine
AQUIFER6	Planning	11/05/2018	Energy & Marine
AQUIFER6	News Article	08/05/2018	BAM UK
AQUIFER6	Planning	11/05/2018	Environ UK
CRYO1	Brochure/advert	18/04/2018	Energy Capital
CRYO1	Report	31/05/2018	Energy Capital
CRYO1	Web Page	31/05/2018	Energy Capital
CRYO1	Web Page	31/05/2018	University of Birmingham
TANK12	Planning	22/02/2018	BuroHappold
TANK12	Report	22/02/2018	Bristol Green Capital
TANK12	Report	07/03/2018	Bristol City Council
TANK12	Web Page	10/05/2018	Bristol City Council
TANK12	Report	22/02/2018	Bristol City Council
TANK12	Web Page	22/02/2018	Sustainable Energy
TANK6	Report	10/05/2018	Islington Council
TANK6	Planning	08/05/2018	Islington Council
TANK6	Brochure/advert	02/05/2018	Islington Council
TANK6	Conference	02/05/2018	Islington Council
TANK6	Report	03/05/2018	Islington Council
TANK6	Report	03/05/2018	Islington Council
TANK6	Report	03/05/2018	Islington Council
MINE2	News Article	30/05/2018	BBC News
MINE2	Report	30/05/2018	Bridgend County Borough
MINE2	Report	30/05/2018	Bridgend County Borough
MINE2	News Article	30/05/2018	Welsh Government
GEOX4	Web Page	06/08/2018	Easton Energy Group
GEOX4	Report	06/08/2018	CHOICES Consortium
GEOX4	Web Page	06/08/2018	CEPRO
GEOX4	Web Page	06/08/2018	Balanced Energy Networks
GEOX4	News Article (paid	06/08/2018	Guardian newspaper
GEOX4	Web Page	06/08/2018	Owen Square Community
GEOX4	Web Page	06/08/2018	ICAX
TANK11	Web Page	30/04/2018	Edina
TANK11	Web Page	30/04/2018	ADE
TANK11	Brochure/advert	27/03/2018	Edina
TANK11	Web Page	30/04/2018	Guardian newspaper
TANK11	Web Page	30/04/2018	Committee on Climate Change

Project	Reference Type	Access Date	Producing organisation
ELECSTOR3	Web Page	14/02/2018	CityWest Homes
ELECSTOR3	Conference	17/01/2018	CityWest Homes
ELECSTOR3	Web Page	14/02/2018	ADE
ELECSTOR3	Web Page	14/02/2018	Energy Assets
TANK13	Report	10/05/2018	Coventry City Council
TANK13	Brochure/advert	10/05/2018	Engie
TANK13	Web Page	11/05/2018	Coventry & Warwickshire LEP
TANK13	Report	10/05/2018	Sustainability West Midlands
SOLAR1	News Article	09/04/2018	Building Research
SOLAR1	News Article	17/05/2018	EON
SOLAR1	Brochure/advert	17/05/2018	Exeter & East Devon Enterprise
SOLAR1	News Article	01/05/2018	Renewable Energy Focus
SOLAR1	News Article	17/05/2018	Exeter & East Devon Enterprise
SOLAR1	Web Page	17/05/2018	University of Exeter
SOLAR1	Pamphlet	17/05/2018	Solar Trade Association
SOLAR1	Planning	17/05/2018	Halcrow Group Ltd
SOLAR1	Web Page	17/05/2018	EON
HEATBATT1	Conference	17/05/2018	Sunamp
HEATBATT1	Report	08/05/2018	Sunamp
HEATBATT1	Web Page	08/05/2018	Local Energy Scotland
HEATBATT1	Web Page	16/05/2018	Energy Saving Trust
HEATBATT1	News Article	07/03/2018	BBC News
HEATBATT1	Web Page	16/05/2018	Energy Saving Trust
HEATBATT1	Web Page	08/05/2018	CIH Scotland
HEATBATT1	Conference	10/05/2018	Sunamp
HEATBATT1	Web Page	08/03/2018	Interface Knowledge
HEATBATT1	Conference	16/05/2018	Sunamp
HEATBATT1	Report	23/05/2018	Sunamp
HEATBATT1	News Article	02/05/2018	Solar Power Portal
GEOX1	Web Page	30/04/2018	Erda Energy
GEOX1	Web Page	30/04/2018	FridgeHub
GEOX1	Conference Paper	02/05/2018	Sainsburys (employee of)
GEOX1	Web Page	23/04/2018	Erda Energy
GEOX1	News Article	30/04/2018	FridgeHub
GEOX1	Interview	23/04/2018	Renewable Energy Magazine
GEOX1	Report	30/04/2018	Oxford University
GEOX1	Planning	14/05/2018	Synergy Building Services
TANK1	Web Page	27/02/2018	ADE
TANK1	Planning	07/03/2018	Parsons Brinckerhoff
TANK1	Web Page	14/02/2018	Gateshead Council

Project	Reference Type	Access Date	Producing organisation
TANK1	Planning	07/03/2018	Parsons Brinckerhoff
TANK1	Web Page	23/02/2018	Gateshead Council
TANK1	Web Page	14/02/2018	Gateshead Council
TANK1	Pamphlet	08/06/2018	ADE
TANK1	News Article	07/03/2020	the energyst
TANK1	Report	07/03/2018	Gateshead Council
TANK5	Audiovisual	22/05/2018	SHARC Energy Systems
TANK5	Web Page	22/05/2018	LCITP - Scottish government
TANK5	Web Page	23/05/2018	Clyde Gateway Urban
TANK5	Web Page	23/05/2018	SHARC Energy Systems
TANK5	Report	23/05/2018	Clyde Gateway Urban
TANK5	News Article	19/06/2018	SHARC Energy Systems
MINE1	Audiovisual	01/05/2018	The Coal Authority
MINE1	News Article	01/05/2018	Guardian newspaper
MINE1	Web Page	01/05/2018	British Geological Survey
MINE1	Report	23/05/2018	Clyde Gateway Urban
MINE1	News Article	23/05/2018	Glasgow Live
MINE1	Conference	24/05/2018	Newcastle University
MINE1	Web Page	01/05/2018	Durham University
TANK2	Audiovisual	11/05/2018	SHARC Energy Systems
TANK2	Report	19/06/2018	Glasgow City Council
TANK2	Web Page	11/05/2018	SHARC Energy Systems
TANK3	Web Page	20/02/2018	Kings Cross
TANK3	Web Page	20/02/2018	Camden Council
TANK3	Web Page	01/05/2018	Vital Energi
TANK3	Report	20/02/2018	Islington & Camden councils
TANK3	Brochure/advert	14/02/2018	Vital Energi
TANK3	Brochure/advert	14/02/2018	Metropolitan
TANK3	Brochure/advert	14/02/2018	Metropolitan
NETWORK1	Audiovisual	01/03/2018	Mitsubishi Electric
NETWORK1	Web Page	11/05/2018	24 Housing Awards
NETWORK1	Web Page	11/05/2018	CiBSE
NETWORK1	Web Page	02/03/2018	Inside Housing
NETWORK1	Web Page	11/05/2018	The Building Centre
NETWORK1	Conference	01/03/2018	Mitsubishi Electric
NETWORK1	Planning	11/05/2018	White Associates
TANK4	Report	11/06/2018	Leeds City Council
TANK4	Planning	23/02/2018	Vital Energi
TANK4	Planning	22/02/2018	Vital Energi
TANK4	Legal Rule or	23/02/2018	Leeds City Council

Project	Reference Type	Access Date	Producing organisation
TANK4	Web Page	23/02/2018	WYCA
TANK4	Report	23/02/2018	Leeds City Council
TANK4	News Article	11/06/2018	Leeds City Council
TANK4	Report	23/02/2018	Leeds City Council
TANK4	Web Page	23/02/2018	Leeds Enterprise Partnership
TANK4	Minutes of	23/02/2018	WYCA
TANK4	Report	23/02/2018	WYCA
TANK4	Report	23/02/2018	WYCA
GEOX2	Web Page	02/05/2018	Balanced Energy Networks
GEOX2	Web Page	02/05/2018	ICAX
GEOX2	Audiovisual	02/05/2018	Balanced Energy Networks
GEOX2	Web Page	02/05/2018	Upside Energy
GEOX3	Web Page	06/08/2018	ICAX
GEOX3	Planning	06/08/2018	Halcrow Yolles
GEOX3	Web Page	06/08/2018	ICAX
GEOX3	Planning	16/08/2018	ICAX
AQUIFER2	News Article	08/06/2018	Building4Chnge (part of BRE)
AQUIFER2	Web Page	08/06/2018	Royal Museums Greenwich
AQUIFER2	Web Page	08/06/2018	Green Tech Europe
AQUIFER2	Web Page	08/06/2018	European Ground Source Heat
AQUIFER2	Web Page	08/06/2018	IF Tech
AQUIFER2	Report	08/06/2018	Royal Museums Greenwich
AQUIFER2	Web Page	08/06/2018	Mott MacDonald
TANKCRYO1	Report	16/05/2018	Ofgem
TANKCRYO1	Web Page	17/05/2018	SSE - as DNO
TANKCRYO1	Report	16/05/2018	SSE - as DNO
TANKCRYO1	Report	17/05/2018	SSE - as DNO
TANKCRYO1	Conference	17/05/2018	SSE - as DNO
TANKCRYO1	Published letter	16/05/2018	Ofgem
TANK7	Planning	07/06/2018	Engie
TANK7	Planning	07/06/2018	Engie
TANK7	Web Page	07/06/2018	Science Central
TANK7	Web Page	07/06/2018	UK Government
TANK7	News Article	07/06/2018	The Chronicle
TANK8	Pamphlet	14/02/2018	City of Westminster
TANK8	Web Page	14/02/2018	CityWest Homes
TANK8	Published letter	14/02/2018	CityWest Homes
TANK9	Web Page	06/07/2018	East London Energy
TANK9	Web Page	12/03/2018	Engie
TANK9	Web Page	06/07/2018	Queen Elizabeth Olympic Park

Project	Reference Type	Access Date	Producing organisation
TANK9	Brochure/advert	12/03/2018	London Legacy Development
TANK9	Web Page	12/03/2018	CEEQUAL from BRE
AQUIFER5	Planning	28/02/2018	Boyer Planning
AQUIFER5	Brochure/advert	07/03/2018	SSE Enterprise
AQUIFER5	Web Page	07/03/2018	IF Tech
AQUIFER5	Web Page	07/03/2018	SSE Enterprise
CRYO2	Report	31/01/2018	Geothermal Communities
CRYO2	Web Page	02/05/2018	Engie
TANK10	Web Page	23/05/2018	Signal 2
TANK10	Planning	31/01/2019	GT Energy
TANK10	Press Release	23/05/2018	UK Government
TANK10	News Article	22/05/2018	City of Stoke-on-Trent
TANK10	Report	22/05/2018	Royal Town Planning Institute
TANK10	Report	23/05/2018	City of Stoke-on-Trent
TANK10	Web Page	23/05/2018	StokeStaffsLEP
ELECSTOR1	Report	31/01/2019	North Lanarkshire Council
ELECSTOR1	Published letter	21/03/2018	OVO Energy VCharge
ELECSTOR1	Conference	21/03/2018	OVO Energy VCharge
ELECSTOR1	Report	08/02/2019	LCITP - Scottish government
AQUIFER4	Web Page	07/03/2018	IF Tech
AQUIFER4	Planning	28/02/2018	Hoare Lea
AQUIFER1	Conference	02/05/2018	IF Tech
AQUIFER1	Web Page	22/03/2018	IF Tech
AQUIFER1	Web Page	08/06/2018	Gardner Stewart Architects
ELECSTOR2	Published letter	08/01/2018	OVO Energy VCharge
ELECSTOR2	Report	08/02/2019	National Energy Action
ELECSTOR2	Web Page	02/05/2018	National Energy Action
ELECSTOR2	Report	08/01/2018	OVO Energy VCharge

Appendix D Chapter 5 semi-structured interview script

Background to interviews

Local actors will be interviewed who represent a range of organisations which have developed or are in the process of developing one of A/B/C below:

A – Geoexchange (ground-coupled heating and cooling with seasonal balancing / seasonal balanced heating and cooling with centralised thermal storage)
B – Shared ground loop (ultra-low temperature heat network connecting 2 or more heat pumps)
C – District heating (traditional high-temperature heat network)

Interviewees will represent one of the following types of organisation:

- Municipality
- Registered social landlord
- Community-led development
- A private sector project partner
- Clean energy technology developer

A separate set of questions is provided for each below, tailored to the interviewee and the organisation they represent.

For all interviews

Introduction

- Introduction and thanks for agreeing to be interviewed.
- Confirm who is present (the interviewee may have other people present for a phone call).

Consent

- Can you confirm that you have read the information sheet and consent form?
- Do you have any questions about the information sheet or consent form?
- Are you happy for the interview to be recorded?

For a telephone interview, the consent form will be obtained via email prior to the start of the interview. For a face-to-face interview, two forms will be provided for signature: one for me to keep and one for the interviewee.

Interviewee representing: a local authority (example)

(Separate scripts were used for interviewees representing: geoexchange developers, social landlords, intermediaries, and community-led developers)

Background knowledge and understanding

1. Can you tell me about your organisation your role?
2. Can you tell me about the project you are working on?

- Ask them to describe the project
- The project story and how they got to where they are now
- Their experiences and the challenges they have faced

Enablers and barriers

3. What are your organisation's key drivers for developing A/B/C?

- Has this changed over time?
- Do you have a strategy around sustainable heating projects?

4. What are the key barriers to your organisation developing A/B/C projects?

- Prompt to discuss understanding, technical, economic, policy, behavioural
- Has this changed over time?

5. Who do you believe is best placed to develop A/B/C projects in your local area?

- Why is this?
- Has this changed over time?

Local energy actors

6. What do you see as the role of the local authority in unlocking development sustainable heating projects like A/B/C?

- Has this changed over time?
- What about the role of other

7. Do you provide support to other organisations who are seeking to develop A/B/C?

- If so, what form does this take?

8. Do you carry out any form of citizen/resident engagement in decisions about A/B/C? If so:

- What form does this take?
- What impact has this had on decisions made?

Business model

9. What delivery model have you used/are planning to use for A/B/C?

- Prompt if required with examples such as project in-house, third party management through an ESCo etc.
- Why have you chosen this model?
- Has this changed over time?

- What have been the main benefits and challenges of this model?

10. Tell me about funding and investment in the A/B/C project.

- How are you funding the initial investment?
- How do you (plan to) earn revenue from the project?
- What role does government funding have on your ability to develop A/B/C?
- Has this changed over time?

Local and national policy

11. Does national policy have any effect on your decisions about development of A/B/C?

- If yes, how?
- Has this changed over time?

12. Have local planning guidelines local planning guidelines had an impact on the development of A/B/C?

- Has this changed over time? If so, how?

Wrap up – all interviews

Any other issues that you would like to raise

Thank you for your help

Mention what is happening next and check if follow-up clarifications can be sought

Appendix E Chapter 5 ethical approval

The Secretariat
University of Leeds
Leeds, LS2 9JT
Tel: 0113 3434873
Email: ResearchEthics@leeds.ac.uk

UNIVERSITY OF LEEDS

David Barns
School of Chemical and Process Engineering
University of Leeds
Leeds, LS2 9JT

MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC)
University of Leeds

4 March 2019

Dear David

Title of study	**The role of local energy actors in supporting geoexchange**
Ethics reference	**MEEC 18-024**
Grant reference	**EPSRC 1958986**

I am pleased to inform you that the application listed above has been reviewed by the MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC) and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
MEEC 18-024 D_Barns_Ethical_Review_Form_v2_21-02-19(changes_tracked).doc	2	21/02/19
MEEC 18-024 D_Barns_Invitation_to_Interview_v2_19-02-19.docx	2	21/02/19
MEEC 18-024 D_Barns_Interviews_Participant_Information_Sheet_v2_19-02-19(changes_tracked).doc	2	21/02/19
MEEC 18-024 D_Barns_Interviews_consent_form_v1_28-01-19	1	01/02/19
MEEC 18-024 D_Barns_Indicative_interview_script_v1_28-01-19	1	01/02/19
MEEC 18-024 D_Barns_Workshop_Participant_Information_Sheet_v2_19-02-19(changes_tracked).doc	2	21/02/19
MEEC 18-024 D_Barns_Workshop_consent_form_v1_28-01-19	1	01/02/19
MEEC 18-024 D_Barns_Data_Management_Plan_v1_28-01-19	1	01/02/19

Please notify the committee if you intend to make any amendments to the information in your ethics application as submitted at date of this approval as all changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation and other documents relating to the study, including any risk assessments. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Dr Dawn Groves, Chair, MEEC FREC

CC: Student's supervisor(s)

Appendix F Chapter 5 'notice of change' ethical approval

From: On Behalf Of MEECResearchEthics
Sent: 10 July 2019 12:56
To: David Barns <D.G.Barns1@leeds.ac.uk>
Cc: MEECResearchEthics <MEECResearchEthics@leeds.ac.uk>
Subject: RE: MEEC 18-024 Notice of Change (1) - Confirmation

Dear David

MEEC 18-024 – NoC1 - The role of local energy actors in supporting geoexchange

With many apologies for the delay in responding due to annual leave.

Many thanks for your email. I can confirm the change to the withdrawal period does not pose any additional ethical issues to those already considered in the original application and as such can be considered as a 'Notice of Change' which can be implemented with immediate effect.

Please retain this email in your study file as evidence of approval to implement the change.

I hope the study goes well.

Best regards
Rachel

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Rachel de Souza, Research Ethics & Governance Administrator, The Secretariat, Room 9.29, Level 9, Worsley Building, Clarendon Way, University of Leeds, LS2 9NL, Tel: 0113 3431642, r.e.desouza@leeds.ac.uk
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Appendix G Chapter 5 participant information sheet

School of Chemical & Process Engineering

UNIVERSITY OF LEEDS

Participant Information Sheet – Research Interview

Project: The role of local energy actors in supporting geoexchange

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information and take time to decide whether or not you wish to take part.

What is the purpose of the project?

I am researching the potential for 'geoexchange' systems to deliver low carbon heating to cities in the UK and the role that local energy actors can play in this.

Geoexchange is a form of electrically-powered heating and cooling which comprises centralised thermal storage (typically via a borehole array), a distribution network (such as a shared loop ground array or a more traditional district heating network), and heat pumps (to raise the temperature to a suitable level to supply heating and hot water).

Local energy actors refers to those not traditionally involved in energy provision who operate at a local scale including representatives from local authorities, social landlords, community groups etc.

I would like to understand your experience of developing geoexchange and/or heat network projects.

Why have I been chosen?

You have been contacted because I believe that you may have relevant knowledge in this area. I hope to interview between 15-20 people in total to gather data.

What do I have to do?

I would be very grateful if you would help me with my research by taking part in a face-to-face or telephone interview. The interview should last between 45-60 minutes.

The interview style will contain open as well as closed questions and you will be encouraged to speak about any of the aspects of geoexchange or heat network development with which you have experience.

What are the possible disadvantages and risks of taking part?

You may be asked about financial or other information about projects that you feel to be commercially sensitive. This may be the cost of delivering a project or the funding received from third parties, for example. You are under no obligation to provide any information that you would prefer not to share, and you will not be required to give a reason. If after the interview you decide that any answer or information you provided may present a problem in this way, you are able to contact David Barns within 4 weeks of the date of your interview and the information will be struck from the record.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will facilitate the wider deployment of geoexchange systems and other low carbon heating infrastructure to support carbon reduction.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time up until your interview date. You do not have to give a reason.

Will my taking part in this project be kept confidential?

All information given in an interview will be treated with great care to avoid revealing the source of any data that may be sensitive. An audio recording will be made of your interview (if your permission is given) for the purposes of transcription, but will be erased after a transcript has been made.

During the course of the research data will be stored securely on the computer network at the University of Leeds, and the access will be restricted to the research team.

Names of interviewees will not be published. However as well as analysing the data I would like to use direct quotes from interviews in my thesis, academic presentations and papers. These comments will not include your name but will be identified by a relevant descriptor e.g. 'Local Authority officer 1 [LA1]' or 'Registered Social Landlord 1 [RSL1]', 'Clean Energy Company 1 [CAC1]'. This process is known as *pseudonymisation*. During the research I will retain a lookup table in order that I can identify you should you decide you want to withdraw from the study (see below) but this will be kept confidential. This lookup will be destroyed at the end of the research period and so the data will become fully anonymised.

There is a small risk that these descriptors together with the expressed view could be used to identify you, but I will try to ensure that this does not happen. If, after the interview, you decide that the answer you gave to a certain question may lead to your loss of anonymity, you can contact David Barns within 4 weeks of the date of your interview and this answer will be struck from the record.

Following the end of the research period, and line with best practice for publically-funded research, anonymised data will be shared with the University of Leeds Research Data Leeds Repository.

The storage and use of research data will comply with the Data Protection Act (1998), the Human Rights Act, and the University's Code of Practice on Data Protection.

What will happen to the results of the research project?

Findings from the study may be published in scientific journals and presented at conferences, and you will be offered a copy of the published results.

Withdrawing

You can withdraw at any point prior to the interview, and you don't need to give a reason. If you decide after the interview that you no longer wish your data to be used in the research project please notify me by within 4 weeks of the date of your interview and it will be withdrawn.

Complaints procedure

Should you have a complaint about the conduct of the researcher or any part of the research process, an independent complaints procedure can be followed by contacting:

Jennifer Blaikie
Senior Research Ethics Administrator
The Secretariat, University of Leeds
Leeds LS2 9JT
T: +44 (0113) 34 34873 | E: j.m.blaikie@leeds.ac.uk

Who is organising/ funding the research?

The research is being funded by the Engineering and Physical Science Research Council (EPSRC) under grant award 1958986.

Contact for further information

This research project is being carried out by David Barns, a PhD student in the University of Leeds School of Chemical and Process Engineering.

David Barns
Postgraduate Researcher
University of Leeds
School of Chemical and Process Engineering
Leeds LS2 9JT
T: +44 (0)113 343 7557 | E: D.G.Barns1@leeds.ac.uk

Supervisor contact details:
Prof Peter Taylor
E: P.G.Taylor@leeds.ac.uk

I would like to thank you for taking the time to read through this information.

You will be provided with a copy of this information sheet and a signed consent form to keep.

"This study has been reviewed and given a favourable opinion by University of Leeds MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC) on [01 March 2019], ethics reference [MEEC 18-024]"

Project title	*Document type*	*Version #*	*Date*
The role of local energy actors in supporting geoexchange	Participant information sheet – research interviews	3	18/06/2019

Appendix H Chapter 5 ethical consent form

School of Chemical and Process Engineering

UNIVERSITY OF LEEDS

Consent to take part in: Research interview, for 'The role of local energy actors in supporting geoexchange' Leeds, 2019	Add your initials next to the statement if you agree
I confirm that I have read and understand the information sheet dated 18/06/2019 explaining the above research project and I have had the opportunity to ask questions about the project.	
I understand that my participation is voluntary and that I am free to withdraw without giving any reason and without there being any negative consequences by contacting David Barns at d.g.barns1@leeds.ac.uk prior to the interview. I understand that if I decide after the interview that no longer wish my data to be used in the research project I can notify David Barns by **within 4 weeks of the date of your interview** and it will be withdrawn. In addition, should I not wish to answer any particular question or questions, I am free to decline.	
I give permission for members of the research team to have access to my pseudonymised responses. I understand that my name will not be linked with the research materials, and I will not be identified or identifiable in the report or reports that result from the research.	
I understand that at the end of the research period, anonymised data will be shared with the University of Leeds Research Data Leeds Repository. I understand that other researchers may use my words in publications, reports, web pages, and other research outputs, but these will not be identifiable to me following anonymisation.	
I understand that relevant sections of the data collected during the study may be looked at by auditors from the University of Leeds where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	
I agree to take part in the above research project.	

Name of participant		Name of lead researcher	David Barns
Participant's signature		Lead researcher's signature	
Date		Date*	

*To be signed and dated in the presence of the participant.
Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the letter/ pre-written script/ information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be kept with the project's main documents which must be kept in a secure location.

Project	*Document type*	*Version #*	*Date*
The role of local energy actors in supporting geoexchange	Research interview consent form	2	18/06/2019

Appendix I Geoexchange critical success factors framework

Framework element	Critical success factors
National direction and policy	- National decisions to pursue an electrified heat future - Implement changes to Building Regulations to reflect up-to-date carbon factors - Build evidence and influence to counter the prevailing discourse around grid impact of mass shift to electrified heat - Gap funding availability to support internal champions - Build technology awareness and encourage a vibrant marketplace
Local policies and support	- Local authorities to use of local planning policy to deprioritise gas in new build, with resource and political commitment to implement - Give greater powers for local authorities to set local policies - Local authorities to use powers to require up-to-date grid carbon factors in planning assessments - Organisations take decision to standardise their estate in line with highest local planning requirements - Local authorities to choose geoexchange for their own estate to build local niche
Organisational and business case	- Explore novel long-term business models which don't rely on haphazard national funding - Consider direct control of heating systems to provide heat-as-a-service within agreed parameters whilst earning income from the assets - Consider organisational restructuring to take geoexchange assets / costs out of normal development process into separate business unit - Consider non-financial and long-term benefits to residents in development of business case - Exploit counterfactual case to reduce effective cost where available - Exploit the benefit of a single decision-maker where available for retrofit projects - Consider how leaseholders can be supported to accept geoexchange - Explore synergies between different organisation units made possible by geoexchange - Consider how energy consultants can be engaged and persuaded

Technology aspects and system design	- Combine geoexchange with ambient heat networks (i.e. SGHE) to supply multiple residential units
	- Take an SGHE approach to:
	    - reduce heat losses and overheating
	    - better manage low occupancy levels
	    - not have to take on the role of energy retailer
	    - bring in a variety of waste heat sources to reduce costs and energy
	- Consider local competition for ground energy source
	- Consider how in-dwelling TES can be provided
	- Consider property efficiency standard and suitability for heat pump system

Installation and post-installation	- Consider installation process especially resident engagement for retrofit projects - Collect pre-installation energy bill evidence for later comparison - Maintain long-term interest in system operation and improvement

Appendix J Chapter 6 list of empirical data sources

Subcase	Source type	Date
ASHPCOMM1-1	Energy Strategy	08/01/2020
ASHPCOMM1-2	Energy Strategy	02/02/2020
ASHPCOMM1-3	Planning authority decision	13/11/2020
ASHPCOMM1-4	Planning authority committee minutes	24/06/2020
ASHPIND1-1	Sustainability statement	20/09/2018
ASHPIND1-2	Planning authority decision	24/05/2019
ASHPIND1-3	Sustainability statement	11/10/2017
ASHPIND1-4	Council team intervention	13/12/2017
ASHPIND1-5	Council team intervention	13/03/2018
ASHPIND1-6	Planning officer report	07/11/2018
ASHPIND1-7	Energy Strategy	27/03/2020
ASHPIND1-8	Sustainability statement	14/05/2020
ASHPIND1-9	Planning authority committee minutes	07/11/2018
CITYDH1-1	Planning authority decision	06/09/2018
CITYDH1-1	Sustainability statement	07/09/2017
CITYDH1-3	Sustainability statement	22/05/2017
CITYDH1-4	Energy Strategy	13/09/2017
CITYDH1-5	Sustainability statement	21/09/2017
CITYDH1-6	Planning officer report	20/12/2017
CITYDH-2	Energy Strategy	26/03/2019
CITYDH-3	Sustainability statement	26/03/2019
CITYDH-4	Planning officer report	22/10/20
CITYDH-5	Planning authority committee minutes	22/10/2020
DIRELEC1-1	Unassigned	17/12/2019
DIRELEC1-2	Unassigned	11/2019
DIRELEC1-3	Financial viability assessment	02/2020
DIRELEC1-4	Interview transcript	03/02/2021
DIRELEC2-1	Financial viability assessment	29/4/19
DIRELEC2-11	Planning authority committee minutes	02/09/2020
DIRELEC2-11	Council team intervention	26/10/2018
DIRELEC2-2	Financial viability assessment	18/02/2020
DIRELEC2-3	Energy Strategy	17/08/2018
DIRELEC2-4	Energy Strategy	22/09/2018
DIRELEC2-5	Council team intervention	23/02/21
DIRELEC2-6	Planning authority decision	17/03/2021
DIRELEC2-7	Planning officer report	24/02/2021
DIRELEC2-8	Council team intervention	27/11/18
DIRELEC2-9	Planning officer report	02/09/2020
DIRELEC3-1	Planning officer report	15/10/2015
DIRELEC3-2	Planning authority decision	15/06/2016
DIRELEC3-3	Planning officer report	25/06/2016

Subcase	Source type	Date
DIRELEC3-4	Sustainability statement	09/06/2015
DIRELEC3-5	Brochure	09/2020
DIRELEC3-6	Planning authority committee minutes	15/10/2015
DIRELEC3-7	News article	20/12/2019
DIRELEC3-8	Design & Access statement	09/06/2015
DIRELEC4-1	Energy Strategy	27/09/2019
DIRELEC4-2	Energy Strategy	09/09/2019
DIRELEC4-3	Energy Strategy	13/11/2019
DIRELEC4-4	Planning authority decision	18/02/2020
DIRELEC4-5	Energy Strategy	26/11/2019
DIRELEC4-6	Planning officer report	23/01/2020
DIRELEC4-7	Planning authority committee minutes	23/01/2020
DIRELEC4-8	Energy Strategy	19/12/19
DIRELEC4-9	Energy Strategy	10/01/2020
DIRELEC5-1	Planning authority decision	14/07/2016
DIRELEC5-10	Planning officer report	31/05/2018
DIRELEC5-11	News article	05/09/2020
DIRELEC5-12	Brochure	2018
DIRELEC5-13	News article	19/01/2021
DIRELEC5-14	Design & Access statement	01/2018
DIRELEC5-15	Energy Strategy	15/01/2018
DIRELEC5-16	Planning authority committee minutes	24/03/2016
DIRELEC5-17	Planning authority committee minutes	31/05/2018
DIRELEC5-2	Planning authority committee minutes	24/03/2016
DIRELEC5-3	Energy Strategy	16/11/2015
DIRELEC5-4	Sustainability statement	11/11/2015
DIRELEC5-5	Planning application form	30/01/2018
DIRELEC5-6	Planning authority decision	02/08/2018
DIRELEC5-7	Planning officer report	02/08/2018
DIRELEC5-8	Energy Strategy	15/01/2018
DIRELEC5-9	Planning officer report	31/05/2018
DIRELEC6-1	Design & Access statement	27/09/2017
DIRELEC6-10	Planning authority committee minutes	31/10/2019
DIRELEC6-2	Planning authority decision	13/07/2018
DIRELEC6-3	Planning officer report	02/11/2017
DIRELEC6-4	Design & Access statement	24/05/2017
DIRELEC6-5	Planning authority decision	28/05/2020
DIRELEC6-6	Energy Strategy	15/07/2019
DIRELEC6-7	Energy Strategy	13/08/2019
DIRELEC6-8	Planning officer report	31/10/2019
DIRELEC6-9	Planning authority committee minutes	02/11/2017
DIRELEC7-1	Sustainability statement	02/2005
DIRELEC7-2	Planning authority decision	08/02/2021

Subcase	Source type	Date
DIRELEC7-3	Planning officer report	28/01/2021
DIRELEC7-4	Energy Strategy	16/09/2020
DIRELEC7-5	Sustainability statement	16/09/2020
DIRELEC7-6	Planning officer report	16/04/2015
DIRELEC7-7	Planning authority committee minutes	28/01/2021
DIRELEC8-1	Planning authority decision	26/10/2017
DIRELEC8-2	Planning officer report	26/10/2017
DIRELEC8-3	Design & Access statement	07/03/2017
DIRELEC8-4	Energy Strategy	14/02/2020
DIRELEC8-5	Planning authority decision	28/05/2020
DIRELEC8-6	Energy Strategy	25/11/2020
DIRELEC8-7	Planning authority decision	29/01/2021
DIRELEC8-8	Energy Strategy	25/11/2020
GASCOMM1-1	Planning authority decision	01/03/2019
GASCOMM1-2	Planning officer report	27/02/2019
GASCOMM1-3	Council team intervention	21/09/2018
GASCOMM1-4	Sustainability statement	12/06/2018
GASCOMM1-5	Planning authority decision	27/02/2020
GASCOMM1-6	Energy Strategy	01/05/2019
GASCOMM1-7	Council team intervention	23/09/2019
GASCOMM1-8	Planning officer report	16/10/2019
GASCOMM2-1	Energy Strategy	01/2020
GASCOMM2-2	Energy Strategy	04/01/2019
GASCOMM2-3	Energy Strategy	02/2020
GASCOMM2-4	Council team intervention	14/02/2019
GASCOMM2-5	Council team intervention	04/03/2020
GASCOMM2-6	Planning officer report	29/04/2020
GASCOMM2-7	Planning authority committee minutes	29/04/2020
GASCOMM4-1	Planning officer report	21/11/2019
GASCOMM4-10	Financial viability assessment	11/11/2019
GASCOMM4-2	Energy Strategy	13/02/2019
GASCOMM4-3	Energy Strategy	15/03/2019
GASCOMM4-4	Planning authority decision	11/03/2021
GASCOMM4-5	Design & Access statement	18/03/2019
GASCOMM4-6	Interview transcript	04/02/2021
GASCOMM4-7	Planning officer report	12/03/2020
GASCOMM4-8	Planning authority committee minutes	12/03/2020
GASCOMM4-9	Planning authority committee minutes	21/11/2019
GASCOMM5-1	Planning authority decision	20/09/2018
GASCOMM5-10	Brochure	2020
GASCOMM5-2	Planning officer report	10/10/2017
GASCOMM5-3	Council team intervention	25/09/2017
GASCOMM5-4	Energy Strategy	15/07/2017

Subcase	Source type	Date
GASCOMM5-5	Planning officer report	18/10/2017
GASCOMM5-6	Planning conditions	16/04/2019
GASCOMM5-7	Energy Strategy	16/04/2019
GASCOMM5-8	Energy Strategy	16/04/2019
GASCOMM5-9	Planning authority committee minutes	18/10/2017
GEOX1-1	Design & Access statement	05/12/2017
GEOX1-10	News article	19/08/2019
GEOX1-11	Website	11/09/2018
GEOX1-12	News article	21/08/2019
GEOX1-13	Website	2020
GEOX1-14	Interview transcript	02/09/2020
GEOX1-15	Planning authority committee minutes	04/04/2018
GEOX1-16	Interview transcript	08/01/2021
GEOX1-17	Interview transcript	26/08/2020
GEOX1-18	Website	20/08/2019
GEOX1-19	Website	2020
GEOX1-2	Energy Strategy	23/03/2018
GEOX1-20	Planning authority decision	10/09/2018
GEOX1-3	Planning authority decision	30/05/2018
GEOX1-4	Council team intervention	16/03/2018
GEOX1-5	Planning officer report	04/04/2018
GEOX1-6	Sustainability statement	23/03/2018
GEOX1-7	Council team intervention	02/02/2018
GEOX1-8	Planning officer report	01/04/2018
GEOX1-9	Energy Strategy	25/07/2018
GEOX2-1	Planning application form	27/09/2019
GEOX2-10	Interview transcript	05/02/2021
GEOX2-2	Energy Strategy	09/2019
GEOX2-3	Planning authority decision	09/02/2021
GEOX2-4	Planning officer report	13/05/2020
GEOX2-5	Energy Strategy	01/2020
GEOX2-6	Note	02/02/2021
GEOX2-7	Planning officer report	01/05/2020
GEOX2-8	Planning authority committee minutes	13/05/2020
GEOX2-9	Interview transcript	02/02/2021
GEOX3-1	Planning authority decision	20/01/2011
GEOX3-2	Design & Access statement	07/02/2008
GEOX3-3	News article	11/08/2008
GEOX3-4	Brochure	05/2006
GEOX3-5	Planning application form	07/02/2008
GEOX4-1	Planning authority decision	26/04/2019
GEOX4-2	Planning officer report	05/09/2018
GEOX4-3	Energy Strategy	16/03/2018

Subcase	Source type	Date
GEOX4-4	Council team intervention	30/05/2018
GEOX4-5	Energy Strategy	10/05/2019
GEOX4-6	Council team intervention	08/07/2019
GEOX4-7	Planning authority committee minutes	05/09/2018
GEOX5-1	Energy Strategy	27/03/2017
GEOX5-2	Sustainability statement	27/03/2017
GEOX5-3	Planning officer report	16/08/2017
GEOX5-4	Planning authority decision	14/03/2019
GEOX5-5	Energy Strategy	30/04/2019
GEOX5-6	Planning authority decision	05/09/2019
GEOX5-7	Planning authority committee minutes	27/09/2017
GEOX5-8	Website	Unassigned
GEOX5-9	Website	27/03/2020
GEOX6-1	Planning authority decision	08/01/2019
GEOX6-10	Energy Strategy	15/09/2017
GEOX6-11	Planning authority decision	29/05/2019
GEOX6-12	Planning officer report	21/12/2017
GEOX6-2	Council team intervention	02/11/2018
GEOX6-3	Energy Strategy	15/09/2017
GEOX6-4	Planning authority decision	21/12/2017
GEOX6-5	Sustainability statement	09/2017
GEOX6-6	Council team intervention	08/12/2017
GEOX6-7	Planning officer report	29/05/2019
GEOX6-8	Design & Access statement	31/07/2018
GEOX6-9	Sustainability statement	07/2018
INDGAS2-1	BREEAM Communities statement	28/09/2016
INDGAS2-2	Energy Strategy	09/2016
INDGAS2-3	Planning authority decision	02/02/2018
INDGAS2-4	Planning officer report	12/07/2017
INDGAS2-5	Planning authority committee minutes	12/07/2017
INDGAS3-1	Energy Strategy	10/06/2019
INDGAS3-2	Design & Access statement	11/2018
INDGAS3-3	Planning authority decision	26/08/2020
INDGAS3-4	Sustainability statement	17/12/2018
INDGAS3-5	Energy Strategy	17/02/2021
INDGAS3-6	Planning officer report	12/03/2020
INDGAS3-7	Planning authority committee minutes	12/03/2020
LA1-1	Report	10/2018
LA1-10	Interview transcript	10/12/2020
LA1-11	Planning officer report	09/2019
LA1-12	Report	29/10/2020
LA1-13	Planning Inspector correspondence	07/04/2020
LA1-14	Planning Inspector correspondence	07/04/2020

Subcase	Source type	Date
LA1-15	News article	16/04/2018
LA1-16	News article	02/08/2019
LA1-17	News article	02/08/2019
LA1-18	Planning authority committee minutes	26/09/2019
LA1-2	Planning policy supporting note	07/2020
LA1-3	Strategic (non-planning) policy	16/07/2019
LA1-4	Planning policy document	06/2011
LA1-5	Planning policy document	03/2019
LA1-6	Strategic (non-planning) policy	14/09/2020
LA1-7	Interview transcript	25/01/21
LA1-8	Strategic (non-planning) policy	02/2020
LA1-9	Planning authority committee minutes	14/09/2020
LA2-1	Planning policy document	Unassigned
LA2-10	Planning policy supporting note	2015
LA2-11	Report	2019
LA2-12	Planning policy document	04/09/2019
LA2-13	Planning Inspectorate review	27/08/2019
LA2-14	Planning policy document	01/2020
LA2-15	Planning policy document	03/11/2020
LA2-16	Planning authority committee minutes	03/11/2020
LA2-17	Planning authority committee minutes	12/11/2019
LA2-18	Report	07/01/2020
LA2-19	Planning policy document	18/05/2021
LA2-2	Report	12/11/2019
LA2-20	Planning authority committee minutes	18/05/2021
LA2-21	Planning authority committee minutes	02/03/2021
LA2-22	Planning authority committee minutes	02/03/2021
LA2-23	Email from study participant	10/05/2021
LA2-24	Planning policy supporting note	2019
LA2-26	Planning authority committee minutes	08/09/2020
LA2-27	Planning officer report	08/09/2020
LA2-28	Report	2020
LA2-29	Video recording of meeting	08/09/2020
LA2-3	Report	07/01/2020
LA2-30	Planning officer report	13/10/2020
LA2-31	Planning officer report	13/10/2020
LA2-32	Report	03/11/2020
LA2-33	Legislation	26/03/2015
LA2-34	Planning policy supporting note	08/2011
LA2-35	Planning policy supporting note	06/2020
LA2-36	Planning policy supporting note	20/04/2017
LA2-37	Planning authority committee minutes	29/07/2020
LA2-38	Planning policy document	18/05/2021

Subcase	Source type	Date
LA2-39	Planning policy document	18/05/2021
LA2-4	Planning policy document	11/09/2019
LA2-40	Report	11/2017
LA2-41	Report	27/05/2021
LA2-42	News article	23/06/2021
LA2-43	News article	28/06/2021
LA2-44	Strategic (non-planning) policy	27/03/2019
LA2-5	Planning policy document	10/2019
LA2-6	Report	17/04/2019
LA2-7	Report	2017
LA2-8	Interview transcript	14/01/2021
LA2-9	Strategic (non-planning) policy	10/2016
PASSIVE1-1	Energy Strategy	09/08/2016
PASSIVE1-10	Website	2021
PASSIVE1-2	Planning authority decision	25/10/2016
PASSIVE1-3	Sustainability statement	18/04/2016
PASSIVE1-4	Planning authority decision	24/01/2019
PASSIVE1-5	Sustainability statement	03/12/2018
PASSIVE1-6	Planning application form	06/10/2016
PASSIVE1-7	Planning authority committee minutes	06/10/2016
PASSIVE1-8	Planning officer report	06/10/2016
PASSIVE2-1	Sustainability statement	17/04/2015
PASSIVE2-10	Planning conditions	11/06/2015
PASSIVE2-11	Planning application form	14/05/2015
PASSIVE2-12	Interview transcript	22/02/2021
PASSIVE2-13	Planning authority committee minutes	11/06/2015
PASSIVE2-14	Planning authority committee minutes	14/05/2015
PASSIVE2-2	Planning officer report	11/06/2015
PASSIVE2-3	Planning authority decision	04/08/2015
PASSIVE2-4	Sustainability statement	02/02/2015
PASSIVE2-5	Planning officer report	04/01/2018
PASSIVE2-6	Planning authority decision	29/06/2018
PASSIVE2-7	Sustainability statement	20/12/2017
PASSIVE2-8	Sustainability statement	16/02/2021
PASSIVE2-9	Sustainability statement	03/11/2020
PASSIVE3-1	Planning authority decision	29/10/2013
PASSIVE3-2	Planning authority decision	26/05/2011
PASSIVE3-3	Design & Access statement	07/03/2011
PASSIVE3-4	Planning officer report	26/05/2011
PASSIVE3-5	Energy Strategy	12/2020
PASSIVE3-6	Review of heating systems	12/2020
PASSIVE3-7	Energy Strategy	03/2011
PASSIVE3-8	Interview transcript	06/05/2021

Subcase	Source type	Date
SGHE7-1	News article	17/06/2020
SGHE7-10	Report	28/05/2020
SGHE7-11	Report	14/07/2020
SGHE7-2	Report	09/04/2020
SGHE7-3	Note	05/07/2020
SGHE7-4	Planning officer report	20/04/2020
SGHE7-5	Report	16/10/2020
SGHE7-6	Report	26/11/2020
SGHE7-7	Report	05/03/2021
SGHE7-8	Website	19/05/2021
SGHE7-9	Report	18/09/2019
SGHE8-1	Planning authority decision	23/09/2010
SGHE8-10	News article	20/09/2009
SGHE8-11	News article	02/04/2014
SGHE8-12	Social media post	28/08/2010
SGHE8-13	Social media post	28/08/2010
SGHE8-14	Social media post	28/08/2010
SGHE8-2	Planning application form	31/03/2005
SGHE8-3	News article	10/01/2011
SGHE8-4	News article	29/07/2011
SGHE8-5	News article	29/03/2019
SGHE8-6	News article	02/03/2011
SGHE8-7	Planning authority decision	12/06/2006
SGHE8-8	Design & Access statement	23/09/2010
SGHE8-9	Article	07/2015
GOV-1	Central government policy	10/2019
GOV-2	Central government policy	10/2019
GOV-3	Carbon assessment methodology	09/2019
GOV-4	Written Ministerial Statement	25/03/2015
GOV-5	National building regulation	05/04/2018
GOV-6	Carbon assessment methodology	06/2014
GOV-7	Carbon assessment methodology	24/07/2018
UNKNOWN1-1	Planning authority decision	20/10/2017
UNKNOWN1-2	Energy Strategy	31/08/2017
UNKNOWN1-3	Planning authority committee minutes	14/09/2017
UNKNOWN1-4	Planning officer report	14/09/2017

Appendix K Chapter 6 ethical approval

David Barns

From:	John Hardy on behalf of EPSResearchEthics
Sent:	12 June 2020 15:46
To:	David Barns
Cc:	EPSResearchEthics; Peter Taylor
Subject:	LTSCPE-004 - Conditional Approval

Dear David,

LTSCPE-004 - Exploring the urban energy transition for heat through low carbon innovative technologies

I am pleased to inform you that the above research ethics application has been reviewed by Engineering and Physical Sciences Research Ethics Committee and on behalf of the Chair, I can confirm a conditional favourable ethical opinion based on the documentation received at date of this email and *subject to the following condition/s which must be fulfilled prior to the study commencing:*

1) Ensure the projects *meets EPSRC grant compliance* requirements to have a Data Management Plan (DMP) as part of their in-project documentation. This will support activity to deposit data in a trusted data repository eg. the Institutional Data Repository to be consented for and as indicated on the ethical review form. Further advice and assistance is available at researchdataenquiries@leeds.ac.uk.

The study documentation must be amended where required to meet the above conditions and submitted for file and possible future audit.

Once you have addressed the conditions and submitted for file/future audit, you may commence the study and further confirmation of approval is not provided.

Please note, failure to comply with the above conditions will be considered a breach of ethics approval and may result in disciplinary action.

Please retain this email as evidence of conditional approval in your study file.

Please notify the committee if you intend to make any amendments to the original research as submitted and approved to date. This includes recruitment methodology; all changes must receive ethical approval prior to implementation. Please see https://leeds365.sharepoint.com/sites/ResearchandInnovationService/SitePages/Amendments.aspx or contact the Research Ethics & Governance Administrator for further information EPSResearchEthics@leeds.ac.uk if required.

Ethics approval does not infer you have the right of access to any member of staff or student or documents and the premises of the University of Leeds. Nor does it imply any right of access to the premises of any other organisation, including clinical areas. The committee takes no responsibility for you gaining access to staff, students and/or premises prior to, during or following your research activities.

Please note: You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, risk assessments and other documents relating to the study. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited.

It is our policy to remind everyone that it is your responsibility to comply with Health and Safety, Data Protection and any other legal and/or professional guidelines there may be.

I hope the study goes well.

Best regards
John Hardy
On behalf of Matthew Campbell, Chair EPS FREC

John Hardy
Research Ethics & Governance Administrator
The Secretariat,
University of Leeds, LS2 9LT

Appendix L Chapter 6 ethical consent form

School of Chemical and Process Engineering

UNIVERSITY OF LEEDS

Consent to take part in: Research interview, for 'Exploring the urban energy transition for heat through low carbon innovative technologies' Leeds, 2020	Add your initials next to the statement if you agree
I confirm that I have read and understand the information sheet dated 09/04/2020 explaining the above research project and I have had the opportunity to ask questions about the project.	
I understand that my participation is voluntary and that I am free to withdraw without giving any reason and without there being any negative consequences by contacting David Barns at d.g.barns1@leeds.ac.uk prior to the interview. I understand that if I decide after the interview that no longer wish my data to be used in the research project, I can notify David Barns by **within 4 weeks of the date of your interview** and it will be withdrawn. In addition, should I not wish to answer any particular question or questions, I am free to decline.	
I understand that my name will not be published but that I may be identifiable in the report or reports that result from the research.	
I understand that at the end of the research period, anonymised data will be shared with the University of Leeds Research Data Leeds Repository. I understand that other researchers may use my words in publications, reports, web pages, and other research outputs, but I will not be identified by name.	
I understand that relevant sections of the data collected during the study may be looked at by auditors from the University of Leeds where it is relevant to my taking part in this research. I give permission for these individuals to have access to my records.	
I agree to take part in the above research project.	

Name of participant		Name of lead researcher	David Barns
Participant's signature		Lead researcher's signature	
Date		Date*	

*To be signed and dated in the presence of the participant.
Once this has been signed by all parties the participant should receive a copy of the signed and dated participant consent form, the letter/ pre-written script/ information sheet and any other written information provided to the participants. A copy of the signed and dated consent form should be kept with the project's main documents which must be kept in a secure location.

Project	*Document type*	*Version #*	*Date*
Exploring the urban energy transition for heat through low carbon innovative technologies	Research interview consent form	1	09/04/2020

Appendix M Chapter 6 participant information sheet

School of Chemical & Process Engineering

UNIVERSITY OF LEEDS

Participant Information Sheet – Research Interview

Project: Exploring the urban energy transition for heat through low carbon innovative technologies

You are being invited to take part in a research project. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information and take time to decide whether or not you wish to take part.

What is the purpose of the project?

I am researching the potential for 'geoexchange' systems to deliver low carbon heating to cities in the UK. Geoexchange is a form of heating and cooling which comprises centralised thermal storage (typically via a borehole array) and usually involves a distribution network (such as an ambient loop combined with heat pumps).

Specifically, my research is exploring why projects including new developments and retrofit schemes in two cities (Leeds and Bristol) which include these innovative approaches may succeed or fail, or why such technologies are not specified in the first place.

As part of this I would like to explore and how these technologies interact with other aspects of the city 'selection environment' such as the local planning system. I would like to understand your experience of the development of projects in Leeds or Bristol with the aim of producing real-world outcomes to help cities in their journey to net zero carbon.

Why have I been chosen?

You have been contacted because I believe that you may have relevant knowledge in this area.

What do I have to do?

I would be very grateful if you would help me with my research by taking part in a face-to-face or telephone interview. The interview should last around 45 mins.

The interview style will contain open as well as closed questions and you will be encouraged to speak about any of the aspects of geoexchange or heat network development with which you have experience.

What are the possible disadvantages and risks of taking part?

You will not be named in the reporting of the research findings and any quotes used will be given via a pseudonym such as 'Housing Developer 1 [HD1]'. There is a possibility that because of the small numbers of people in the field, you could be identified. Whilst you will be encouraged to speak freely about the project or projects you have been involved in, you are under no obligation to provide any information that you would prefer not to share, and you will not be required to give a reason. If after the interview you decide that any answer or information you provided may present a problem in this way, you are able to contact me within 4 weeks of the date of your interview and the information will be struck from the record.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will facilitate the wider deployment of geoexchange systems and other low carbon heating infrastructure to support carbon reduction.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep (and be asked to sign a consent form) and you can still withdraw at any time up until your interview date. You do not have to give a reason.

Will my taking part in this project be kept confidential?

All information given in an interview will be treated with great care to avoid revealing the source of any data that may be sensitive. An audio recording will be made of your interview (if your permission is given) for the purposes of transcription but will be erased after a transcript has been made.

During the research, data will be stored securely on the computer network at the University of Leeds, and the access will be restricted to the researcher.

Names of interviewees will not be published. However, as well as analysing the data I would like to use direct quotes from interviews in my thesis, academic presentations and papers. These comments will not include your name but will be identified by a relevant descriptor e.g. 'Local Authority 1 [LA1]' or 'Registered Social Landlord 1 [RSL1]', 'Housing Developer 1 [HD1]'. There is a risk that these descriptors together with the expressed view could be used to identify you. You can contact me within 4 weeks of the date of your interview and any answer you have provided, or the whole interview, will be struck from the record.

Following the end of the research period, and line with best practice for publically-funded research, anonymised data will be shared with the University of Leeds Research Data Leeds Repository.

The storage and use of research data will comply with the Data Protection Act (1998), the Human Rights Act, and the University's Code of Practice on Data Protection.

What will happen to the results of the research project?

Findings from the study may be published in scientific journals and presented at conferences, and you will be offered a copy of the published results.

Withdrawing

You can withdraw at any point prior to the interview, and you don't need to give a reason. If you decide after the interview that you no longer wish your data to be used in the research project, please notify me by within 4 weeks of the date of your interview and it will be withdrawn.

Complaints procedure

Should you have a complaint about the conduct of the researcher or any part of the research process, an independent complaints procedure can be followed by contacting:

Clare Skinner
Head of Research Integrity and Governance
The Secretariat, University of Leeds
Leeds LS2 9JT
T: +44 (0113) 34 34897 | E: c.e.skinner@leeds.ac.uk

Who is organising/ funding the research?

The research is being funded by the Engineering and Physical Science Research Council (EPSRC) under grant award 1958986.

Contact for further information

This research project is being carried out by David Barns, a PhD student in the University of Leeds School of Chemical and Process Engineering.

David Barns
Postgraduate Researcher
University of Leeds
School of Chemical and Process Engineering
Leeds LS2 9JT
E: D.G.Barns1@leeds.ac.uk

Supervisor contact details:
Prof Peter Taylor
E: P.G.Taylor@leeds.ac.uk

I would like to thank you for taking the time to read through this information.

You will be provided with a copy of this information sheet and a signed consent form to keep.

This study has been reviewed and given a favourable opinion by University of Leeds MEEC (Faculties of Maths, Engineering & Physical Sciences) Research Ethics Committee on 12/06/2020, ethics reference LTSCPE-004

Project title	*Document type*	*Version #*	*Date*
Exploring the urban energy transition for heat through low carbon innovative technologies	Participant information sheet – research interviews	1	09/04/2020

Appendix N Chapter 6 semi-structured interview script

Background to interviews

This research project takes the form of a comparative case study of two UK cities and will investigate how the municipal regime is favourable or otherwise to the development of low carbon heating projects and why projects are more likely to succeed in some locations. Within each case city, several subcases will be chosen for investigation. These subcases are housing developments (either new build or retrofit projects).

Interviewees will likely represent one of the following types of organisation:

- Local authority
- Housing developer
- Registered social landlord
- Community-led development

The research interviews are intended to complement documentary evidence to complete missing information and explore motivations behind decisions to include or not include geoexchange or other sustainable heating technologies. The format of the interviews will be semi-structured but because each subcase will be different, and the set of questions on which the interview will be based will be tailored to the specific circumstances of that development. A set of questions has been provided below for a real case [descriptor B1] such that a review of the types of questions that will be asked in all interviews can be made.

For all interviews

Introduction

- Introduction and thanks for agreeing to be interviewed.
- Confirm who is present (the interviewee may have other people present for a phone call).

Consent

- Can you confirm that you have read the information sheet and consent form?
- Do you have any questions about the information sheet or consent form?
- Are you happy for the interview to be recorded?

Interview for sub-case B1 (example)

Project details

In this case a housing development is under construction and includes geoexchange heating combined with an ambient loop heat network to supply heat energy to the dwellings. An investigation in to the project history has revealed that when it was submitted to the planning authority, natural gas boilers in every dwelling were specified. Planning authority officers had instructed the developer to investigate more sustainable options and the developer submitted a revised planning application which featured other sustainable measures, but the heating option specified was still natural gas. The project was approved for development. A significant amount of documentary evidence around the subcase has been gathered including information on the more sustainable system that is currently under installation. No evidence is available about the change in approach, however. In this case the interview or interviews would be undertaken to find out when this change was made, what the drivers were behind this change, whether this was due to local or national policy changes, or further instruction from the planning authority which is not documented etc.

Interview questions for interviewee representing the project developer in subcase B1

As a semi-structured interview these questions are a guide only and the interview will be conducted in a conversational manner to encourage open discussion

1. Can you tell me about your organisation and your role?
2. Can you tell me about the project [subcase B1]?
3. Can you describe why natural gas heating was chosen as the specified heating option in the initial panning application?
4. Were any alternative options explored at this stage? Can you remember what these were and why they were not pursued?
5. Could you explain if local or national planning policies affected the decision?
6. Can you describe the dialogue with the Sustainable Cities team? Did this have any impact on your decision?
7. When was the decision made to change from the specified option to geoexchange heating? Can you discuss who was involved in that decision and what were the min drivers behind that change at the time?
8. Can you expand on how that change in direction was managed? What were the main challenges, and did you have to deal with any opposition around the change?
9. Can you suggest what would help other developers in your situation to choose sustainable options such as geoexchange?
10. What kinds of projects are you developing in other areas? Have you adopted similar geoexchange approaches or are you likely to in the future?
11. What could the local council / planning authority that would support the earlier choice of geoexchange types of systems?

Wrap up – all interviews

Are there any other issues that you would like to raise?

Thank you for your help

Mention what is happening next and check if follow-up clarifications can be sought

Appendix O Chapter 6 subcase descriptions and timelines

Identifier	Subcase description	Timeline
Bristol subcases		
SGHE1	New development of 133 homes by partnership of local authority and private developer. SGHE chosen after initial specification of individual and communal gas boilers.	2018-2019
CITYDH1	New development of 375 homes by private developer. Site-wide communal heat network, future connection to city-DH scheme, with local authority providing temporary plant until connected.	2017-2018
DIRELEC1	New development of 158 homes by private developer. Direct electric panel heaters chosen, with addition of hot water heat pumps at revised stage.	2019-current
SGHE2	Community-led regeneration of 120 homes and community facilities. SGHE with micro ambient heat network for 62 dwellings with ASHP for remaining following initial direct electric panel heaters.	2019-2021
SGHE3	Retrofit development of existing factory site by private developer of 442 homes and 17 live/work units. SGHE supplemented by a biomass boiler.	2008-2012
SGHE4	Regeneration scheme for 350 homes initially by local authority then private developer. SGHE following initial gas CHP and biomass with communal network.	2018-2019
DIRELEC2	New development of 146 homes by Registered Provider. Direct electric heating with 25 individual ASHP. Planning permission refused, failure to meet heat hierarchy cited.	2018-2021
GASCOMM1	Large mixed development of 1,435 homes with offices, education, community buildings by private developer. Communal heat network with gas CHP and biomass boiler preferred option.	2018-2020
ASHPCOMM1	New build development of 173 homes by private developer. ASHP with communal heat network, future connection to city DH with individual ASHP for houses.	2020
GASCOMM3	New development of 261 homes by private developer. Communal heat network fired by gas boiler for apartments and with individual gas boilers for houses.	2017-2019
INDGAS1	Development comprising retrofit and new build elements for 306 homes by private developer in partnership with local authority and Registered Provider. Individual gas boilers approved.	2016-2018
SGHE5	New development of 49 homes by community land trust with owner self-finish. SGHE specified after ASHP proposed as original technology.	2017-2019
SGHE6	New development of 33 retirement homes by private developer. SGHE specified, planning refused	2017-2019

Identifier	Subcase description	Timeline
GASCOMM2	Retrofit and new development of 46 homes and commercial space by private developer. Gas-fired heat network for later connection to city DH. Changed from individual gas boilers following threat to refuse permission.	2019-2020
ASHPIND1	New development of 33 homes by community-led developer. Initial option for owners to install gas boilers ruled out following intervention, replaced with direct electric heating for flats and individual ASHPs for houses.	2017-2020
Leeds subcases		
DIRELEC3	New development of 76 homes and commercial space by private developer. Planning application specified gas CHP with communal network. No discharge of conditions or intervention, brochure shows direct electric panel heaters.	2015-2016
DIRELEC4	New development of sheltered and general needs housing by Registered Provider. Direct electric panel heaters. Intervention to enforce carbon emissions reduction policy.	2019-2020
SGHE8	Retrofit development of 172 homes by private developer with shared facilities and office space. SGHESGHE and solar thermal. No intervention.	2005-2010
GASCOMM4	New development of 263 apartments and houses by private developer. Gas CHP with communal heat network. No intervention. Approved at initial submission.	2019-2021
DIRELEC5	Large new private development of 1,367 build-to-rent apartments and student flats. Initial heating gas CHP with communal and direct electric for phase one. Direct electric for phase two. No intervention.	2015-current
CITYDH2	New development of 322 homes and commercial space by private developer. Gas CHP with communal heat network and ready for connection to city DH. No intervention.	2019-2020
PASSIVE1	New development of 204 homes with commercial space by private developer (with modern methods of construction model and transfer to community ownership). Passive heat with high fabric efficiency.	2016-2019
SGHE7	Retrofit heating of 120 apartments in two blocks by local authority. SGHESGHE. Planned as exemplar for further retrofit rollout.	2020-2021
DIRELEC6	New residential development of 101 apartments by private developer. Direct electric heat, following initial specification of hot water heat recovery. No intervention	2017-2020
UNKNOWN1	New community-led development of 59 dwellings including cohousing self-build and over 55s. No heating type specified. No intervention	2017
PASSIVE2	New development of 312 apartments and houses by private developer (MMC model and transfer to community ownership). Passive heat through high fabric efficiency. No intervention.	2015-2018

Identifier	Subcase description	Timeline
DIRELEC7	New development of 213 homes by private developer. ASHP for communal hot water, direct electric for heating, gas boilers for houses. No intervention.	2005 (outline) – 2021
DIRELEC8	New development of 23 supported living apartments by religious organisation. ASHP for communal areas, direct electric heating for dwellings. Intervention to refuse initial strategy.	2017-2021
PASSIVE3	Community-led development of 23 homes with straw bale construction. Mainly passive heating through high fabric efficiency, with solar thermal hot water and gas boiler for top-up.	2011
INDGAS2	Large residential scheme of 431 homes by private developer. Individual gas boilers, no intervention.	2018-2021