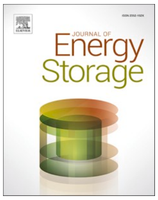
Journal of Energy Storage 41 (2021) 102877

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



Important social and technical factors shaping the prospects for thermal energy storage

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ARTICLE INFO

Keywords:
Thermal energy storage
100% Renewable Energy Systems
Sociotechnical transitions
Business models
District heating and cooling
Smart energy systems

ABSTRACT

Thermal energy storage is likely to be integral to a sustainable, secure and affordable energy system facing ever greater challenges in matching supply and demand. Techno-economic studies have explored the potential for thermal storage deployment, but transitions in the energy system are also influenced by the activities and decisions of an array of actors. We gathered new empirical evidence from a desk-based survey on thermal energy storage in the UK and through a sociotechnical analysis explored the status and role of thermal storage in the energy transition. We find the technology remains a relatively niche approach in the UK subject to complex national and local policy and governance arrangements and the impacts of a stable fossil-based heating regime benefitting from significant lock-in effects. Whilst we acknowledge the limitations of a focus on single technology-systems to deliver the transformative energy system change required, we find thermal storage delivering both local and national benefits to support system balancing and mitigate seasonal peaks in demand, whilst having the potential to deliver other benefits. Promising innovations in business models are helping to enable thermal storage deployment, and these are also applicable to low carbon heat provision more widely.

1. Introduction

Radical decarbonisation of all sectors of society is required to limit the trajectory of climate breakdown. System-wide change is required to transition to a post-carbon society in the shortest possible timeframe [1]. The provision of heating and cooling accounts for over 50% of global final energy consumption and one-third of carbon emissions [2]. The demand for cooling is smaller but expected to increase dramatically in the coming decades [3–5]. The transition to sustainable heating and cooling is particularly challenging because infrastructure is distributed and changes will require direct intervention in many millions of homes and businesses [6]. This means a complex interplay of actors is involved in any changes to heat provision, and new business strategies may be required to deliver low carbon infrastructure. A broader sociotechnical approach can therefore provide useful insights into how the challenges in enabling sustainable heat infrastructure investment can be addressed.

In addition to the decarbonisation of heat, the transition to sustainable energy provision is likely to require significantly electricity generation [7–9,10], p. 21]. Thermal energy storage can enable intermittent renewable electricity to supply heating and cooling when needed by coupling with other technologies such as heat pumps [11–14]. Thermal storage enables surplus electricity supply to serve heating and cooling loads and balance the electricity grid, and has been shown to mitigate the challenges and costs of electrifying heating [15–17]. Three key routes have been identified through which thermal storage coupled with heat pumps can support a decarbonised energy system: through providing grid benefits such as capacity reductions and voltage control; offering a price benefit through making the most of variable pricing; and supporting the integration of renewable electricity through load shifting [18,19]. Acknowledging that electrical energy storage can play a more direct role in helping to integrate fluctuating renewable energy into the energy system, thermal energy storage is around 100 times cheaper than electrical storage when comparing investment costs on a simple per unit of capacity basis [20]. International studies have shown that thermal storage can play an integral role in delivering energy systems which are affordable, resilient, based on

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Abbreviations: CHP, Combined heat and power; CCHP, Combined cooling, heat and power; EfW, Energy from Waste; ESCo, Energy Services Company; kWh, Kilowatt-hour; LEP, Local Enterprise Partnership; PCM, Phase change material; RHI, Renewable Heat Incentive; RP, Registered Provider; SPV, Special Purpose Vehicle.

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https://doi.org/10.1016/j.est.2021.102877
Received 31 March 2021; Received in revised form 19 May 2021; Accepted 18 June 2021

100% renewable energy, and create millions of new jobs. [21–23].

As an important part of a fully decarbonised energy system, it is key to understand the development, application and carbon reduction impact of thermal energy storage, and what can be done to enable deployment in place of fossil-based alternatives. From a UK perspective there has been relatively little focus on the potential role of thermal energy storage to support decarbonisation of the energy system, or to explore the range of factors which could impact on deployment [24,25]. Various techno-economic studies have explored the technology readiness and the potential for cost reduction of thermal storage in the UK [26–30]. However, the transition to a sustainable energy system involves an array of factors including the motivations of the different actors involved, the interactions between them, and the choices that must be made along the way [31–33].

Applying a sociotechnical approach to the role of thermal storage in the energy transition opens up a range of research areas for further exploration. A sociotechnical perspective incorporates mechanisms through which large-scale infrastructure systems undergo transformative change [34,35]. To deliver thermal storage infrastructure, new business models may be required which capture the array of values that thermal storage can deliver, as well as aligning with the variety of motivations of local actors in the energy system [36,37]. Using the case of the UK as an entry point, we explore sociotechnical factors in the development, application and carbon reduction impact of thermal energy storage. We investigate this through the following research questions:

1. What is the current state of UK thermal storage deployment in terms of technology types and functions, geographical spread of projects, and organisations involved?
2. What are the important sociotechnical characteristics of the current deployment of thermal energy storage in the UK?
3. How does consideration of the range of values sought by project developers help to understand the potential future deployment of thermal energy storage?

The article proceeds as follows: in the next section we explore the context of thermal energy storage including the technology's potential role and why the UK energy system provides a useful case to apply a sociotechnical analysis. We review relevant literature on sociotechnical transitions with a focus on coevolutionary aspects of energy infrastructure systems. Section three describes how this literature shaped the research methods and how this was applied to a desk-based survey of thermal energy storage schemes in the UK. Section four presents the results of our study into the current landscape and exploration of sociotechnical factors impacting on thermal storage deployment. In section five we explore the implications of our analysis for the development of thermal energy storage and consider broader consequences.

2. Context and theoretical approach

2.1. *Technological context*

Thermal energy storage can be applied in diverse ways and over a range of settings. Heat energy can be stored in small hot water cylinders distributed amongst homes or businesses, through to large centralised facilities capable of serving the heating demands of towns and city districts such as Rostock in Germany or Marstal in Denmark [38–40]. Storage duration can range from minutes for balancing short-term fluctuations in demand, through to seasonal operation to meet winter heat demands such as has been applied at Drake Landing in Canada or Neckarsulm Amorbach in Germany [27,41,42]. Whether centralised or distributed within individual properties, thermal storage is usually operated in combination with other technologies to deliver the heating or cooling to the point where it is needed. In centralised storage configurations, thermal energy is transferred to users typically through a heat network which brings additional complexities and sociotechnical challenges [43]. In the UK most heat networks are third generation (high temperature) which frequently see significant heat loss from poorly designed systems or uninsulated pipework [44]. This can lead to high energy costs for end users and overheating in dwellings [45]. Fourth (lower temperature) and even fifth (ambient temperature) generation heat networks are being developed to tackle these issues and enable the use of a wider range of heat sources, but are currently a niche approach especially in the UK [46–49].

Most thermal storage is *sensible*, where the storage medium is raised in temperature but does not change phase during the charge and discharge cycle. This includes water tanks, ceramic bricks in electric storage heaters, or the thermal mass of buildings themselves [13,17]. Sensible heat storage is by far the lowest cost and most ubiquitous approach at present [12,20,50]. A key limiting factor of sensible heat storage is the low energy density available, which means that large volumes of storage material are required. There is now an upsurge in interest in using the huge volume of flooded mine shafts as heat reservoirs for seasonal storage [51]. Other approaches are possible and becoming more technologically and commercially viable as well, including *latent* heat storage through phase-change materials and *thermochemical* heat storage through reversible chemical reactions [40].

2.2. *International context*

Thermal energy storage deployment is highly country and context dependent. It is impacted by physical factors such as climate, geography and geology which affect heating and cooling requirements and natural resources, as well as historical and sociocultural trends which have shaped heat provision arrangements [52–55]. Whilst in this study we focus on the UK deployment of thermal energy storage, the aim is to produce useful insights which will have cross-border relevance. Many countries are struggling with energy system decarbonisation, especially the provision of heating, hot water and cooling, whilst having made similar net zero commitments which entail rapid transition away from natural gas for heating [2,6,56–58].

Progress against heat decarbonisation goals is highly variable, with the UK's European neighbours such as Sweden, Finland and Denmark having made significant gains, supported by an abundant biomass resource combined with incumbent municipal district heating networks [57,59,60]. The UK context is most usefully compared to other countries with a temperate climate and extensive incumbent natural gas grids providing domestic heating. We can effectively think of the UK as 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 [57]. In addition to the UK, countries including the USA, Canada, the Netherlands, Italy, South Korea and Russia supply a significant proportion of households through a natural gas grid [52,61,62]. Whilst total heat decarbonisation remains low, the Netherlands has become a global leader in aquifer thermal energy storage and the US in ground thermal storage along with ice storage to mitigate summer peak cooling loads [52,55,56,62–65]. Global urbanisation trends mean that thermal storage applications which support decarbonisation in cities are particularly important [66–69]. In financial terms the global thermal storage market was valued at US$ 3.2 billion in 2016 and is expected to reach US$ 12.5 billion in 2025 [70]. This is small compared to the spend of US$ 280 billion (in 2018) on renewable energy development [71].

2.3. *UK national context*

The UK is a helpful case through which to explore the role of thermal storage in the energy transition. This is because its sociotechnical context, which whilst being unique to the UK, is broadly comparable in some respects to other countries as outlined in Section 2.2, and here we explore this context in more depth. Whilst UK carbon emissions have fallen by 49% between 1990 to 2020, this progress has largely been delivered by the electricity sector through grid-scale renewable generation developments which are remote from consumers [72,73]. The provision of heating and cooling accounts for 37% of UK carbon emissions [44], and 20% of UK emissions result from the natural gas grid which serves the heating and hot water needs of 84% of UK homes mainly through individual gas boilers [74–76]. Despite historically low fuel prices supported by its access to North Sea oil and gas, the poor standard of UK housing compared to its European neighbours has contributed to the fuel poverty rate being amongst the highest in Europe [77,78].

Continuing to meet heating demand through natural gas is incompatible with the UK's legally-mandated commitment to net-zero carbon emissions by 2050 [79]. This means that the vast majority of fossil fuel combustion for heating must be removed in three decades, including across the 23m UK households supplied by a gas or oil boiler. In comparison to the power sector where much of the energy infrastructure is centralised and distant from end users, technological options available to deliver low carbon heat will require some level of disruption for end users [80]. Current progress on heat decarbonisation is woefully adrift of the trajectory needed to reach the UK's legally-binding carbon reduction targets [81].

The continued lock-in of natural gas for heating in the UK is in part due to the extensive reach of the natural gas grid and the physical disruption that would be required replace the distributed infrastructure and appliances [82]. Gas boilers for home heating enjoy very high levels of user satisfaction and are seen as being convenient and familiar. This is supplemented by central government policy which has largely levied the costs of decarbonisation on to electricity but not gas bills, leading to the UK having one the highest gas to electricity price differentials [59,83–85]. The fossil-fuel system has traditionally satisfied the significant fluctuations in UK heat demand through storage in depleted oil and gas fields [86]. However, the closure of the UK's largest gas storage facility is expected to lead to greater reliance on gas imports [87–90]. Whilst the natural gas network currently delivers twice the energy of the electricity grid, it is the peak levels which represent the greater challenge [91,92]. The magnitude of the peaks, the maximum rate of demand increase, and the ability of these to be met by other technologies, is subject to continued debate [93].

These reasons contribute to claims that in the UK the heat sector will be the slowest and most challenging to decarbonise [80,91,94,95]. The figures on low carbon heating options reinforce this, with heat pump deployment in the UK being one of the lowest in Europe [96]. This is despite heat pumps (and associated thermal storage) playing a significant role in most heat decarbonisation scenarios in the UK [97–99]. The lack of progress, whilst not unique to the UK, as we have seen is in marked contrast to significant heat decarbonisation progress in some other European countries [59,60].

The ability to store heat on an interseasonal basis is seen as vital for the ability to mitigate winter peak loads [21,100]. Despite recognition of the need to develop this sector, the UK lags far behind other northern and central European countries [28,29]. In the UK, most thermal storage operates over short durations in the form of in-home hot water cylinders powered by electricity or in combination with gas boilers [25]. In the last 40 years in-home thermal storage has decreased because households have tended to replace their heating systems with condensing combi boilers which produce instantaneous hot water and do not require a cylinder [101]. It is estimated that tanks remain in around 11 million, or 40%, of UK homes, and another 1.8 million homes use some form of electric storage heating (through resistive heating of ceramic bricks) [28].

Despite the traditionally centralised nature of the UK energy system, there is evidence of a localising trend in the development of energy infrastructure such as heat networks, smart-grid developments and small-scale energy storage [102]. This has brought with it the active involvement of non-traditional actors such as local authorities, city regions and community organisations, who may have a range of motivations beyond profit maximisation [37,103]. This may be accelerated by the devolution of powers from central government to local and regional bodies with greater levels of responsibly for local infrastructure [102,104,105]. This may offer local authorities and other local actors the opportunity to become infrastructure providers and potentially capture some of those wider benefits. To deliver thermal storage infrastructure, new business models are required which recognise and capture the values that thermal storage can deliver, and work with the motivations of local actors in the energy system.

2.4. Theoretical basis for analysis

There are a range of thermal storage technologies available and we consider these in relation to their role in the UK energy system, including as a balancing mechanism to support growing renewable power integration. We recognise 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 [106–109]. Taking a sociotechnical perspective on the role of thermal storage in the energy transition recognises that fundamental change is complex and involves a range of aspects including user practices and institutional structures [110,111]. A number of theories have been proposed to help understand and analyse sociotechnical change, with the multi-level perspective emerging as the dominant framework [34,108].

Based around three analytical levels of micro (niche), meso (regime) and macro (landscape), the primary source of stability in the multi-level perspective is provided from within 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 [109,112]. In the case of home heating in the UK, the stable fossil-based regime encompasses 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. It is sometimes possible that exogenous landscape influences can put pressure on existing regimes and open up opportunities for novel technologies [110]. 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 [1,113–115]. 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 we explore in this research, 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 [25,108,116,117]. It is possible for niche innovations to develop in such a way that they are able to successfully compete with incumbent approaches however [118]. 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 (identified as *fit and conform empowerment*, and *stretch and transform empowerment* respectively) [119]. We consider the niche status of thermal energy storage and its potential impacts on future potential deployment.

Thermal energy storage is part of the energy infrastructure system which is inherently complex and connected in nature, and where change is influenced by a range of institutions and actors including governments, regulators and lobby groups [25,33,109,120]. The coevolutionary framework was proposed as an alternative to the MLP which gives a more explicit consideration of the role of actors and places greater emphasis on economic factors [36,121]. The coevolutionary model considers sociotechnical change through a focus on five interlocking systems: *technologies, institutions, business strategies, user practices* and *ecosystems*. Acknowledging that the systems of institutions node is particularly difficult to define, we follow the approach proposed by Foxon to broadly encompass ways of structuring human interactions, or 'rules of the game' such as policy and governance frameworks [36,122]. Whilst each system is understood to be evolving under its own dynamics, it is connected to and affects the other evolving systems though interactions and causal relationships [36,123,124]. Prior work applied the coevolutionary framework to 'open up' regimes for thermal and electrical storage in the UK, and proposed three potential pathways for how storage technologies might develop: *user-led, decentralised*, and *centralised* [25]. Whilst there was a role for electrical storage in all three pathways, thermal storage was limited to user-led (household-level storage, active user participation), and decentralised (local network storage, community and city scale, key roles for local authorities and other intermediaries) pathways.

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 [102,125–127]. 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 [37,128]. Prior work applied a classic commercial business model tool to smart grid and heat network infrastructure investments [126,129]. This found that both are complex investments which entail high upfront costs and face other lock-out challenges, but can deliver a range of values to the users, to wider society, and to investors which can help business case viability if those are factored in. Local authorities were found to pursue fuel poverty reduction and other social benefits as primary drivers in heat network investments, as well as carbon reduction [126,130]. An enhanced version of the tool, the *infrastructure extended business model canvas*, was proposed, which specifically recognises *social, environmental* and *economic development* values to aid those making infrastructure investment decisions. We apply this extended model to thermal storage projects to explore how consideration of the values sought by project developers can help to understand potential future deployment.

A focus on geographical context in the energy transition for heat, including concepts of space, place and scale, opens up questions such as: Why do niches emerge in some places and not others? What is the role of local and regional institutions, policies and forms of governance in the emergence and diffusion of innovations? [131–133]. There has been a growing interest in the role of cities in shaping and delivering sustainable transitions [134–137]. Cities are sites of local policy interventions which may impact on thermal storage and associated heat network deployment [138–140]. They are also agglomerations of consumers and producers of heat with the potential to be connected together through heat networks employing thermal storage [47,100]. We consider the locational aspects of UK thermal storage and how this may impact future deployment.

Finally, within sociotechnical transitions, the role of organisations has been explored through their role as intermediaries to nurture innovations [141–143], niche actors [144], incumbents [54], and institutions [103]. These can include national and local governments, traditional energy supply companies, novel energy services companies (ESCos), community organisations, research and technology firms, industry associations, and so on [145]. We explore the organisations involved in current thermal storage developments and their role in the changing UK energy system.

3. Method

We undertook a desk-based survey of thermal energy storage projects in the UK between January 2018 and February 2019. The projects reviewed were identified from prior work, web searches, and snowballing from personal contacts. This was a broad survey of the field without attempting to achieve data saturation, and employed a criterion approach to purposeful sampling to include a range of technology and project types [146]. Project data included local authority meeting minutes, officer reports, planning application submissions and a range of other published sources. A full list of 186 source materials is included in supplementary data.

The analysis took place in two phases. First, we classified thermal storage projects according to a framework of sociotechnical attributes. This framework was based on the literature referred to in Section 2.3 and adapted for the specific needs of this research. Table 1 provides a summary of the project attributes from the survey field.

Once each project was assigned a set of attributes, we then applied an analysis of technology, location, and organisational characteristics, as well as an exploration of sociotechnical factors using the nodes of the coevolutionary framework. Finally, we carried out a qualitative thematic analysis on the source materials, applying the extended infrastructure business model canvas to identify the types of traditional economic values and non-traditional social, environmental and local economic development values project developers sought to capture.

Project data included publicly available materials including reports, presentations, videos, news articles, and a range of other sources (for a full record see supplementary materials). However, the study was limited by the availability of good quality data sources and we discounted sixteen potential projects due to lack of available data. The standard for project eligibility for inclusion was that they were at least in development phase, and each of the classification attributes could be assigned. An example of where this standard was not met was with a new housing development in the city of Nottingham where a communal electric battery and thermal store were initially proposed as part of a community energy demonstration project. The project was interesting and within scope but we could find no evidence that the thermal storage element had progressed beyond the theoretical stage.

Table 1
Project classification framework 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
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

We found that local authority developers tended to make good information publicly available, for example through published reports from officers to councillors seeking decisions or giving updates. Such documents were made public via local authority websites as part of the normal business of holding open meetings. Social housing developers outside of local authorities, known in the UK as Registered Providers (RPs), and other public bodies, provided reasonable but somewhat lower levels of data. It was more challenging to collect enough data from developments led by private companies. However, several projects of different types were undertaken as part of research or demonstrator pilots, and as such published rich data was readily available. Because of the likely bias inherent in the source materials available, a source evaluation process was carried out on each material to explore aspects such as audience, originator, likely motivations, relation of source to project, relation of source to thermal storage, etc.

To identify thermal storage projects included in the sample, each was given an alphanumeric identifier, based on the type of thermal storage employed. Table 2 lists the identifiers along with a brief description of the project including the type of thermal storage. A full classification of each project by attribute is included in supplementary materials.

A map of projects with associated identifiers can be seen in Fig. 1 showing geographic spread across the UK. These identifiers are used in results section below when attributing direct quotations from source material.

4. Results

In this section we present the results from our desk-based survey and analysis to address the three research questions in turn. To address the first question around the current state of thermal energy storage in the UK, we analysed the data collected on the thirty-three thermal energy storage projects. Our analysis covered 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.

4.1. Technology

We explored technological aspects of thermal storage deployment including the physical storage medium itself, whether this was used for 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. We found a diverse range and combination of technologies and approaches and we present a summary in Table 3 with a more detailed analysis below in sections 4.1.1-4.1.4 below.

4.1.1. Storage type, approach and horizon

Table 3 shows that a large array of different technological options and combinations for thermal storage were being adopted in the projects surveyed. Whilst tank-based storage was the most common technology, eight other types of storage were identified. Considering the type of storage as being either 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. Whilst we didn't find any projects employing thermochemical storage, we identified three latent heat approaches with storage to reduce peak cooling demand in commercial premises, and phase-change materials as part of a dwelling-based 'heat battery' system where the phase-change material (PCM) is charged through grid or on-site electricity and releases thermal energy to deliver on-demand heating and hot water when needed.

We found several approaches to the use of thermal storage which we collectively termed 'geoexchange'. Instead of the continual removal of

Table 2
Project identifier codes with associated project description.

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.
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

(continued on next page)

Table 2 (*continued*)

Project identifier	Description
	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.
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.

Table 3

Summary of technology analysis and number of projects with each attribute indicated in square brackets (Note some projects feature multiple attributes so numbers do not equal 33 in all attribute class sections.)

Storage Type	Location of storage	Heat generation	Heating system type
Aquifer [6]	Centralised within network [27]	Balancing heating and cooling [6]	Domestic [5]
Borehole [3]	Distributed throughout network [2]	Air source heat pump [2]	Communal (one building) [3]
Cryogenic [3]	Decentralised within end-user property [5]	CHP/CCHP [7]	District (several buildings) [10]
Electric storage heater (ceramic bricks) [3]		Grid electricity [3]	District (neighbourhood) [8]
Phase-change material [1]		Locally generated electricity [2]	District (city-scale) [6]
Tank [15]		Energy from Waste [2]	
Heat sharing network [2]		Geothermal [4]	
Mine shafts [2]		Sewerage [2]	
Underground mass transit [1]		Solar thermal [1]	
		Water source heat pump [5]	
		Waste heat [7]	
Heating/cooling	**Storage horizon**	**Grid balancing**	**Heat network type**
Heating only [16]	Short-term [23]	Yes [14]	High temperature [11]
Both heating and cooling [17]	Seasonal [12]	No [19]	Low/ambient temperature [6]
			Not applicable / unknown [17]

heat typical of most ground source heat projects, these arrangements actively recharged heat sources over the year using waste energy to prevent system decline and enable constant balancing. This was through: a series of university buildings connected to each other and to aquifer thermal storage via an ambient temperature heat network; standalone commercial sites recycling internal heating and refrigeration with ground thermal storage through novel directional drilled boreholes; summer heat recycling from a local authority centre with large cooling needs; and, an ASHP powered through excess summer solar PV electricity generation for a community-owned facility and connected to small ambient heat network to serve nearby homes. Another approach found was to forgo the ground storage element altogether and use the network itself as a store and internal balancing mechanism, in this case to share heating and cooling needs across a mixed residential and hotel complex.

Twelve projects operated on a seasonal basis where heat energy was stored to meet some winter peak demand, and Table 4 shows some technical and configurational characteristics of these seasonal storage projects. These projects featured centralised network storage primarily through aquifers, abandoned mine shafts and boreholes, and were combined with heat networks to deliver heat to end users. No decentralised dwelling-based seasonal storage was identified. In one case the chalk aquifer was used to meet the seasonal heating and cooling needs of a new wing of a national museum and was recharged with waste coolth over winter from the provision of heating, and vice versa. At the start of summer, the scheme takes cold energy directly from the aquifer through a "cold" borehole. As the season moves on, a heat pump is used to lower the temperature. The cooled water circulates and is returned to a different part of the aquifer store for use in winter through the "warm" borehole.

4.1.2. *Heating system type and storage location*

Heating systems in which thermal storage was employed ranged in scale from individual dwelling storage through to forming part of city scale district heat networks. Most projects in our sample employed storage centrally and connected to end users through heat networks for heat delivery. Some projects in our sample employed traditional third generation high temperature heat networks, and 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 low or ambient temperature (fourth or fifth generation) heat networks with thermal storage, and these included geoexchange projects as well as the project which combined river source heat with 'energy loop' heat sharing network. Decentralised dwelling-based storage was variously employed in the direct provision of heat through electric storage heaters which store heat in ceramic bricks or through water tanks forming part of the dwelling heating system. Storage was used to balance the internal heating and cooling needs of single commercial sites through the ground or through use of the underlying aquifer.

Table 4

Seasonal storage project characteristics.

Storage type	Heat generation
Aquifer [6]	Balancing heating and cooling [2]
Abandoned mine shafts [2]	Air source heat pump [1]
Borehole [3]	Energy from Waste [1]
Cryogenic [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]

4.1.3. Heat generation source and the role of thermal storage

Eleven types of heat generation were identified across the projects and all, apart from the CHP projects, relied on electricity (grid or locally generated) to power the provision of heat. Whilst CHP generation is not low carbon when fired with natural gas, 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 (heating, cooling and electricity) 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, onsite renewable electricity, but also included using 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 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 and within the energy centre, a thermal store vessel had been installed to complement two gas-fired CHPs which supply electricity directly to the heat pump when the power from the grid was most expensive.

We linked the primary heat generation to the type of thermal storage and this is shown in Table 5. We found in our sample that some heat generation sources were more closely aligned to particular types of thermal storage, such as all CHP/CCHP projects utilising tank thermal storage, and the electric storage heater projects utilising grid electricity. Some storage types were more flexible, with waste heat for example being compatible with four different approaches to heat storage.

4.1.4. Grid balancing provision

Fourteen projects in the survey were identified as fulfilling 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 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. This was reflected in project business models, with income from grid flexibility payments or savings from dynamic pricing tariffs forming part of project viability. A summary of key attributes of grid balancing projects is shown in Table 6 and demonstrates that this functionality was compatible with a range of thermal storage types, heat generation and supply arrangements.

Table 5
Heat generation type with associated thermal storage type.

Heat generation	Storage type
ASHP [2]	Borehole [1], Tank [1]
Balancing heating and cooling [6]	Aquifer [2], Borehole [3], Heat sharing network [2]
CHP/CCHP [7]	Tank [7]
Energy from Waste [3]	Cryogenic [1], Tank [2]
Geothermal [4]	Cryogenic [1], Mine shafts [2], Tank [1]
Grid electricity [3]	Electric storage heater (ceramic bricks) [3]
Locally generated electricity [2]	Phase change material [1], Cryogenic/Tank [1]
Sewerage [2]	Tank [2]
Solar thermal [1]	Tank [1]
Waste heat [7]	Aquifer [2], Borehole [1], Heat sharing network [1], Tank [3]
Water source heat pump [5]	Aquifer [4], Heat sharing network [1]

Table 6
Grid balancing project characteristics.

Storage type	Heat generation	Heat network type
Tank [6]	Balancing heating and cooling [3]	High temperature [5]
Borehole [3]	Air source heat pump [1]	Low/ambient temperature [3]
Electric storage heater (ceramic bricks) [3]	CHP/CCHP [4]	Not applicable (decentralised) [6]
Heat sharing network [1]	Grid electricity [3]	
Phase-change material [1]	Locally generated electricity [2]	
	Energy from Waste [1]	
Location of storage	**Heating system type**	**Business strategy**
Centralised within network [8]	Domestic [5]	Experimental/demonstrator [6]
Distributed throughout network [1]	Communal (one building) [2]	Commercial basis [2]
Decentralised within end-user property [5]	District (several buildings) [2]	Non-commercial basis [6]
	District (neighbourhood) [3]	
	District (city-scale) [2]	

4.2. Geographical context

We mapped the thermal energy storage projects by primary location to examine geographical spread and locational context. The distribution of the projects across the UK is shown in the map at Fig. 1. Projects were located across England, Scotland and Wales (but 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. We found hotspots of activity in developing aquifer storage in London, using the London Basin chalk aquifer, with one more 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 [28]. 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 [147]. We found activity in urban centres above previously worked coal seams in South Wales, the Midlands, and central Scotland. Many towns and cities developed due to their proximity to coal reserves, and it is believed that around 28% of homes in the UK are suitably located to benefit from this [121].

We found a clear clustering of projects in urban locations with only one site in a non-urban setting. In Table 7 we identified the projects by area and ranked these areas in population terms to illustrate the weighting towards urban areas in our sample, with a hotspot of projects visible in the #1 ranked population centre in the UK.

4.3. Organisations

To investigate the role and importance of organisations in the context of thermal energy storage, we classified each organisation identified during the research. A total of 195 named organisations were identified in the delivery of the thirty-three projects. These were classified using a framework of organisational types we derived from literature and self-description by the organisations. Fig. 2 summarises the results of this classification showing that the most prominent types of organisation involved in thermal storage projects were local authorities, technology developers, consultants and universities.

To assess the roles that these different organisations were undertaking in thermal storage projects, for each of the source materials included in the desk survey we assessed the type of organisation

Fig. 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).

Table 7
Project locations identified by broader 'built-up area' [148] 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

producing the material, what relation they had to the project in that case, and why the source material was produced. Table 8 shows a summary of this analysis. This shows the prominence of consultants, local authorities and the technology developers in thermal storage development in our sample. It also demonstrates the complexity of roles that organisations take in relation to the successful rollout of thermal storage projects. A significant proportion of sources were produced in order to promote the project or technology, and this emphasises that thermal storage is seen as a positive 'selling point' for a project, development or area. Materials had also frequently been produced at the point of investment decision, in order to demonstrate business case viability and seek approval, or were submitted to planning authorities to demonstrate that thermal storage was delivering benefits which helped the development meet planning requirements.

4.4. Sociotechnical characteristics of thermal energy storage in the UK

In Sections 4.1–4.3 we examined the current state of thermal energy storage deployment in the UK focusing on technologies, locations and organisations. To explore broader sociotechnical characteristics of the context which appeared to be impacting on deployment of thermal energy storage, we explored the role and visibility of the other four categories in the coevolutionary framework: *ecosystems, institutions, business strategies* and *user practices*.

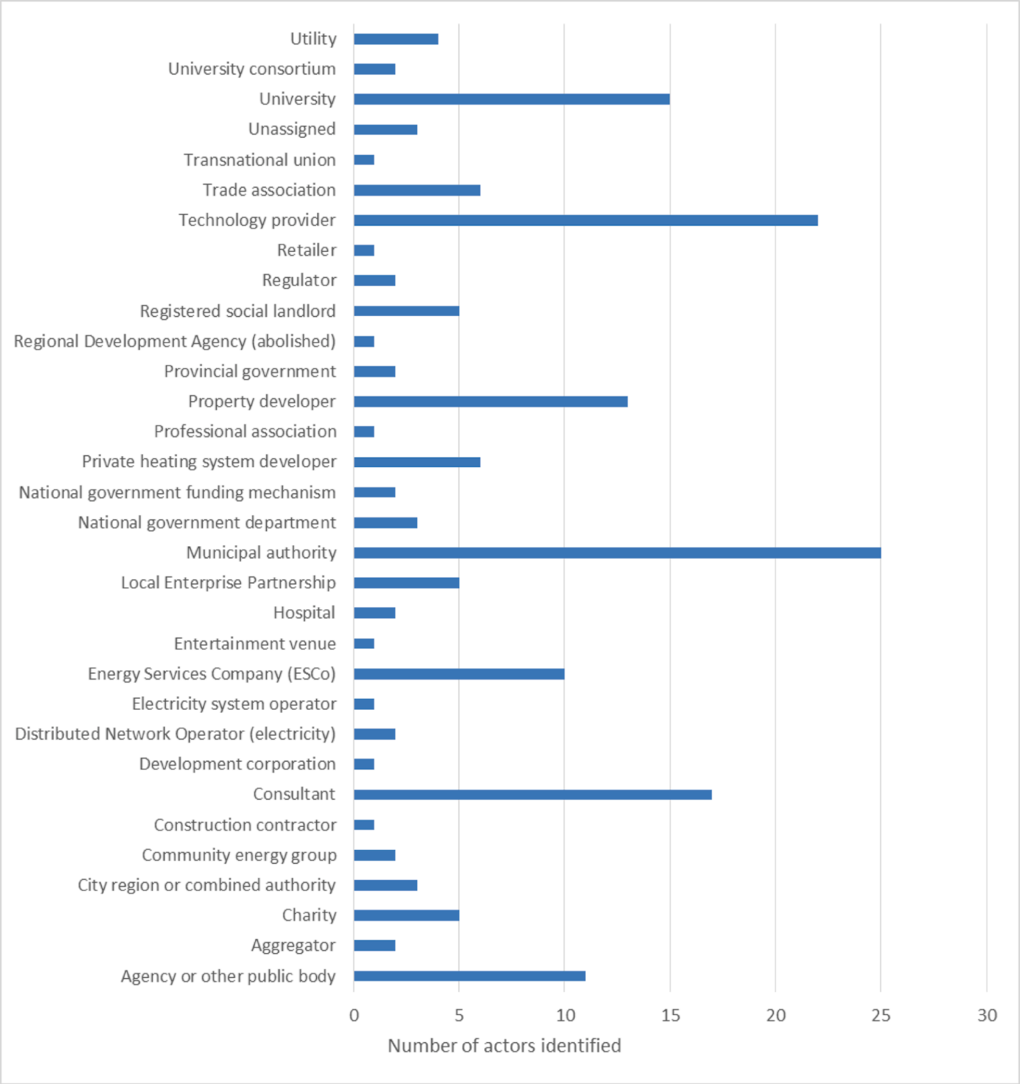

Fig. 2. Organisations involved in survey projects classified by organisation type.

4.4.1. *Ecosystems*

A key dynamic we identified was the desire by thermal storage project developers to deliver carbon reduction benefits. The ability of thermal energy storage to help reduce air pollution as part of an alternative to gas boilers was also identified as a driver by nine of the projects. 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 the prominent thermal storage tank supported the heat network to make the most of waste heat from a nearby coal power station.

We also found potential ecosystems consequences of some types of thermal energy storage, especially aquifer-based systems. Our survey found five projects making use of the London Basin chalk aquifer to provide heating. Licensing for water abstraction for heating or cooling purposes is regulated by the Environment Agency, and they had reported increased aquifer temperatures caused by demand for cooling in central London. This is 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 [149,150]. 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, and the Coal Authority is keen to explore the use of these assets for energy purposes [151].

4.4.2. *Institutions*

Taking a similar broad definition of this node as proposed by Foxon, we find energy policy and governance arrangements impacting on the deployment of thermal energy storage, including a prominent role for central government policy and mechanisms to support low carbon heat provision which has an impact on thermal storage 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. The non-domestic RHI is due to close to new applications in March 2021 [152]. The mechanism operated by guaranteeing a financial return to the scheme operator on a p/kWh of useful heat delivered basis (for 20 years in the case of the non-domestic version of the scheme). It therefore relied on willingness from scheme developers to incur the higher initial cost with a recognition that this is recovered over time. The RHI focused on the low carbon generation aspect of a development rather than

Table 8
Organisations producing materials on thermal storage, their relation to the project, and motivation for production.

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

thermal storage per se but it covered ground, water and air source heat pumps. 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.

We also considered local policy and governance arrangements and their impact on thermal storage deployment by searching for references to devolved powers instruments relevant to urban locations, such as strategic regional authorities, city deals, and national devolved powers instruments. Eighteen projects were identified where funding or other support had been received 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 mine shafts. The projects featured 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 was national planning policy, building regulations and the ability of devolved administrations to have local control over their planning policies. We found seven projects which involved construction of a new development where thermal energy storage was chosen. Six of these projects were in London and satisfying local planning permission requirements for carbon reduction was referenced as part of the decision to choose heat pumps with thermal energy storage. National planning policy applies to most local planning authorities, requiring new developments to achieve 20% reduction in carbon emissions (compared to a standard model of the building). However, following devolution of powers in 1999 [153], 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. The need to meet these more stringent carbon reduction targets, and the choice of heat pumps with thermal energy storage to fulfil this because of its carbon benefits, was cited in a number of these cases.

4.4.3. *Business Strategies*

Here we found evidence of innovation in business models to make thermal energy storage viable, for both type of ownership and operational model employed. Within the chosen model, a range of values were 'stacked' to attain viability. We identified eight thermal storage schemes which intended 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 storage was rolled up in the overall build cost of the site to be recovered through sale of apartments, office space, etc. Taking a broader definition of commercial viability to include schemes designed to be internally financially viable (rather than being undertaken as research or demonstrator projects supported by one-off or time-limited funding streams) we 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 demonstrate wider applicability of thermal storage business models on this basis. Finally, there were eleven projects where the approach was being piloted as part of experimental or subsidised demonstration projects and relied on research or central government innovation funding. These included novel concepts such as phase-change material heat batteries and the minewater heat 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. In the multi-level perspective, these would be identified as 'niche' developments operating within 'protected spaces' where they are not subject to the commercial pressures of the regime.

The cases used a range of business models for project ownership and operation across the survey and these are summarised in Table 9.

Local authority ownership was most prevalent across the sample, and these tended to be large district heat schemes employing centralised thermal storage. 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 model. As an example of this in operation, one of the

Table 9
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

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 are combined with a 330,000-litre thermal store to enable heat supply to continue overnight when the engines are not operating. The local authority entered in to a 30 year "*cooperation agreement*" with the ESCo which "*binds the parties to work together to develop and expand the system*" [TANK11]. 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.

4.4.4. *User practices*

The documentary evidence collected was focused on the business case and decision to undertake the project rather than the experiences of users following installation. However, in some cases the importance of individuals in other aspects of project feasibility and development was clear. We identified key individuals within the lead organisations involved in thermal storage developments playing a prominent role in pressing for the low carbon option, including specifically for the thermal storage elements. This was evident in one of the projects where a private developer had constructed a mixed-use residential and hotel complex balancing 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, this role would be interpreted as a niche actor, and as such would indicate the continued niche status of the technology. We did find one project where follow-up analysis of user experiences was undertaken because one of the research criteria required significant follow-up and analysis of the user experience after installation. The post-installation analysis of the decentralised dwelling based heat storage project [HEATBATT1] showed that cost reductions were being delivered to the residents as a result of the thermal energy storage, despite anecdotal feedback from residents that they were not seeing any savings. This suggests that user experiences are unlikely to be universally positive and there is a need for monitoring and evaluation of thermal storage technologies to complement and support successful rollout.

4.5. *Values of thermal energy storage*

In the final part of our research we applied a qualitative thematic analysis to the source materials to explore the stated motivations and drivers behind thermal storage projects. We explored whether these were limited to a more traditional neoclassical understanding of value through simple financial returns as would be expected in traditional 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. We applied the extended infrastructure business model framework to classify the range of values targeted according to four headline value streams: *social, environmental, economic development* and *fiscal*. Following the Extended Infrastructure Business Model Canvas approach, the *fiscal* value stream was expanded 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.

Overall, we found that thermal storage project developers were looking to achieve multiple forms of value beyond simple financial returns. Through our thematic analysis we identified forty-seven non-traditional values which we coded beneath the headline themes. Table 10 provides an overview of these drivers across the thirty-three projects ranked in order of prevalence. Beneath these headline themes we indicate and rank the two most prevalent values targeted. We note that the values and subsequent ranking are subject to interpretation in our coding, and this is evident when considering some of the values which spanned more than one category.

Table 10
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)**
• Energy bill reduction 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]
Economic development	**21**	**(4)**
• Enhancing reputation of area	12	[∼6]
• Take part in research programmes	12	[∼6]

The search for environmental benefits, specifically through tackling carbon emissions, was the most prominent non-traditional value sought, with this being identified by twenty-nine projects included in the survey. Seventeen of the projects sought to capture values in all four value capture headline categories. We applied the project classification framework to run a series of cross-tabulations for the search for non-traditional values against a range of project attributes such as storage type, ownership model, pathway alignment, and so on. There was little evidence of clear patterns of value capture being correlated with particular project attributes. Local authority owned projects sought a wide variety of social benefits including health improvements, the 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.

5. Discussion

We set out to explore, in the case of the United Kingdom, the current state of thermal energy storage 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. This work was also intended to have relevance to non-UK settings, especially those with broadly similar sociotechnical characteristics such as an incumbent natural gas grid for domestic heating.

Overall our analysis has revealed thermal energy storage projects in the UK exhibit a vibrant mix of technologies and supply arrangements in various combinations, from micro scale domestic storage in single dwellings through to centralised storage integral to city-scale heat networks serving many thousands of end users. We found thermal storage in various formations is enabling a range of renewable heat sources to be used including capturing heat which would otherwise be wasted, and is helping to link up and create synergies between isolated urban energy systems. The diversity of technology types and project attributes in our sample suggests strong potential and innovation activity in the sector. However, the lack of clear 'winners' can be an indicator that thermal storage technologies have yet to progress beyond niche status in the UK

[154], or that of the many possible thermal storage niches, none have yet emerged as a 'strategic' niche capable of transforming the environmentally unsustainable regime [118].

Whilst we found applications of decentralised domestic heat storage in tanks, ceramic bricks and in one case through novel phase-change materials, thermal storage 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. These network and thermal storage combinations were being used along with distributed heat pumps to capture waste heat such as from the sewerage system, as well recycle heat and coolth between connected nearby buildings and different types of energy users in the same network. Our 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 [46–48,100]. However, these findings have 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 [102]. Future work will explore the legal and governance complexities of later generation heat network development. Our findings may also support the proposition that local authorities are key local actors in enabling wider deployment of both district heating and thermal storage because of their ability to facilitate connections between disparate heat consumers and producers [141,155].

A promising area of development was application of thermal energy storage in geoexchange configurations. This was where ground-coupled heat exchangers and ground/water source heat pumps were employed to store heat and cold energy both on a daily and seasonal basis with active ground or aquifer recharge. This approach originated in the US where there are now over 600,000 installations, but it is seen as a relatively novel approach in the UK especially for domestic purposes [55]. Whilst some research effort is exploring the technical potential of this approach in Europe and internationally [156–158], little research with a specific UK sociotechnical focus exists and future work will need to explore the potential for wider deployment in urban settings in the UK. We also found interest in the potential for storing heat in abandoned flooded mine shafts, although this was at an early stage with the three projects identified in early development phases. This compares to the Heerlen project in Netherlands for example which entered development phase in 2003 [51]. This is a vibrant area of emerging research which in the UK is mainly focused on the technical challenges of harvesting heat energy from challenging hydrogeological environments [147,159–161], but in Europe where these approaches are more established, 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 [51]. Contrary to earlier research which found little evidence of seasonal or long term storage in the UK [28,29], we identified a third of projects in our sample employing storage to meet seasonal peaks, which suggests 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 [40,50], and this is backed up by our findings with seasonal storage delivered through five aquifer schemes and three with borehole ground storage.

Our results indicate that thermal storage is being employed to help in actively balancing the electricity grid, and in turn, to support greater renewables integration and reduce costs of grid reinforcement. Indeed, we 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) [18,19]. 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 is otherwise passed on to consumers via energy bills. This is especially the case for dwellings served by electric night storage heaters (in ceramic bricks). Because non-local authority social landlords retain a greater proportion of dwellings with electric storage heating [162], upgrading these old systems with smart controls and giving access to a revenue stream from grid balancing, may present an opportunity for them to improve the 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 [11,14].

We applied the coevolutionary framework to explore other aspects of the sociotechnical transition for thermal storage and low carbon heat, and this helped to identify that deployment is intertwined with a complex set of institutional and governance arrangements. These include national policy measures to drive low carbon heat which are helping attain project viability, as well as restrictions on how national planning rules can be applied locally and which can put pressure on developers to choose thermal storage and heat pump combinations over fossil-based heating where these rules have been toughened. There are also outstanding national decisions about the future of the natural gas grid, and whether the UK pursues a hydrogen, electrification or mixed route to heat decarbonisation [91,163]. On an individual project level these are likely to have an impact in regard to the types of support or incentive available to enable business model viability, as well as impacting on national planning policy which is implemented on a local basis within the requirements of the National Planning Policy Framework. With the emphasis in our findings 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, and our results suggest innovation in business models is helping to enable project delivery, following earlier findings in regards to other aspects of the local energy system [37]. These business models we found to be coevolving with the institutions and technologies systems for example, as 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 [25] highlighted that developing new business and commercial arrangements will be one of the key challenges to the deployment of thermal storage technologies, and we found that this is well underway with evidence of stacking multiple forms of financial and non-financial value [127]. We found a range of public and private ESCo arrangements were employed and were helping to drive improvements in system operation. This supports prior work which proposed that ESCo models (where an organisation is awarded a contract to meet the energy needs of the client for an agreed cost thus placing an onus on the contractor to take steps to reduce energy demand and costs to improve their own returns) could play an increasingly important role in a low-carbon transition of the UK energy system [164–166]. Whilst not negating the need for financial viability, finding novel business models in our sample does, we believe, provide some evidence that scheme operators and investors are being creative about how they may be able to achieve this.

We 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 [102,130,144]. Local authorities appeared to be prominent actors in our sample, and we identified other local energy actors including social landlords, universities, and devolved authorities, as well as continuing importance of for-profit organisations such as technology developers, consultants, and property developers.

Considering the impact of the incumbent natural gas grid, we might expect 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, we saw a clear trend for projects to be located in urban settings which are connected to the gas grid. This suggests three things. Firstly, that thermal storage connected to end users through heat networks is suited to deployment in urban settings given the proximity of heat producers and consumers [130]. Secondly, it supports the case for cities as sites for development and sustainable heat innovation [155,167]. 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, we believe thermal storage is already supporting the vision of urban energy systems based on 100% renewables [14,21,22].

The coevolutionary framework was useful in focusing attention on the importance of business strategies, and this backs up one of the central claims by Foxon [36] of the benefits of providing explicit emphasis on this area. However, we found an important role for actors where key individuals within organisations were acting as the primary drivers of change. As this aspect is split between systems of institutions and systems of user practices elements of the framework, it was not as useful in this regard and it would benefit from a node specifically dedicated to 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 [117]. We also found it useful to draw in elements of the multi-level perspective to shine a light on issues of the incumbent regime and technological lock-in [108–110]. This helped to recognise where some projects were operating within protected spaces where they were insulated from the incumbent regime [119]. In our sample, this was mainly visible through research, demonstrator, or projects reliant on otherwise one-off funding streams to support schemes that would likely not have taken place otherwise (indeed, *additionality* is frequently a prerequisite for eligibility to apply for such funding). The positive but incremental innovation we find evidence of in thermal storage approaches may be symptomatic of a stable regime subject to lock-in mechanisms and path dependence [168]. However, applying the empowerment framing of Smith & Raven [119], we found some evidence that thermal storage advocates 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 technology in documents produced by technology developers in our sample suggests they are tapping into 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. We found 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, we focused on a particular aspect of the business strategies element of the coevolutionary framework, the search for non-traditional values by project developers, through applying the value categories from the extended infrastructure business model canvas proposed by Foxon et al. [126]. The aim of this was to explore whether those making investment decisions in thermal energy storage 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 supporting decisions to invest in lower carbon alternatives. Our primary finding was that project developers were looking to capture a broad range of values across the non-traditional categories, and beyond simple financial returns. We found a clear focus on carbon reduction but also many social, economic development, and traditional and non-traditional fiscal values being sought including cost savings by different actors within the value chain. We infer that the local actors are taking a range of non-traditional values into consideration when making investment decisions. However, our 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, if not the only driver, were still central to thermal storage investment decisions.

With regard to the range of non-traditional values sought, in line with prior research regarding district heating [126,130], we found local authority-led heating projects sought to achieve health and wellbeing, fuel poverty reduction and other social benefits, although we found these second to carbon reduction drivers. We did not find patterns in the data suggestive that certain thermal storage technology configuration, lead organisation type or other project attributes had a significant impact on the types of values sought. In our 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 particular benefits to that element alone. In some cases, such as with the dwelling-based heat batteries for example, it was evident that the thermal storage was the driver behind the benefits the project was looking to deliver. In essence, 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 CRY02). This emphasises that thermal energy storage cannot be considered in isolation from the local energy system of which it forms a part.

In the UK we continue to see the effects of the powerful lock-in of natural gas through a combination of regulations, sunk infrastructure investment and resistance from vested interests identified by others, with potential landscape and regime impacts [54]. At the time of writing, the latest advice from the UK government's independent Climate Change Committee has released their advisory plan for the 6th carbon budget to put the UK on the trajectory to net zero emissions by 2050 [97]. Defying some expectations this advises primary heat decarbonisation through electrification using heat pumps (with associated thermal storage), with relegation of a repurposed hydrogen gas grid to specific regional contexts and industrial clusters. Future work is needed to establish the impact of this changing policy environment on thermal energy storage and explore these issues along with other sociotechnical factors on the deployment of the geoexchange thermal storage approach in the UK.

Whilst the findings discussed here have focused on the specific UK context, thermal storage technology can be applied in any location where there is a temporal mismatch between heating or cooling demand and energy generation. It is helpful to compare our findings to the situation in other countries facing broadly similar decarbonisation commitments, liberalised energy markets, and incumbent natural gas grids. 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 [52,62]. 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 [52,62,64,65]. In the case of the US, with little national federal policy or support [57], the country has become the world leader in geoexchange type systems [55], with 27 known manufacturers serving mainly the domestic heat market [169]. This experience from other countries suggests that there is potential for thermal energy storage technologies to flourish against the backdrop of fossil-fuel based technological lock-in.

Our analysis shows that thermal energy storage can connect the electricity and heat sectors because it can respond to grid price signals to deliver heat provision whilst helping to balance intermittent renewable electricity generation. We identified fourteen thermal storage projects in our sample operating on this basis. Coupled with a decarbonising electricity grid, our findings suggest that thermal energy storage 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. However, it is important to note that not in the UK or in any comparable country do we currently see the drastic pace and scale of energy system transformation required to reach zero carbon in the timeframe which will keep global temperature increases anywhere close to 1.5°C, whether thermal energy storage is being adopted or not. Therefore, whilst specific low carbon technologies and a detached critical social science analysis of those technologies can be useful, this must take place alongside a more fundamental realignment of the energy system and a bold research agenda which recognises and challenges systemic barriers to this.

6. Conclusions

In this work we set out to address gaps in knowledge on the current state of thermal energy storage in the UK, to explore what are some of 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 we present reveals a multiplicity of combinations of heat generation and supply arrangements with little evidence to show that any dominant types or arrangements are emerging. Our 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. Thermal energy storage can support a fully decarbonised energy system through three primary routes: by providing grid benefits, price benefits, and facilitating renewables integration, and we saw examples of the technology being operated to pursue each of these. We found thermal storage capturing waste energy and creating connections and synergies between urban systems including electricity, heat, sewerage, waste and transport. In addition, we saw local energy actors seeking to leverage wider environmental, social and local economic regeneration benefits from thermal storage investments. However, our 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 thermal storage deployment. Our findings suggest that thermal energy storage currently remains a relatively 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, and the closure of the non-domestic RHI in early 2021, the road in the short term at least may be bumpy. However, in the medium to long term, the natural gas grid for home heating must be decommissioned or repurposed for the UK to meet its mandatory carbon emissions reduction targets and this landscape pressure supports the transition to a new regime especially for domestic heating. Acknowledging thermal energy storage can only do so much to address the pace and scale of the transformation which is currently woefully adrift of a climate-safe trajectory, our findings suggest it has an important role to play in transitioning to a fully decarbonised energy system.

Funding

This work was supported by the UK Engineering & Physical Sciences Research Council Doctoral Training Programme

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.est.2021.102877.

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