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Heat and the planning system: how can local authorities encourage deployment of low and zero-carbon heating?

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There is widespread recognition of the need for new homes to feature only low or zero-carbon (LZC) heating. However, residential developers continue to choose conventional high-carbon options such as natural gas boilers over net-zero compatible alternatives. This study explores how UK local authorities (LAs) within the English planning system can encourage residential developers to deploy LZC heating systems within their projects. We adopt an embedded case study design and analyse 30 residential project proposals within two LA areas. Our study examines local planning policies and interactions between developers and LA officers, along with the resultant outcomes, through documentary analysis and expert interviews with local stakeholders. We find that LAs can encourage developers to adopt LZC heating technologies above and beyond what is required nationally. The conditions for this to occur are (1) a planning policy which restricts allowable heating technology options, (2) empowering LA officers to enforce policies, (3) advice and support for developers to consider alternatives, and where necessary, (4) political backing to challenge unwilling developers. Study findings highlight the important role of LAs in creating the conditions for the transition to LZC heating, which show how they can use powers within the planning system to encourage developers to make low carbon choices without the need for direct investment.

KEYWORDS

heat decarbonisation, urban energy transition, real-estate developers, planning policy and practice, local authorities

1 Introduction

As one of 38 countries responsible for 25% of global emissions (Ritchie et al., 2023; ECIU, 2024), the UK has enshrined commitments in law to achieve net-zero carbon emissions by 2050 [The Climate Change Act, 2008 (2050 Target Amendment) Order 2019, 2019]. Globally, buildings are responsible for 37% of greenhouse gas (GHG) emissions (IEA, 2020), with 11.5% directly attributable to homes (Ge et al., 2022). Net-zero targets cannot be met without addressing how our homes and buildings are heated. The challenge of decarbonising the residential sector is illustrated in the UK, where 86% of the country's 29 million homes are heated by natural gas boilers and 1.7 million new boilers are installed every year (BEIS, 2018; MHCLG, 2021a,b). At the current rate of progress in the UK it would take many hundreds of years to replace fossil-fuel heating with low and zero-carbon (LZC) heating alternatives and achieve net-zero emissions from buildings (Rosenow and Thomas, 2020; Rosenow et al., 2020; Shabha et al., 2021). Unlike the electricity system, which can largely be transitioned from high- to low-carbon intensity remotely with little noticeable impact on the end user, heat is typically generated at or near the point of use and tends to be subject to individual household decision-making (National Grid, 2018; Knobloch et al., 2019). Heating transitions in the residential sector are further complicated by the range of tenure types (owner-occupier, private rented, social rented, etc.) within the same area, such as a residential street or even a building (a tower block, for example). This causes challenges for those seeking to take an area or neighbourhood approach or encourage the deployment of shared heating technologies such as heat networks.

In this study, we focus on LZC heating deployment in new residential developments. Whilst the majority of emissions will need to be addressed in homes and buildings already constructed, the UK will likely see eight million new homes by 2050, representing a significant opportunity to implement LZC heating (CCC, 2020). The UK government and their scientific advisors recognise new homes as ideal settings to deploy less-established LZC heat technologies because, for example, they can be designed to accommodate different-sized heat emitters and space for thermal storage (CCC, 2019; BEIS, 2021). This approach will, in turn, help build a supply chain and develop skills across the workforce (Clarke et al., 2020; BEIS, 2021). New homes also offer a single point of decision-making during project development, which may well no longer exist following construction and sale.

Whilst the study applies to a range of technologies, we find particular emphasis within the results on shared ground loops (SGLs) as a suitable LZC heating option. SGLs remain a niche technology, and they have been shown to offer significant opportunities to help decarbonise the UK's housing stock, especially in homes that would struggle to accommodate their own air source heat pump (ASHP) or that are out of the reach of a heat network (Howard and Crook, 2021; Bale et al., 2022; Barns, 2022). SGLs are known by several names, but importantly combine aspects of heat pumps and heat networks and involve distributed heat pumps connected to a shared ground array through an ambient temperature heat network (GLA Etude, 2018; Boesten et al., 2019; Buffa et al., 2019; Lund et al., 2021; Ofgem, 2021a; BEIS Triple Point Heat Networks, 2022; Nesta, 2022; Element Energy, 2023).

The shift to LZC heating technologies in urban settings takes place within a broader socio-political regime (Webb et al., 2016, 2017; Tingey and Webb, 2020). This can impact decisions by those seeking to support or challenge the transition. The regime for residential heating in the UK features lock-in characteristics such as a well-established natural-gas grid serving most UK homes (Dodds and McDowall, 2013; Gross and Hanna, 2019); uncertainty around a shift to electrification vs. a repurposed gas grid to carry hydrogen for residential heating (Lowes et al., 2020b); a large gap between electricity and gas price that makes electrified options less favourable in operating costs (Barnes and Bhagavathy, 2020); a national building regulations policy which has not recognised the decarbonising of electricity grids in prescribed carbon factors (Rees, 2019); and a generally poor housing stock which aligns well with the instant heat and high temperatures of fossil heating, but is very inefficient (Chaudry et al., 2015; Guertler et al., 2015).

Given a challenging UK socio-political regime, the role of a few local authorities (LAs) in creating the conditions for low-carbon heating alternatives to flourish in cities has received significant attention (Bale et al., 2012; Schwanen, 2015; Bush et al., 2016; Fudge et al., 2016; Webb et al., 2017; Adam, 2018; Tingey and Webb, 2020). LAs can potentially take both active and passive policy measures. For example, if they have their own social housing stock, LAs can invest in retrofitting energy-efficient and low-carbon technologies. This has been underway, for instance, in Leeds, where Leeds City Council (LCC) has been connecting LA-owned homes to a city centre district heat network, installing SGL systems, and carrying out other energy efficiency improvements (LCC, 2021). Active investments in LZC measures of this type are, however, subject to the context of severe budget cuts since the early 2010s, which restricts the capacity of many UK local authorities to invest in similar active measures (Gray and Barford, 2018).

Most research about the role of LAs in supporting the energy transition has focused on exploring and evaluating active or strategic measures that typically involve the LA taking a lead role in developing and/or owning low-carbon infrastructure (Sullivan et al., 2013; Fudge et al., 2016; Bush et al., 2017; Webb et al., 2017; Roelich et al., 2018; Tingey and Webb, 2020). The strategic energy planning undertaken by empowered city authorities, especially in Denmark, has also received research attention (Sperling et al., 2011; Thellufsen and Lund, 2016; Krog, 2019). Yet, there has to date been less research focused on the ability of local authorities to encourage developers to choose LZC heating options through the planning system. Local authorities in the UK fulfil statutory responsibilities to develop and implement local spatial planning policies, thus providing both a "stick" (setting and enforcing construction standards) and a "carrot" (designating land for development) (MHCLG, 2019, 2021a; Ellis and Fieth, 2021; Ellis, 2022). This may mean LAs can deliver local decarbonisation objectives without the need for direct investment.

We explored the ability of LAs to shape developer technology decisions in new building settings within the UK's socio-political regime through the following research question:[1]

How can local authorities in England use the planning system to encourage residential developers to deploy low and zero-carbon heating systems in new homes?

Section 2 establishes the socio-technical transitions literature that underpins the analysis in this study. Section 3 details the methods used to address the research question through an embedded case study of two large UK cities across a sample of 30 residential developments. Section 4 presents the results of the case study, which finds that through implementing a set of local conditions, LAs can successfully shape the local domestic heat regime and encourage developers to choose LZC heating in their projects. Section 5 further discusses the implications of the findings on the potential for LAs to shape heat decarbonisation in their area. Section 6 concludes and outlines how the findings, whilst being UK-focused, could still be applied wherever local state actors seek to encourage private developers to install low-carbon technology.

Abbreviations: ASHP, air-source heat pump; CHP, combined heat and power; Comm., communal; DH, district heating; GSHP, ground-source heat pump; Ind., individual; kWh, Kilowatt-hour; LA, local authority; LZC, low or zero carbon; SGL, shared ground loop.

1 At present the same national regulations apply to English LAs outside of Greater London (Tomaney and Colomb, 2018; GLA, 2019; MHCLG, 2021a; Greater London Authority Act, 1999).

2 The shift to low-carbon urban heat as a socio-technical transition

Our study understands residential heating in urban situations as an example of a socio-technical system (STS). This approach has the advantage that it highlights useful considerations when exploring LA action to support the transition to LZC heating locally. Socio-technical transitions refer to the shifting of socio-technical systems from one state to another (Markard et al., 2012), and transition researchers recognise that technologies do not exist in isolation but rather are part of wider systems that include individuals and firms, supply chains, infrastructures, markets and regulations, norms, and traditions (Arthur, 1989; Rip and Kemp, 1998; Geels, 2002, 2010). The STS for UK residential heat supply includes technologies such as gas boilers and the extensive national gas grid, novel technologies such as SGLs, heat pumps and heat networks, national and local policies and regulations, users with existing practises and preferences, and heating installers who work with established networks (Chaudry et al., 2015; Barnes and Bhagavathy, 2020; Simpson et al., 2020; Barns et al., 2021). Socio-technical transition studies have tended to focus on a technology-led transition and assume a national scale (Coenen et al., 2012), although there are exceptions that we discuss later. This has led to a lack of attention to place-based factors that shape local transitions. Cities have been identified by some scholars as important sites where local policy interventions can impact the deployment of low-carbon heat technologies, such as heat networks (Sullivan et al., 2013; Bush, 2016; Webb et al., 2016). For these reasons, we explore socio-technical factors and their impact on action by LAs through the use of frameworks from the socio-technical transitions literature.

Frameworks such as the multi-level perspective (MLP) have been developed over several decades to help those seeking to understand socio-technical transitions. The MLP considers socio-technical transitions primarily through the effect of interactions of three levels of socio-technical systems—niche, regime, and landscape (Geels, 2002; Geels and Schot, 2007). Stability emanates at the regime level through shared norms, rules, beliefs and expectations, which guide the behaviour of actors and can lead to a lock-in of dominant technologies and infrastructures. The stability and high carbon lock-in of UK residential heating are partly due to the regime characteristics highlighted in Section 1 (Taylor et al., 2013). Innovations such as LZC heating can develop in niches that are shielded from the pressures of the incumbent regime. LZC niche support has been provided by public funding streams such as the UK's previous domestic (2014–2021) and non-domestic (2011–2021) Renewable Heat Incentive and the current Boiler Upgrade Scheme (Ofgem, 2021b,c, 2022; BEIS, 2022). These schemes reflect attempts by the UK government to support niche innovation heating technologies by incentivising consumer uptake to compete against incumbent fossil-based options (Lowes et al., 2019; Martiskainen et al., 2021; BEIS, 2022). The socio-political regime concept has been expanded to help consider the power relationships that incumbent regimes may use to resist change (Geels, 2014; Swilling et al., 2016; Feola, 2020). Research on incumbency in the UK energy sector has identified a vigorous coalition of actors at a national level, primarily from the gas industry and established supply companies, working to influence the discourse towards the perceived benefits of retaining the advantages of gaseous fuel through a move to hydrogen (Bolton and Foxon, 2011; Lowes et al., 2019, 2020b; Lockwood et al., 2020). Whilst studies have also tended to focus on a national scale, they suggest value in considering incumbent action and existing power relationships that may resist change at a local level.

Several scholars have sought to apply a socio-technical transition analysis to the city scale (Hodson and Marvin, 2010; Verbong et al., 2010; Raven et al., 2012; Kivimaa, 2014; Truffer et al., 2015; Bush et al., 2017). A general theme across this literature is the crucial role of city actors in creating and nurturing local niches where innovations can develop. For example, through a study of urban district heating as a niche innovation, Bush et al. (2017) found that LAs were key to enabling greater deployment through setting strategic and spatial planning policies that require district heating consideration, as well as by supporting teams responsible for connecting and persuading local stakeholders internally and externally, building social networks required to deliver projects, etc. An analysis of UK LAs found that divergent abilities between large unitary urban authorities and lower-tier district boroughs were more common in rural settings (Tingey and Webb, 2020). A place-based socio-technical analysis of Bristol since 1966 found a strong history of local grassroots activism, which has supported municipal initiatives on the environment (Torrens et al., 2018). This contributed to the establishment of the Bristol City Council's Sustainable Cities Team in 1994 to coordinate sustainability-related activities from different departments and develop a strategic direction. Schwanen (2015) provided a useful template for this work through a comparative case study of the socio-technical transition in low-carbon mobility in two other UK cities, Oxford and Brighton. Schwanen (2015) found that although city contexts were shaped and limited by the national regime, local LA action was possible, shaped by local political and historical contexts, e.g., the importance of local politicians in driving forward specific innovations.

Overall, we propose that LZC heating technologies can be usefully considered as niche innovations subject to a challenging socio-political regime exhibiting a lock-in of high-carbon fossil-based heating. This can help explain low levels of deployment in the UK. Whilst this is a national rather than local or city-specific challenge, there is increasing recognition of the role of cities and city actors in creating and supporting local niches where the conditions for deployment can be fostered. We found the examination of these national-local dynamics employing the concepts and principles of socio-technical transitions to be particularly helpful in our analysis. For example, as outlined in Section 4, this helped to identify that in acting as local incumbents, developers sought to invoke the national regime to challenge LA attempts to implement planning system measures to support LZC niche innovations.

3 Materials and methods

We investigated how LAs were able to use the planning system to encourage developers to choose LZC heating. To do this, we adopted an embedded case study comprising 30 residential

TABLE 1 Summary of developments by case city, identifier, and heating technology.

Bristol			Leeds		
Identifier	Outset technology	Final technology	Identifier	Outset	Final technology
ASHP1	ASHP	ASHP	CITYDH3	Heat network	Heat network
ASHP2	Gas boiler	ASHP	DIRELEC2	Gas communal	Panel heaters
ASHP3	Panel heaters	ASHP	DIRELEC3	Panel heaters	Panel heaters
CITYDH1	Heat network	Heat network	DIRELEC4	Panel heaters	Panel heaters
CITYDH2	Gas boiler	Heat network	DIRELEC5	Panel heaters	Panel heaters
DIRELEC1	Panel heaters	Refused	DIRELEC6	Panel heaters	Panel heaters
GASCOMM1	Gas communal	Gas communal	DIRELEC7	Unknown	Panel heaters
GASCOMM2	Gas communal	Gas communal	DIRELEC8	Panel heaters	Panel heaters
INDGAS1	Gas boiler	Gas boiler	DIRELEC9	Panel heaters	Panel heaters
SGL1	Gas boiler	SGL	GASCOMM4	Gas communal	Gas communal
SGL2	ASHP	SGL	INDGAS2	Gas boiler	Gas boiler
SGL3	SGL	SGL	INDGAS3	Gas boiler	Gas boiler
SGL4	Biomass communal	SGL	SGL7	SGL	SGL
SGL5	ASHP	SHL	SGL8	SGL	SGL
SGL6	SGL	Refused	UNKNOWN1	Unknown	Unknown

developments across two UK cities underpinned by the socio-technical transitions literature established in Section 2.

Leeds and Bristol were selected as the two case cities because they are both:

- Major UK cities with large populations–465,866 in Bristol and 798,796 in Leeds (Bristol City Council, 2020; Leeds City Council, 2020; ONS, 2021).
- Single-tier unitary authorities of the type recognised to be more likely to be "leaders" in energy engagement (Tingey and Webb, 2020).
- Subject to the same regulatory framework which covers all of England outside London (Greater London Authority Act, 1999; Tomaney and Colomb, 2018; GLA, 2019; MHCLG, 2021a).
- Similarly publicly committed to achieving net-zero carbon emissions by 2030 (Bristol City Council, 2018; Leeds City Council, 2019).

Bristol was chosen as the critical case due to evidence in prior work suggesting successful local policies and practises were enabling the deployment of LZC heat technologies (Torrens et al., 2018; Barns, 2022). Leeds was chosen as a comparator case with evidence suggesting good progress in active investment and implementation, but to date, there is little evidence of the local authority using the powers of the planning system to compel developers to select low-carbon heating options. A case study approach was chosen to investigate in-depth place-based contexts since it was considered likely to be key to developing an understanding of why deployment is happening in some cities and not others (Yin, 2018). To avoid researcher bias and allow each case city to be considered on its own terms, we adopted a replication logic approach. This meant each case was analysed in isolation before results were brought together to compare through a cross-case synthesis.

3.1 Data collection

Between June 2020 and May 2021, we collected data by building a repository of documentary evidence on 30 residential developments, with 15 in each case city, as well as relevant local strategic and policy documents. The case boundary was set as the LA geographical limit in each city. We limited the search to residential developments comprising over ten dwellings as this tends to be the lower limit for planning the application of carbon reduction policy measures. A "typical case" approach to purposeful sampling was applied to reflect the situation in each city (Emmel, 2013). In this way, we attempted to include a range of residential developments that broadly reflected the type of projects and technology choices progressing through the planning system in the case cities rather than being unusual or which could be considered outliers. We actively chose cases to include in the sample rather than allowing this to be entirely random so that we could capture a range of cases, particularly where initial sampling indicated there were interactions between LA planning officers and developers. Therefore, the approach can be considered a purposeful sampling strategy. Table 1 shows a summary of projects included in the sample.

In addition to providing an identifier for each residential development, Table 1 includes the heat delivery technology at the outset and final (at the time of data collection) stage in the planning process. This forms the basis of Section 4.3 and is important for the analysis because it highlights where the developer technology choice changed during the process. We gathered information on

TABLE 2 Interviewee identifier and role description.

Identifier	Interviewee description
DEV-1	Senior Development Manager for local authority
DEV-2	Regional Development Manager for a large construction company delivering housing developments
CON-1	Energy and Sustainability Specialist for energy consultant responsible for producing energy strategies
PLANNING-1	Senior Planning Policy Officer with responsibility for climate-related planning policy
CON-2	Principal Sustainability Consultant for energy consultant responsible for producing energy strategies
DEV-3	Mechanical, Electrical, and Heating Manager for local authority responsible for heating and retrofit
DEV-4	Regeneration Team Leader for community development trust
BUILD-1	Associate Director for a medium-sized construction company
CON-3	Director of energy consultant responsible for producing energy strategies
DEV-5	Managing Director of private developer based on a low-car, low-energy, high-density design
PLANNING-2	Principal Planner with responsibility for climate-related planning policy
DEV-6	Founder and current resident of community-led low-energy housing development

the case study cities and housing developments through a desk survey of documentary data from each city's planning portal, published minutes and recordings of local authority meetings, with a summary included in Supplementary material to this article. We also carried out expert interviews with stakeholders representing local authority planning teams, housing developers, building firms, and energy consultants. The process followed recruitment, consent, and data management practices subject to University of Leeds ethics guidelines and approval (ref LTSCPE-004) to carry out 12 interviews. A summary of interviewees is shown in Table 2.

The direct quotes in Sections 4, 5 are identified as a development (as per the identifier in Table 1) to a case city (LA1 and LA2) or interviewee (as per the identifier in Table 2). As per the terms of our ethical approval, we used identifiers to mask identities rather than directly linking subcases to named projects or cities. We also numbered each document within its reference to a case, such that CITYDH2-4, for example, refers to qualitative data source #4 in the sample related to the CITYDH2 project. A summary of documentary reference material is provided in the Supplementary material.

3.2 Data analysis

We examined documentary and interview evidence to construct a detailed picture of each subcase, including the type of heat technology initially specified and whether this changed during the development process. The attribute framework we developed for this analysis is included in Supplementary material. Data analysis involved both quantitative and qualitative investigation. A quantitative analysis was applied to assess the carbon reduction impacts of local planning policy and practice. A time-series analysis following Lee (2012) enabled to establish the sequence of events and interactions between developers, energy consultants, and local authority officers during the development process. We were particularly interested in exploring if the heating technology specified for the development changed during the process from individual gas boilers to LZC alternatives. A more focused exploration of the documentary and interview evidence around the time of any change in the decision was undertaken to search for causal factors in policy and practice.

To further explore causal factors behind developer technology decisions, we applied a template approach to the thematic analysis of documentary and interview evidence (King, 2017). Here, we employed a socio-technical transitions framework to form the basis of an initial coding template for application to a subset of data. In the initial coding template, we used a priori themes from the STS literature discussed in Section 2 to help identify factors shaping the deployment of LZC heating technologies at a local level. This included, for example, how developers as local regime actors were responding to the national regime for residential heat. We developed and evolved the coding template as we applied it to more data, clustering and adding themes as we identified them in the data, and applying them within a logical STS hierarchy. Ninety documents were included in the analysis—45 from each case city, including the interview transcripts; documents were added until there were no additional insights to be gained. This analysis generated evidence on the causal factors driving developer decisions on technology selection and allowed us to draw out the insights as presented in Sections 4, 5.

4 Results

The analysis of 30 residential developments across the two case study cities revealed that whilst shaped and limited by the national socio-political regime, local authorities can still design and enact local policy to support the transition to LZC heat technologies through niche empowerment activities. Beginning with an analysis of the broader socio-political regime in which LAs operate in Section 4.1, Sections 4.2 to 4.5 explore how LA actions in the two cities explain developer technology choices and what lies behind the changes from fossil to LZC heating, where this occurs.

4.1 National context and the impacts of the socio-political regime

Our analysis of the interviews and documentary evidence revealed that the national socio-political regime shapes LA action at the local level. This has, to some extent, limited LA attempts to impose more rigorous carbon reduction standards as we describe here, but importantly, it allowed LAs to implement technology-specific measures such as preventing the installation of gas boilers.

There was prominent evidence to suggest LAs were constrained by national government policy that prevented them from going beyond a carbon reduction requirement of 20% better than current building regulations (MHCLG, 2015). As explored in Section 4.3.1, we found this limit impacted heat technology deployment as it can be met by the addition of solar PV without the need to adopt LZC heating. The impact was exacerbated by the unexpected nature of the policy shift to abolish the zero-carbon homes standard in 2015 through a ministerial statement (MHCLG, 2015) and uncertainty over whether local authorities had any right to demand carbon reductions beyond those stipulated in building regulations [PLANNING-1, PLANNING-2]. This caused additional challenges and delays which held back the implementation of new local plans.

With a less direct policy-related effect, planning officers highlighted the conflict they faced between a desire to implement higher standards and the risk that higher associated costs for developers might cause them to focus on other locations with less ambitious standards [PLANNING-2]. Aside from the local economic consequences, there was concern that higher standards could lead to lower housing development numbers, and potentially missed national targets resulting in a process known as "presumption in favour of sustainable development" (Upton, 2019). This is a technical status within the national English planning framework that means LAs must generally grant planning permission unless the land is protected (MHCLG, 2021a), in effect tilting the balance further in favour of development and potentially away from higher standards. In addition, LAs who challenge developers have to defend their decisions through a legal process if the developer appeals to the Secretary of State, who typically appoints a Planning Inspector to hear the case (Rankl, 2024). This can result in the LA potentially facing large legal bills as planning inspectors have the power to award costs against either party if they believe they have behaved unreasonably (Rankl, 2024), [PLANNING-1]. This has contributed to risk aversion when advocating for higher standards. In addition to the tilted balance of the planning system, an additional dynamic was the process of land valuation calculations which was believed to drive standards lower in areas with comparatively lower land values [DEV-2]. This is because when appraising the amount they may be willing to pay for a site, developers typically follow an income minus costs approach known as gross development value or GDV (Crosby and Wyatt, 2019). This includes income from the sale or rental of the homes, minus land costs, construction costs, and a profit margin, to reach a site appraisal value. This can mean in areas with lower land values and lower expected income, the additional cost of installing measures such as LZC heating would impact the GDV to a greater extent, making a location requiring this less attractive. Evidence at the time of the study found Leeds had a 33% lower average land value than Bristol (£2,150,000/ha in Leeds compared to £3,250,000/ha in Bristol) (MHCLG, 2020). At any given site, the GDV approach can also have the effect of driving competing developers to seek the lowest possible construction costs or risk losing the land and opportunity to build the development to a competitor who builds to lower standards and can, therefore, offer a higher price for the site [DEV-5].

TABLE 3 **Summary of carbon reduction planning policies in Bristol and Leeds.**

Policy detail	Bristol	Leeds
Policy name	BCS14	EN1
Carbon reduction requirement	20% reduction in residual emissions after energy efficiency measures	20% reduction in emissions over Part L
Policy applicable to	All developments	Residential, over ten dwellings
Carbon reduction baseline measure	Building Regulations Part L 2013	Building Regulations Part L 2013
Eligible technologies	Range including non-heating, e.g., solar PV	Range including non-heating, e.g., solar PV
Fabric efficiency requirement	Yes, but no % target	Yes, but no % target
Energy generation requirement	Yes, but no % target	Yes, 10% of onsite needs

4.2 LA policies in each location

Our analysis of local policy design found that local policies were very similar in both case cities, shaped by the socio-political regime dynamics noted in Section 4.1. Both Bristol and Leeds featured planning policies that sought to reduce carbon emissions and specify both eligible and ineligible heating technologies for planning approval.

4.2.1 Carbon reduction policies

Both LAs had adopted a policy requiring developers to demonstrate how their scheme would deliver a 20% reduction in carbon emissions against the national building regulation baseline.[2] In Bristol, this was first included in the planning policy in 2011 (Bristol City Council, 2011), whilst, in Leeds, it was included as Supplementary Planning Guidance from 2011 onwards before becoming a planning policy in 2014 (LCC, 2011, 2019). Table 3 summarises key aspects of the carbon reduction policies in both cities.

Policies were similar in both locations, with both implementing up to the maximum allowed 20% carbon reduction. Importantly, for the results set out in Sections 4.3–4.4, both policies were tied to Building Regulations 2013 as a baseline measurement for a notional building. The impact of this is explored in Sections 4.3–4.5.

4.2.2 Heating technology policies

Both cities also featured heating hierarchy requirements that were implemented into policy at the same time, prioritising certain heating technologies over others, especially heat networks, and excluding gas boilers and direct electric resistive heating. Table 4 provides a summary of the equivalent policies in each location.

2 At the time of the research, the baseline was set by Building Regulations Part L 2013.

TABLE 4 Summary of heat technology planning policies in Bristol and Leeds.

Policy detail	Bristol	Leeds
Policy name	BCS14	EN4
Headline policy requirement	Heat hierarchy of technology options	Heat hierarchy of technology options
Policy applicable to	All developments	Where technically viable, appropriate for development, in an area with sufficient existing or potential heat density
Eligible technologies	- Connection to district heat network - Site-wide heat network - Shared ground loops - Individual building renewable heating	- Connection to district heat network - Site-wide heat network - Collaboration with neighbouring sites - Develop a district heating network
Ineligible technologies	- Individual gas boilers - Direct electric panel heaters	- Individual gas boilers - Direct electric panel heaters

Although the heat hierarchy policies were broadly similar, it can be seen in Table 4 that in Bristol, the policy applied to all new developments, whilst in Leeds, the policy was prefaced with: "Where technically viable, appropriate for the development, and in areas with sufficient existing or potential heat density" [LA2-1], with a requirement for developers to submit assessments along with planning applications. Both policies offered a list of options intended to support the deployment of heat networks and did not include gas boilers or direct electric resistive heating.

Whilst not formally included in the policy hierarchy, we included SGLs in the list of eligible technologies in Bristol because documentary evidence suggests LA support for the approach in the language in LA-developer exchanges, such as: "... micro-district approaches [...] meets the definition of site-wide renewable heating within the heat hierarchy and are therefore supported by policy BCS14" [SGL4-5].

The ineligibility of gas boilers in the heat technology policies was justified citing their significant carbon emissions impact. Similarly, direct electric resistive heating was made ineligible because they it was relatively inefficient compared to heat pumps, caused a strain on the electricity grid, and ruled out future connections to district heat networks [PLANNING1, LA1-2].

4.3 Outcomes of LA planning policy on developer decisions

We analysed development projects for evidence to determine if LA policy and practice had an effect on developer decisions. This included mapping specified heat technologies at the initial submission, during the planning process, and at the final submission. Figures 1, 2 show the heat technologies specified in both cities at the outset and final stages of the development process. These illustrations are based on data summarised in Table 1 but shown here as Sankey diagrams to illustrate visually how the two locations differed.

TABLE 5 Compliance and impacts of carbon reduction policy in Bristol and Leeds.

Compliance detail	Bristol (14 applicable subcases in sample)	Leeds (12 applicable subcases in sample)
20% carbon reduction policy met–initial submission	14	6
20% carbon reduction policy met–final/post-intervention submission	14	9
Max. carbon reduction–(initial/final or post-intervention)	−64%/−83%	−48%/−58%
Min. carbon reduction – (initial/final or post-intervention)	−20%/−20%	−12%/−14%
Av. carbon reduction – (initial/final or post-intervention)	−34%/−40%	26%/−29%
Technology used to achieve carbon reduction	Heating (5), solar PV (8)	Heating (6), solar PV (5)

Figures 1, 2 suggest that developer decisions in Bristol changed more frequently during the development process compared to Leeds, which had more stable conditions. The Leeds situation is also characterised by the specification of direct electric panel heaters, whilst in Bristol, there is a mix of different approaches and a trend away from gas boilers to LZC technologies, particularly SGLs. Planning submissions and records of interactions between developers or their energy consultants and LA planning officers were analysed to assess how the policies impacted developer decisions.

4.3.1 Outcomes of carbon reduction policy

To first assess the impact of carbon reduction policies on technology choice, Table 5 summarises the number of subcases that met the requirement and whether the carbon savings resulting from the proposed heat technology were used by the developer to comply with the policy.

Table 5 shows that all developments met the carbon reduction requirement in Bristol, both at the initial submission and final submission stage. A lower level of compliance was found in Leeds, with 9 of the 12 applicable developments meeting the policy at the final stage. This marked an increase from the initial submission stage, suggesting measures were in place to address policy non-compliance, a result discussed further in Section 4.5. Higher maximum and average carbon reduction levels were demonstrated in Bristol, suggesting overall greater success in policy implementation.

To assess the extent to which carbon reduction requirements impacted developer heating technology decisions, we examined energy strategy documents to ascertain whether the emissions savings from the heating technology (compared to the building reductions baseline) counted towards meeting the carbon target.

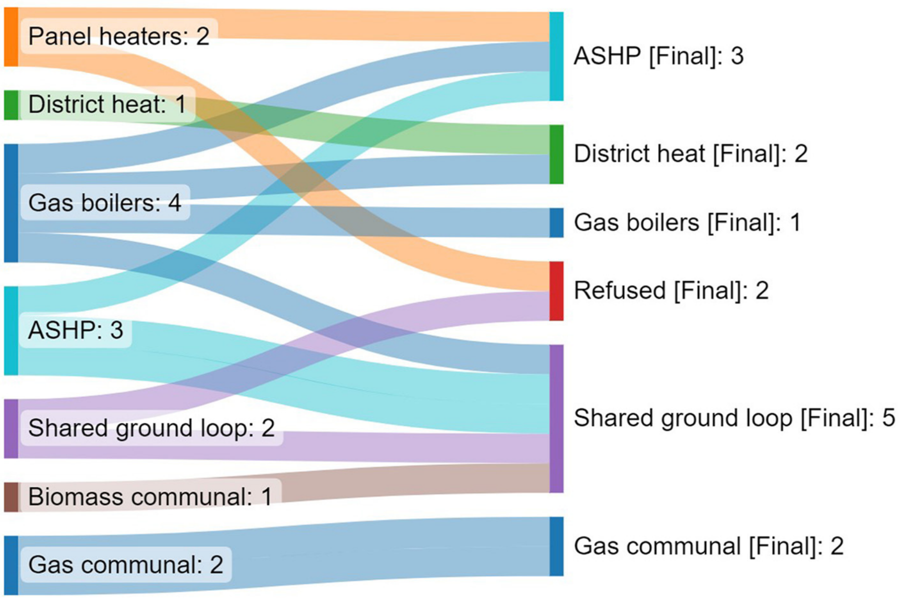

FIGURE 1
Developer technology decisions in Bristol from the outset to the final stage.

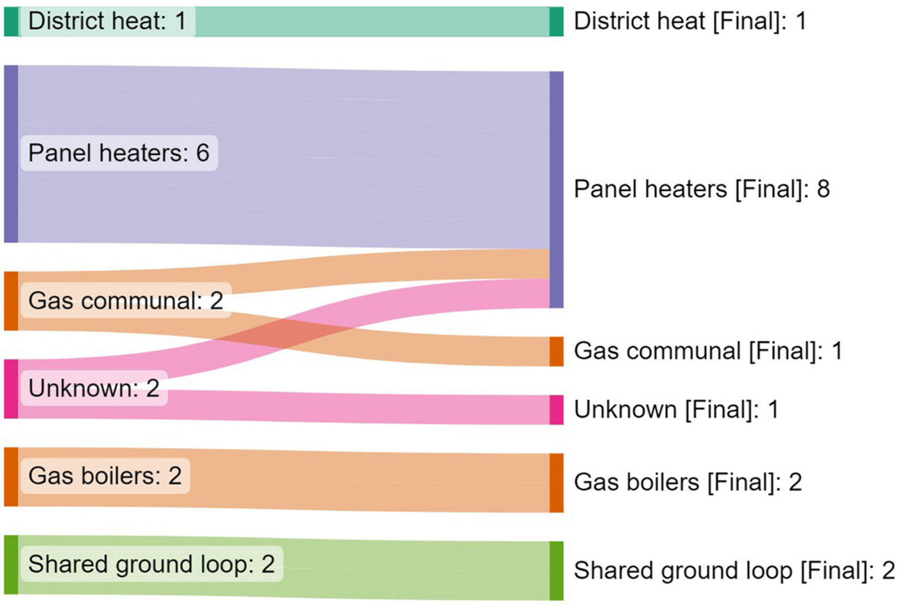

FIGURE 2
Developer technology decisions in Leeds from the outset to the final stage.

Five developments in Bristol and six in Leeds used the specified heat technology to meet the carbon reduction target. However, 13 other schemes did not reference heating to satisfy carbon reduction requirements. This suggests that in both locations, the carbon reduction requirements of 20% (the maximum allowed under the current regime) can be met through other measures such as the addition of solar PV. As a result, the carbon reduction policies were not impactful in encouraging developers to choose LZC heat technologies.

4.3.2 Outcomes of heat technology policy

We examined the impact of the heat technology policies implemented in both locations to ascertain whether meeting the heat hierarchy policy played a role in developer technology choice. Table 6 shows a summary of heating technologies specified in the developments and whether they met the local heating policy.

Table 6 illustrates that the heating technology policy was aligned with developers opting for LZC heating technologies in Bristol but less so in Leeds. All but one development in Bristol

TABLE 6 Heating technologies specified in Bristol and Leeds with heating policy compliance.

Policy approved technology	Bristol	Leeds
Shared ground loop	6	2
ASHP	3	0
Connection to district heat network	2	1
Site-wide network (non-renewable)	2	1
Total	**13**	**4**
Total where policy applied	**13**	**2**
Policy non-approved technology		
Gas boilers	1	2
Direct electric panel heaters	0	8
Unknown	0	1
Total	**1**	**11**
Total where policy applied	**1**	**11**

met the heating policy requirement through the technologies shown in Table 6, with six developments specifying SGLs to achieve BSC14 compliance (although one was refused planning permission for other reasons). One development achieved planning permission without meeting the policy requirement (INDGAS1), with individual gas boilers specified and the application approved at initial submission with no evidence of challenge. Eight projects initially proposed non-compliant technologies, such as gas boilers and direct electric resistive heaters, prior to final compliant specifications and planning approvals. This suggests that in Bristol, the heating policy was successfully implemented to shape developer decisions towards LZC heating when combined with active intervention measures (explored further in Section 4.5).

In Leeds, two developments fully met the heat policy through connection to a future district heat network and a site-wide communal heat network served by gas boilers. However, in six developments, no reference to the heating policy or evidence of compliance was evident, and it was not clear from the submitted materials whether the development was considered appropriate for policy applicability. These schemes primarily specified direct electric resistive heating. The evidence suggests a less successful implementation of a heating policy in Leeds.

4.4 Developer attempts to resist LA planning policy

An important factor in LZC technology deployment was how developers responded to the policy design and implementation approach of the LAs under investigation. We found developer decisions shaped by the national and local regimes, with evidence that developers attempted to invoke stabilising regime dynamics and resist LA efforts to encourage them to choose LZC heating options.

Our analysis found that developers frequently used carbon factors inherent within national building regulations to challenge local policy in both cities. The electricity system in the UK is rapidly decarbonising due to the introduction of renewable technologies, but building regulations have struggled to keep pace with these developments (Rees, 2019). At the time of the study, the in-force National Building Regulations Part L 2013 (with inherent SAP2012 methodology) featured electricity grid carbon emissions per kWh approximately two times that of natural gas per equivalent unit, with the to-be-introduced Part L 2021 Uplift (with inherent SAP10) effectively reversing this situation (MHCLG, 2018; DLUHC, 2022). Table 7 summarises the instances identified against the two versions of SAP and how the carbon factors should justify diverging from local policy requirements.

Table 7 shows this type of incumbent challenge to be a more prominent feature in Bristol, likely in response to the more active intervention measures explored in Section 4.5. Importantly, whilst older national building regulations were used to justify gas boilers because of the apparent lower carbon content of natural gas compared to electricity, newer national building regulations with a lower grid carbon factor were used to justify the specification of direct electric panel heaters.

Aside from the direct challenge of planning policy, there was a clear trend for developers to increasingly opt for direct electric panel heaters. These were proposed in ten projects in the sample. Interview evidence from energy consultants who work with developers to propose heating technologies for their schemes described how this was primarily because developers favour the most straightforward and lowest cost technology to source and install: "[developers] want easiest and cheapest, they always want cheapest!" [CON-3]. It was understood that previously this was gas boilers, but increasingly this will be electric panel heaters in the future as national building regulations are updated and there is growing recognition of the need to move away from gas: "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!" [CON-3].

There was also evidence that developers attempted to resist change locally by appealing to elected councillors directly. As part of the normal governance arrangements for local authorities, a few locally elected councillors serve as members of a planning committee. These committees decide on planning applications with advice and guidance from planning officers (Rankl, 2023). In Leeds, currently, there are three planning committees—the North and East Plans Panel, the South and West Plans Panel, and the City Plans Panel (LCC, 2023). In Bristol, there are two planning committees—Development Control A and B (BCC, 2023). Whilst most planning decisions are made by planning officers through delegated powers, larger and more complex planning applications of the type included in the study are decided through these committees. Planning committee members take into account the detailed officer's reports about each proposal along with their recommendations to approve or refuse applications. However, councillors are not bound to the recommendations made by the officers and can use their own judgement. This opens up potential opportunities for developers to influence the councillors while they

TABLE 7 Number of subcases where developers used carbon factors to challenge local planning policy.

Building regulations	Methodology and carbon factors	Bristol, no.	Leeds, no.	Justification
Part L 2013	SAP 2012, electricity 0.519 $kgCO_2/kWh$, natural gas 0.210 $kgCO_2/kWh$	6	0	Lower carbon factors in natural gas mean gas boilers should be allowed
Part L 2021 Uplift	SAP 10, electricity 0.136 $kgCO_2/kWh$, natural gas 0.216 $kgCO_2/kWh$	3	2	Lower carbon factors in grid electricity mean direct electric panel heaters should be allowed

make the decisions. For example, a developer interviewee described how they had tried but failed to persuade a local councillor to allow them to implement a non-compliant heat solution despite being challenged by the officer. The councillor had responded: "that ain't changing [...] you're going to have to find another solution" [DEV-4].

Overall, the findings indicated that when faced with policies encouraging LZC heating technologies, developers attempted to challenge these to specify non-compliant heat technologies. This included invoking elements of the national regime, such as carbon factors inherent in building regulations, as well as lobbying councillors in their role as planning committee members and making planning decisions. Given these conditions, Section 4.5 explores how Bristol was able to encourage developers to choose LZC heating technologies.

4.5 How the results were derived

It was established in Sections 4.1–4.4 that both locations were subject to the same regime impacts, had broadly similar planning policies in place, and experienced developers attempting to challenge policy measures to choose LZC heating technologies. However, the evidence suggested greater success apparent in Bristol in driving developers to choose LZC heating. We further analysed the case studies to look for evidence which could explain the difference and suggest how Bristol achieved better policy outcomes. This included examining the interactions between planning officers and developers for instances of direct engagement and intervention in the planning process.

Table 8 shows a summary of identified LA intervention activities and the instances where this supported a change in heating technology. In the table, "direct intervention" refers to activities where direct contact between planning officers and developers was identified. This included records of emails and evidence of meetings having taken place. "Indirect intervention" refers to instances where measures operated through the planning process, such as placing conditions on planning approvals for the developer to provide more information about how they would meet the policy prior to construction beginning.

The results in Table 8 show greater evidence of direct intervention in Bristol as well as associated changes in heating technology. In Bristol, identified action was undertaken by a multi-disciplinary team of officers who were external to the planning function and acted in an advisory capacity as well as a statutory consultee on planning applications, much in the same way as the fire service or water authority. Evidence showed that the Sustainable Cities Team had the power to demand changes to the specified heat technology and to recommend the refusal of planning permission for failure to meet policy requirements. An example of one such intervention is illustrated in a communication from officers in response to continued attempts by the developer to opt for direct electric panel heaters, resulting in planning refusal on these grounds:

> "We [the Sustainable Cities Team] remain strongly of the view that our implementation of the heat hierarchy, which excludes electric resistive heating, aligns with government policy and thinking on the decarbonisation of heat, and the independent advice we have received on the decarbonisation of heat in Bristol... For these reasons, we continue to object to this application" [DIRELEC2-5].

Other more supportive interventions by the Sustainable Cities Team took the form of engaging with the developers to explain the heating policy requirements, recommending certain LZC options as a suitable option for some developments, and offering financial support for operations and maintenance costs if they were to choose the preferred LZC option [SGL2-9, SGL2-10]. Technology recommendations by officers were identified in seven subcases and included SGLs, ASHPs, and connecting to a district heat network. Overall, policy non-compliant technologies were changed to compliant options due to active intervention in six instances. Interventions were identified in 11 instances and classified into three broad types (with numbers of each in brackets):

1. Advising planning refusal for failure to meet policy (3).
2. Compliance activities to ensure technology policy was followed (5).
3. Guidance and support for how developers could meet heating policy (3).

Evidence from Bristol showed that officers were supported by the local political leadership to engage in these intermediary activities in cases where developers attempted to circumvent or challenge their authority [DEV-4]. Overall, we found that Bristol's Sustainable Cities Team was a key factor in the relative success of the city in encouraging developers to choose LZC heating technologies.

In Leeds, ten interventions by planning officers were identified across the sample, with two identified as direct interventions similar to that observed in the Bristol sample. In the DIRELEC4 development, for example, a report from officers to the planning committee stated: "Through discussions and negotiations with

TABLE 8 Summary of LA intervention and outcome in Bristol and Leeds.

Case city	Direct intervention	Indirect intervention	Change in technology	No change identified
Bristol	10	1	9 (3 refused)	1
Leeds	2	8	3	7

the developer, the scheme is now considered to be compliant with Policy" [DIRELEC4-6]. This suggests that planning officers were engaging with applicants to try to encourage them to meet policy requirements, but Leeds did not benefit from an equivalent statutory consultee approach from a team with the resources and technical expertise to challenge developer decisions.

In eight other Leeds subcases, evidence from planning documents suggested some intervention via an indirect process. The intervention took place indirectly in the form of a report from the planning officers to the planning committee (which included elected local city councillors making the decision) recommending certain conditions placed on the award to further clarify how policy requirements would be met. Three subcases were identified where this approach resulted in a change or clarification of technology. This suggests limited success from this technology assessment and evaluation activity. However, there was no evidence of interventions leading to a change in heat technology. Three developments achieved local planning permission despite incomplete or incorrect information. There was some evidence that the situation was beginning to change in Leeds with more active intervention since the LA'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].

Figure 3 shows a summary of the developer journeys in both case cities. Whilst both locations featured similar policy inputs to the process, it led to different outcomes through more active engagement and intervention in the planning process. In Bristol, heat technology planning policies were combined with action from the Sustainable Cities Team and support from elected politicians to create the conditions whereby developers were more likely to choose LZC heating options, thus creating the conditions for local heat transition.

Summarising the results across Sections 4.1–4.5, we found that the LA in Bristol had put in place four conditions that contributed to the successful deployment of LZC heat technologies:

1. Implemented a heat technology planning policy that excluded conventional technologies of gas boilers and direct electric heating.
2. Empowered local authority officers to enforce the heat technology planning policy.
3. Supported developer decisions through awareness raising of LZC options and providing advice and support to consider them.
4. Provided political commitment to challenge developers who sought to invoke regime dynamics to resist local planning requirements.

The evidence we found indicates that implementing more of these elements increases the likelihood of deploying LZC heat technology. When only one element was in place, for example, a heat hierarchy policy in Leeds, but was not supported by other intermediary activities, the outcome was that conventional heat technologies were more likely to be installed.

5 Discussion

This study set out to explore what actions LAs can take to shape the deployment of LZC heat technologies in residential settings and the effect this has. Overall, the study found that local authorities were able to implement policy and practice measures within the current regulatory framework, which helped bring forward LZC heating options. These were being employed successfully in Bristol, and developers were encouraged to choose LZC heating for new developments.

A key measure within the planning system was a heating technology policy specifying a certain range of heating technology options and, importantly, prohibiting conventional gas boilers or direct electric heating. This was effective in driving developers to choose LZC heating technologies when combined with active intervention, support, and enforcement. Our findings suggest the both the design and implementation of local policies are subject to a broader socio-political regime, which impacts the LA's ability to take such steps. In addition, developer technology decisions and how developers respond to local policy and practise are itself shaped by wider factors. The English planning system enabled LAs to take measures that encouraged the uptake of LZC, but at the same time, it also placed distinct limits on them. For instance, LAs are required to limit carbon reduction to no more than 20%.

There was evidence that residential developers generally favoured the lowest cost and lowest hassle heat technologies. When challenged by local LA planning policies to encourage the adoption of LZC heating, developers attempted to resist by leveraging the institutional framework of National Building Regulations. Under prior national building regulations, higher carbon factors for electricity compared to natural gas tended to be applied to individual gas boilers. However, evidence shows developers are increasingly likely to opt for direct electric panel heaters and use the lower carbon factors of grid electricity as justification to challenge local attempts to force them to choose LZC alternatives.

The trend towards direct electric panel heaters may increase as national policy recognises the reducing carbon content of grid electricity (DLUHC, 2023). With the much higher power consumption compared to LZC alternatives, this carries challenges and risks for the electricity grid, especially when combined with the electrification of other sectors, including transport (Lowes et al., 2020a; Chaudry et al., 2022). Electric resistive heating is not generally featured in UK heat decarbonisation scenarios, and an unplanned technology shift towards this technology may

FIGURE 3
Illustration of developer journey through the planning process in Bristol and Leeds.

pose risks to the UK energy system and decarbonisation efforts (Slorach and Stamford, 2021). Whilst the details of the new building regulations—the Future Homes and Buildings Standards—are yet to be confirmed, this study's evidence suggests that local planning authorities keen to prioritise LZC heating options in new developments can successfully implement local policies and practises within the current national regulatory framework that will enable them to do this.

The study found evidence that the English planning system places considerable power in the hands of developers and tilts the balance away from LAs and their ability to demand higher standards. This has been supported by central government housing delivery targets for LAs, which effectively favour volume housebuilders. The developer valuation and appraisal approach that favours the lowest cost and equivalent lowest standards and penalises those developers keen to take a more progressive approach also potentially makes it more challenging for local authorities with lower land values to implement higher standards. Overall, our study emphasises the challenges faced by planning authority officers to simultaneously design, implement, and enforce environmental building standards in support of organisational commitments whilst also promoting local economic development and growth.

Our findings also suggest that Bristol's Sustainable Cities Team was a key factor in the relative success of the city in encouraging developers to choose LZC heating options through a dual role of supportive and enforcement activities. It is important for wider application to consider whether the conditions put in place in Bristol could be replicated elsewhere. Torrens et al. (2018) described how over four decades Bristol's approach developed through co-evolution between urban experimentation and governance, leading to the establishment of the multi-disciplinary Sustainable Cities Team in the 1990s to work across local authority departments and intermediate between the city's environmental groups and the council. The existence of the Sustainable Cities Team, the measures they were empowered to take, and the political backing needed to implement the agenda are key factors in the current success found in this study. The study's findings also indicated that comparatively higher land values in Bristol may have reduced the disincentive for developers to implement higher-cost LZC heating measures, supporting the LA's objectives to implement and enforce higher standards. Recognising that not every LA will have the distinctive history and local socio-political regime of Bristol, other LAs can create local conditions that will encourage developers to choose LZC heating options. While each condition supports niche innovations on its own, when combined, they amplify each other and work together to shape the local socio-political regime.

Since data collection ended, both Leeds and Bristol have embarked on highly ambitious programmes to update their climate and carbon-related planning policies, including further requirements around LZC heating technologies as well as embodied carbon from construction (Bristol City Council, 2022; Leeds City Council, 2022). These will require approval by the UK's Planning Inspector in line with regulatory requirements. Recent evidence finds that the Planning Inspector is willing to reject similar bold planning policies, further illustrating the challenging socio-political landscape faced by UK local authorities keen to take ambitious climate action (Ellis, 2022). With the measures set out in this study already operating successfully, there is reason to be hopeful they can be applied elsewhere in the current institutional regime. We also note that since data collection ended, Leeds City Council recruited a dedicated officer to assess climate and energy aspects of planning applications.

The study benefitted from the transparent nature of the UK's planning system, which makes all documents submitted in pursuit of planning permission publicly available. However, the challenge of gathering and analysing material limited the study to 2 case cities and 30 subcase developments. There would be a benefit from analysing other cities in the UK and beyond, as well as smaller and more rural authorities that face different regime contexts. In addition, as the measures explored in this study take place within the English (outside London) planning system, the findings are applicable primarily to the new building sector rather than the enormous challenge of retrofitting homes and buildings already constructed. The ability of LAs to usher the transformative change required to retrofit existing properties is constrained by the lack of a regulatory framework as well as acute financial difficulties (Gray and Barford, 2018). Despite these factors, the findings are significant and offer a useful framework for LAs keen on taking action to reduce the climate impacts of the residential heat sector in their area. Many features of the institutional framework which shape the findings in the study relate to the specific context of the English planning system. However, many cities around the world are struggling with residential heat decarbonisation, challenging socio-political regimes, and incumbency in the energy and development sectors. The findings and proposed city authority measures set out in the study are, therefore, applicable internationally.

6 Conclusion

In this paper, we applied a socio-technical analysis to an embedded case study of two UK cities. Through an analysis of local authority policy and practice in regard to 30 residential developments, the study demonstrated how LAs could shape the local regime for residential heating and create the conditions for low-carbon heat technologies to come forward in support of the net-zero transition. LAs are identified as key actors who need to be recognised in the analysis of infrastructure transitions. However, the ability of LAs to shape the local regime for residential heat decarbonisation is limited by the national socio-political regime, which is subject to the effects of lock-in and incumbency. The study findings emphasise the importance of considering location-based aspects of transitions and the need explicitly to recognise power and politics in the socio-technical analysis of how new infrastructure systems can be brought forward.

This study took place in the UK context of decarbonising the electricity grid and expected changes to building regulations, both of which are likely to support the shift to electrified heating options. However, the study finds that without intervention, developer technology decisions are likely to trend from gas boilers towards direct electric panel heaters, and they are willing to invoke national policies to challenge local attempts to compel them to choose more efficient but less well-established technologies. Widespread deployment of direct electric panel heaters could lead to issues of grid stability, challenge future energy system flexibility, and run counter to the need to use low-carbon electricity as efficiently as possible. The findings underscore the case for local intervention in the energy system and for the UK's heat transition. Based on this study's evidence, we recommend a series of overlapping conditions that local authorities, as key city actors in the net-zero transition, can put in place as part of the planning process for residential developments. These include a heat technology policy which excludes conventional options of gas boilers and direct electric resistive heating; resourcing and empowering officers to enforce the policy; providing advice and support to developers in their technology decision processes to consider low-carbon heat technologies, and providing political commitment and support against challenge from incumbent developers. Whilst the findings set out above must be viewed in the context of the UK (and specifically English) planning and regulatory system, they can apply to other cities and locations where local commitments to decarbonise residential heating meet challenges of incumbency, centralisation, and a liberalised economy that places significant power in the hands of developers.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Ethics statement

The studies involving humans were approved by the University of Leeds MEEC (Faculties of Maths, Engineering & Physical Sciences) Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DB: Conceptualization, Data curation, Methodology, Visualization, Writing—original draft. CB: Conceptualization, Funding acquisition, Writing—review & editing. PT: Conceptualization, Writing—review & editing. AO: Writing—review & editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2024.1339709/full#supplementary-material

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