Department for
Energy Security
& Net Zero

Exploring the take-up and usage of thermal energy storage in heat networks

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Contents

Glossary

ASHP (Air Source Heat Pump)	A heat pump is a device that transfers heat energy from a heat source to a demand destination. Heat pumps are often designed to move thermal energy in the opposite direction of spontaneous heat transfer by absorbing heat from a cold space and releasing it to a warmer one. Air-source heat pumps are used to transfer heat between two heat exchangers: one located outside, fitted with fins through which air is forced by a fan, and the other, which directly heats water, which is then circulated, often via storage, to a heat emitter (in the case of district heating).
ATES (Aquifer Thermal Energy Storage)	A thermal energy storage system that uses groundwater aquifers to store heat or cold for later use in heating or cooling buildings. The system injects and extracts water at different temperatures according to seasonal needs.
BTES (Borehole Thermal Energy Storage)	A method of storing thermal energy in the ground through an array of boreholes. Heat is transferred to or from the ground via vertical pipes in these boreholes, typically used for seasonal storage in district heating systems.
CHP (Combined Heat and Power)	A technology that generates electricity and captures the heat that would otherwise be wasted to provide useful thermal energy for space heating, cooling, domestic hot water, and industrial processes.
DHN (District Heat Network)	A system of insulated pipes that distributes heat from a central source to multiple buildings or homes in a district, neighbourhood, or city. Heat sources include renewable technologies, waste heat recovery, or conventional heating systems.
DNO (Distribution Network Operator)	Organisations that own and operate the distribution network of towers and cables that bring electricity from the national transmission network to homes and businesses. They must be notified of major electrical changes, such as installing heat pumps.

EfW (Energy from Waste)	The process of generating energy in the form of electricity and/or heat from the incineration of waste materials. This provides an alternative to landfill disposal while recovering energy from waste that cannot be recycled.
EPC (Energy Performance Certificate)	A rating scheme (from A to G) that summarises the energy efficiency of buildings in the EU and the UK. Certificates are valid for 10 years and provide information about a property's energy use, typical energy costs, and recommendations for improvement.
FERC (Federal Energy Regulatory Commission)	An independent agency in the United States that regulates the interstate transmission of electricity, natural gas, and oil. It oversees wholesale electricity markets and interstate electricity transmission.
GHNF (Green Heat Network Fund)	A UK government funding scheme designed to support the development of low and zero-carbon heat networks by providing capital funding to public, private, and third-sector applicants in England and Wales.
GSHP (Ground Source Heat Pump)	A ground-source heat pump transfers heat from the ground—whether through a horizontal ground loop or a vertical borehole—to heat water (usually in a tank), which is then used to provide heat and hot water within a property. It is powered by electricity.
HN (Heat Network)	A distribution system of insulated pipes that takes heat from a central source and delivers it to multiple buildings. Also known as district heating, it can reduce carbon emissions by utilising waste heat or renewable heat sources at scale.
HNDU (Heat Networks Delivery Unit)	A unit within the UK government that provides funding and expert support to local authorities in England and Wales for the development stages of heat network projects.
HNSU (Heat Network Support Unit)	A Scottish government initiative that provides technical, commercial, and financial support for developing heat networks in Scotland.
HNIP (Heat Networks Investment Project)	A UK government capital investment programme that offered grants and loans to public and private sector organisations to increase the number of heat networks being built in England and Wales.

IRENA (International Renewable Energy Agency)	An intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international cooperation on renewable energy.
LCITP (Low Carbon Infrastructure Transition Programme)	A collaborative partnership between the Scottish Government and Scottish Enterprise, Highlands and Islands Enterprise,
LDES (Long Duration Energy Storage)	Energy storage systems can store large amounts of energy for extended periods (typically more than 10 hours), allowing for the matching of energy supply and demand over longer timeframes.
NESO (National Energy System Operator)	An organisation responsible for managing the flow of electricity across a nation's transmission system, ensuring a balance between supply and demand, and maintaining system stability.
PCM (Phase Change Material)	Materials that can store and release large amounts of energy through changing their physical state (e.g., from solid to liquid). They are used in thermal storage systems for heating and cooling applications.
PTES (Pit Thermal Energy Storage)	A large-scale thermal energy storage method using a pit filled with water or a mixture of water and gravel covered with an insulating lid. It is typically used for seasonal storage in district heating systems.
R&D (Research and Development)	Activities undertaken by businesses or organisations to innovate and introduce new products, systems, or improvements to existing ones. This includes developing more efficient technologies and approaches in the context of heat networks.
SHNF (Scotland Heat Network Fund)	A funding program from the Scottish Government designed to support the development and expansion of heat networks across Scotland as part of the country's transition to net zero emissions.
SHNZHF (Social Housing Net Zero Heat Fund)	A Scottish funding program that supports social housing providers in retrofitting their properties with zero-emission heating systems to reduce carbon emissions and tackle fuel poverty.

STES (Seasonal Thermal Energy Storage)	The storage of heat or cold for periods of up to several months. The thermal energy can be collected whenever it is available and be used whenever needed, such as storing summer heat for winter heating.
TCS (Thermochemical Storage)	A form of energy storage based on reversible chemical reactions that can store and release heat with minimal losses over long periods, offering higher energy density than sensible or latent heat storage.
TES (Thermal Energy Storage) or Thermal Storage	The temporary storage of heat or cold for later use, which can help balance energy supply and demand, increase system efficiency, and enable the integration of renewable energy sources.
TTES (Tank Thermal Energy Storage):	A type of thermal energy storage system that uses large, insulated water tanks to store heat for later use. They can be used for both short-term and seasonal thermal energy storage.
UTES (Underground Thermal Energy Storage):	A collective term for thermal energy storage methods that use underground media (soil, rock, groundwater) to store heat or cold for later use, including ATES, BTES, and other underground storage technologies.

Executive summary

Thermal storage offers significant potential for the UK energy system. It can deliver multiple benefits by facilitating the integration of renewable energy sources, reducing carbon emissions, enhancing energy security, lowering customer costs, augmenting system resilience, and enabling better integration between the heat and electricity sectors to increase grid flexibility.

However, the research found that, despite heat network designers, developers, and operators recognising the benefits of thermal storage, system deployment (both individual and collective assets) is not happening at the pace or scale needed. This is primarily due to high upfront capital costs, particularly for longer-duration systems, and a lack of confidence in the investment case stemming from a combination of factors, including knowledge gaps, access to equivalent storage incentives in the electricity market, and the fragmented nature of heat network development and ownership in the UK.

This research examines the use of thermal storage technologies in UK heat networks, comparing it with international practices and identifying barriers to greater uptake.

In summary, thermal storage offers substantial benefits for UK heat networks, with evidence demonstrating improvements in operational expenditure, decarbonisation potential through renewable integration, and enhanced system resilience. The research found that:

- While short-duration sensible heat storage is relatively common in UK heat networks, predominantly through tank thermal energy storage, there remains significant untapped potential, particularly in long-duration and seasonal storage solutions that have seen success in countries like Denmark, Sweden and Finland.
- Poor integration between heat and electricity market regulations actively blocks grid flexibility benefits and peak demand management, preventing full economic and environmental returns.
- High capital expenditure and urban space constraints remain critical barriers to thermal storage deployment, but evidence shows that emerging technologies like phase change materials could address these limitations.

Current use of thermal storage in UK heat networks

There is a significantly lower level of deployment in the range and scale of thermal storage technologies in the UK heat network market compared to established markets, such as Scandinavia and other parts of Europe. Current applications in the UK primarily focus on short-duration tank thermal energy storage (TTES), designed for peak shaving and improved system resilience. As of now, the research found no operational large-scale interseasonal thermal storage projects in the UK, whereas countries like Denmark and the Netherlands have successfully implemented these technologies.

Several factors limit widespread adoption in the UK, including:

- High land costs in urban areas, making large thermal storage installations expensive.
- Sub-optimal sizing of thermal storage during the design stage, often due to limited space.
- Lack of available performance data to support business cases.
- Significant upfront capital costs, despite lower long-term operational expenses.
- Fragmented ownership models that misalign incentives between development and operational stages.

Benefits of thermal storage technologies

Thermal storage implementation offers benefits across multiple areas. Financial advantages arise through peak shaving, optimised CHP operations, and deferred infrastructure investments. Environmental gains can be realised through substantial potential CO2 reductions for electrically driven heat networks, while energy security benefits arise through improved grid flexibility and reduced fossil fuel dependence. Additional advantages include improved local air quality and the enabling of low-grade recovered heat integration.

Financial benefits

Thermal storage delivers operational cost reductions and new revenue opportunities for heat network operators. For heat network systems that employ Combined Heat and Power (CHP) as a primary heat source, thermal storage has been proven to optimise engine operation and reduce the need for expensive peak load capacity. In electrically driven heat networks, thermal storage can maximise access to cheaper off-peak electricity and reduce operational expenditure, though these benefits are not yet fully realised in the UK. Thermal Storage has also been proven to extend the lifecycle of central generation plant on heat networks, reducing maintenance costs and deferring replacement expenditure.

Environmental benefits

Thermal storage significantly contributes to reducing carbon emissions in heat networks through improved system efficiency. A recent UK study showed that CO_2 emissions could be reduced by 83.4% in a heat pump-driven network with long-duration thermal storage compared to the same network without storage. Thermal storage facilitates these savings by allowing networks to purchase electricity during periods of low grid demand when renewables constitute a more significant proportion of the energy mix.

Heat network and grid system resilience

Thermal storage enhances the resilience of heat network systems by providing backup heat during outages and managing peak demand. In Denmark and Sweden, it has been used to support the integration of renewable energy sources with heat and enhance flexibility between grid and heat network systems. A recent study of the heat supply system options of a residential area in Norway has shown that low temperature heat networks with seasonal thermal storage would reduce peak power demand by up to 31%. This would significantly reduce the grid capacity enhancements needed in the area to meet growing electrical demand.

Barriers to greater thermal storage adoption

The research identified six categories of barriers that inhibit the implementation of thermal storage in UK heat networks. The most significant barriers were high land costs, limited space availability (particularly in urban areas), and fragmented ownership models that misalign incentives between the development and operational stages.

Technical barriers

Technical challenges persist around integrating existing infrastructure and space constraints in urban environments. While simple hot water tanks (TTES) are well-established in the UK, there is minimal deployment of larger-scale options that are common in Scandinavia:

- Space constraints: Urban heat networks often lack the physical space necessary for optimal thermal storage sizing, resulting in compromised installations.
- Retrofit complexity: Integrating thermal storage into existing heat networks involves navigating congested underground infrastructure and complex building connections.
- Technology limitations: Phase change materials (PCMs) have promising space-saving benefits but are limited by their fixed operating temperatures. Research in this area is advancing at pace but with limited commercial application to date.

Skills and supply chain gaps

The research identified operational and skills gaps in specifying, installing, and managing thermal storage systems, as well as information gaps, particularly regarding long-term performance data and comprehensive UK-specific case studies:

- Design expertise: A lack of experienced consultants who can confidently design and specify thermal storage systems, especially for newer technologies.
- Installation knowledge: Limited domestic capability for manufacturing large thermal storage vessels, creating reliance on international suppliers.
- Operational confidence: Heat network operators often lack experience in optimising thermal storage to balance heat demand and supply, requiring better data and automation.

Economic barriers

Economic considerations include high capital costs relative to long payback periods and misalignment with flexibility contract lengths in the electricity markets:

- Capital vs. operational misalignment: While thermal storage reduces operational costs over time, high upfront capital expenses deter investment, particularly for larger systems.
- Payback period mismatch: Thermal storage typically requires 5-10 years to break even, but flexibility contracts that could provide revenue offer only offer 3-year terms, creating investment uncertainty.
- Construction risk: Uncertainty in identifying qualified contractors with thermal storage expertise increases project risk and capital cost provisions, especially for technologies less common in the UK, like aquifer thermal energy storage.

Regulatory and market structure barriers

The current regulatory landscape creates a disconnect between heat and electricity sectors, which affects the full realisation of electricity grid integration benefits.

- Planning inconsistency: The absence of national planning guidance specific to thermal storage leads to local authorities making independent decisions, creating uncertainty for developers.
- Market access limitations: Heat networks with thermal storage struggle to access electricity flexibility markets and balancing mechanisms that could provide additional revenue streams.
- Electricity/gas price differential: Even though thermal storage can help reduce the impact of electricity price volatility (the time-of-use differential), it mitigates rather than challenges the baseline price gap between electricity and gas energy sources. Consequently, operators are not consistently choosing to operate or transition to a fully electric heat network without gas peaking or backup plants.

Ownership and control barriers

The UK's fragmented heat network development process and ownership structures fundamentally undermine optimal thermal storage deployment:

- Developer-operator disconnect: When developers don't operate the networks they build, they often prioritise minimising upfront capital costs rather than long-term operational efficiency. This disconnect consistently leads to undersized thermal storage systems that fail to capture long-term operational savings. Aligned incentives between development and operational stages have proven to lead to a greater adoption and optimisation of thermal storage.

- Mixed ownership structures: The UK landscape features both public and private models. Danish and Swedish examples demonstrate how unified municipal, or cooperative ownership models yield better thermal storage integration by prioritising whole-system efficiency.

Evidence gaps

There is a substantial skills shortage in the UK thermal storage sector, particularly for larger-scale installations. Critical knowledge gaps in the following areas prevent confident investment in thermal storage:

- Limited UK case studies: There are few comprehensive UK demonstrations of thermal storage performance, particularly for larger systems. This lack of case studies affects both the promotion and awareness of the opportunity for thermal storage and an absence of reference cases to build a business case around.
- Performance data shortages: Lack of standardised, reliable data on system efficiency, fuel consumption, and economic metrics for different technologies. This leads to risk being factored into the business case and conservative performance estimates.
- Financial impact uncertainty: Insufficient evidence regarding the long-term economic viability and financial benefits, particularly for heat pump integration and electricity market opportunities. This creates investment inertia for heat network developers and operators due to a lack of confidence in achieving target Return on Investment (RoI).

Addressing these interconnected barriers requires targeted policy intervention. While cost barriers are significant, the most fundamental challenges relate to market structure, ownership models, and bridging the knowledge gap between heat networks and electricity markets.

Future prospects and innovations

Looking ahead, the prospects for thermal storage appear promising. Emerging technologies such as phase change materials and thermochemical storage show potential to address current limitations, particularly in space-constrained environments. Smart systems and AI are enhancing integration capabilities, while decarbonisation targets are driving increased demand.

Significant research is dedicated to developing advanced materials for thermal storage, including phase change materials (PCMs) and thermochemical storage (TCS) methods. These innovations could overcome space restrictions by utilising non-water heating elements that can retain more heat in a smaller space, potentially addressing one of the significant barriers to thermal storage optimisation.

Smart control systems could transform thermal storage operations through sophisticated monitoring capabilities and data-driven management. AI algorithms can process complex variables to optimise charging strategies, while cloud-based platforms facilitate the integration of multiple storage units within heat networks.

Several forthcoming policies, such as the Review of Electricity Market Arrangements (REMA), Regulated Energy Storage Providers (RESPs), Smart Systems and Energy Programme (SSEP), and Heat Network Zoning, could enhance the value proposition of thermal storage through better recognition of its grid benefits.

Conclusion and policy implications

Realising the full potential of thermal storage requires addressing several interconnected challenges. Success depends on key developments: enhancing the integration between heat and electricity markets; aligning stakeholder agendas within heat network development to prioritise whole-life considerations; continuously engineering to achieve a lower levelised cost of heat and establishing comprehensive performance monitoring systems. Creating targeted training programmes for specification and implementation, while developing supportive regulatory frameworks that recognise thermal storage as critical infrastructure, would establish a robust foundation for market growth.

Whilst investment in thermal storage is expected to grow naturally alongside heat network expansion, the evidence suggests that coordinated development of the sector could help ensure thermal storage technologies are appropriately sized, selected, and implemented to maximise benefits for network operators and customers alike. The research indicates that such coordination would support the alignment of heat networks with an electrified, low-carbon future and could help unlock the full potential of thermal storage in the UK energy system.

Introduction

Background to the project

Heat networks are systems where heating, cooling, or hot water is generated centrally and then distributed to multiple customers. They are a vital technology in decarbonising heat and so making net zero a reality. The UK Government expects that approximately one-fifth of heat demand will be met by heat networks by 2050, compared to around 3% currently (DESNZ 2024a).

In high-density urban areas, they are often the lowest cost low carbon heating option. This is because they offer a communal solution that is more efficient than individual solutions and can access local heat sources that are otherwise not available to consumers. Furthermore, by reducing the electricity needed to generate heat for consumers and operating flexibly to take advantage of lower-carbon and lower-cost periods, heat networks can reduce electricity bills for everyone and ease the task of decarbonising the electricity network.

However, their ability to operate flexibly, and so reduce costs and carbon for consumers, is dependent on their ability to draw upon multiple sources of heat – including being able to store and draw upon energy from thermal storage. A growing body of international research indicates that integrating thermal storage into heat networks reduces renewable curtailment, increases efficiency, and decreases operating costs (Guelpa & Verda 2019).

Previous research commissioned by BEIS in 2016 (Evidence Gathering: Thermal Energy Storage (TES) Technologies, BEIS 2016) had identified barriers to thermal storage uptake in the UK, including high upfront costs, supply chain limitations, and a lack of technological expertise. DESNZ is re-evaluating these questions in 2025, as the heat network market has evolved considerably since then, shaped by support mechanisms such as the Green Heat Network Fund (GHNF), a heightened focus on the electrification of heat, the integration of heat networks with the electricity grid, emerging TES innovations, and proposed heat network zoning.

In England and Wales, the government has supported heat network project development since 2013 through the Heat Networks Delivery Unit (HNDU), as well as capital investment support through the Heat Networks Investment Project (HNIP, 2017-2022) and the Green Heat Network Fund (GHNF, 2022-ongoing).

Scotland, where heat network strategy is partly devolved, supports heat network growth by providing funding and advice for the pre-capital development of heat networks via the Heat Network Support Unit (HNSU). Additionally, capital support to heat networks is provided by the Scottish Government’s Low Carbon Infrastructure Transition Programme (LCITP), the Scotland Heat Network Fund (SHNF), and the Scottish Government Social Housing Net Zero Heat Fund (SHNZHF).

In England and Wales, thermal storage can be funded through the GHNF as part of heat network development. Currently, however, there is no targeted support for thermal storage implementation in England, Wales or Scotland. By comparison, the UK government offers targeted energy storage support in the electricity market in different contexts, specifically Long-Duration Electricity Storage (LDES) (DESNZ 2024b).

This study examines the role of thermal storage (also known as Thermal Energy Storage, or TES) in supporting the growth of heat networks in the UK and their integration with the power network. While challenges exist and are explored in this study, consensus from academia and industry is aligned on the view that using thermal storage to shift heat demand is an enabler of a low-carbon heat network (Pans & Eames 2024). This study examines the conditions necessary for thermal storage deployment and the barriers that need to be overcome to realise these benefits. It reviews the economic case, technical requirements, critical knowledge gaps and regulatory and organisational structures that currently limit our ability to fully leverage the role of thermal storage in scaling low-carbon heat infrastructure.

Aims

The aim of this study was to understand the current and potential role of thermal storage in heat networks in the UK. The study compared UK and international experience and gathered technical and cost data on relevant thermal storage solutions to inform future work and departmental strategy on thermal storage in the heat networks sector.

The contents of this report are guided by the research questions below:

1. Describe how thermal storage technologies currently feature in heat networks in the UK and internationally (including the range of technologies currently employed).
    a. Why is thermal storage currently used in heat networks in the UK and internationally?
    b. What are the benefits of thermal storage that could be realised in the UK?
    c. What can we learn from international examples of thermal storage use in district heating?
2. What are the barriers to deploying thermal storage in the UK?
3. What are the current costs associated with thermal storage?
    a. Has there been any change in the direction of thermal storage costs in the last 5 years and what are the future cost projections (if available)?
4. What is the current evidence on thermal storage efficiency and storage durations (% peak demand shift due to use of thermal storage, if available)?
5. What evidence gaps exist in answering these research questions?

Technology introduction

There are three major categories of thermal storage: Sensible, Latent, and Thermochemical. Each category encompasses a range of techniques for storing heat using different technologies and materials. This section describes these categories, drawing on Energy Storage Systems: Fundamentals, Classification, and a Technical Comparative (Márquez et al. 2023) and Thermal Energy Storage: Systems and Applications (Dincer & Rosen 2021).

Table 1 provides an overview of each type of thermal storage. Note that, in general, each type can accommodate both short and long-duration storage. For sensible storage (the most common and mature TES technology category), the storage duration is generally linked to the volume and type of storage medium container (e.g., tank or borehole).

Table 1: Thermal storage technology categories (summary)

Thermal Storage Technology	Features	Types	Maturity
Sensible Heat Storage (SHS)	Stores energy by raising or lowering the base temperature of a storage material. Hot water tanks are the most common SHS technology. Their storage capacity is a function of temperature and volume. Materials such as rocks, concrete, thermal oils and molten salts can be used efficiently in SHS systems. They can be heated to much higher temperatures than water, requiring less volume (and thus space) to store the same amount of energy.	Tank TES (TTES) Pit TES (PTES) Aquifer TES (ATES) Borehole TES (BTES) Solid material storage (rocks, concrete, bricks, etc.)	Mature / common (depending on region). See the section below: *Current state of thermal storage technologies in UK heat networks.*

Thermal Storage Technology	**Features**	**Types**	**Maturity**
Latent Heat Storage (LHS)	Stores energy released via a material's phase change (e.g., from solid to liquid). Paraffin waxes are typical examples of these phase change materials (PCMs), alongside certain salts, polymers and metals. The amount of energy stored by LHS systems will vary according to the thermal conductivity of the PCM, as well as the PCM's chemical stability over various phase change cycles. Although the phase changes used in LHS systems are reversible, PCMs may degrade over time, reducing their ability to store thermal energy over more extended periods. LHS systems can be more cost-effective than SHS systems as they provide more heat per unit volume. However, the innovative technologies required to operate and maintain them is often more complex and expensive.	Phase Change Materials such as (but not limited to): Salt hydrates Paraffin waxes	Emerging innovation

Thermal Storage Technology	Features	Types	Maturity
Thermochemical Storage (TCS)	Stores the energy released by reversible chemical reactions (chemical reaction systems) or chemical adsorption processes. Common TCS reactions include adsorption/desorption and hydration/dehydration, where gas or water is added or removed from a material or compound. These reactions release heat in one direction and absorb heat in the other. Because the energy is stored within the chemical composition of their base materials, they waste almost no energy, particularly when compared with SHS. This option is optimal for longer-term thermal storage systems, with some of these systems able to retain heat over periods of several months.	Sorption-based systems Chemical reaction systems	Emerging innovation

In technical terms, thermal energy storage (TES) systems can also be categorised based on their duration or discharge time capabilities, although there is no single, universally standardised classification system. Again, drawing on Energy Storage Systems: Fundamentals, Classification, and a Technical Comparative (Márquez et al. 2023) and Thermal Energy Storage: Systems and Applications (Dincer & Rosen 2021), thermal energy storage can be classified as:

- **Short-duration storage:** Typically spans hours to a few days (up to ~72 hours). These systems often manage daily load shifting or provide short-duration backup. Technologies include sensible heat storage in water tanks, phase change materials with low thermal losses, and certain building thermal mass applications.
- **Medium-duration storage:** Covers periods from several days to a few weeks (approximately 3-30 days). These systems help manage weekly variations in energy demand or supply. Examples can range from larger short-duration storage technologies to the smaller end of the underground thermal energy storage technologies (Pit, Aquifer, Borehole).

- **Long-duration or Interseasonal storage**: Designed to store thermal energy for months (typically 1-6 months). These systems capture excess thermal energy (for example, solar energy) during the summer for use in meeting winter heating demands. Technologies include large-scale aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and pit thermal energy storage (PTES).

The actual retention time depends on several factors, including the properties of the storage medium (specific heat capacity, phase change temperature), the system size (volume-to-surface area ratio), the quality of insulation (R-value), the temperature difference between the storage and the environment, and the specific technology implementation.

In heat network design, the heat source significantly affects the design and performance of thermal storage systems. For instance, energy-from-waste (EfW) plants typically provide a consistent and high-temperature heat supply, which aligns well with large-scale sensible or latent heat storage systems for district heating. Conversely, air-source heat pumps (ASHPs) exhibit more variable performance due to their reliance on ambient air temperatures, which fluctuate seasonally.

Thermal storage integration with ASHPs and other heat pumps can mitigate efficiency fluctuations by storing excess heat during mild weather for use in colder periods when performance declines (Ermel et al. 2022). Beyond efficiency improvements, thermal storage systems also enable heat networks to incorporate multiple generation technologies operating in parallel. London's Bunhill Heat and Power Network exemplifies this integration, where an ASHP extracts waste heat from an Underground ventilation shaft to complement a gas CHP system (Ludgate 2021, writing for Cenergist). Combining varied heat sources with thermal storage optimises energy efficiency and reduces carbon emissions, though the effectiveness and benefits depend significantly on the specific storage technology employed.

Overview of the methodology

To achieve the research goals, two approaches were taken to data gathering and analysis: qualitative primary research with expert stakeholders and a Rapid Evidence Assessment (REA). The technical annex accompanying this report includes a more extensive description of the research methods.

Interviews

The purpose of the stakeholder interviews was to gain perspectives on the current situation and outlook for thermal storage in UK heat networks compared to countries with more extensive heat network infrastructure.

Forty interviews were conducted with the following stakeholder groups: heat network consultants (including engineering design, commercial and legal), thermal storage manufacturers and innovators, heat network developers/investors, heat network operators, and others (policymakers, researchers, trade association representatives). Groupings reflected the heat network value chain. Interview sampling was designed to represent each group's influence on the specification and operation of thermal storage systems within heat network infrastructure, as described in **Table 2**.

The sampling strategy determined that 20 interviews should be conducted with UK stakeholders and 20 with international stakeholders, as shown in

Table 3. Interviewees from Sweden and Denmark were prioritised due to the prevalence of thermal storage-integrated heat networks in those countries. To broaden understanding, other European and North American geographies were included. These regions have extensive thermal storage-integrated heat networks, but their ownership models and infrastructure development rationale differ from those of Sweden and Denmark.

Table 2: Target and completed interviews

	Target number of interviews	Completed interviews
International Consultant	5	5
UK Consultant	5	5
Manufacturer	6	5
Investors	4	4
International Operator	7	6
UK Operator	8	10
Other	5	5

Table 3: Sampling representation by Country

Country	Completed interviews
UK	20
Sweden	5
Denmark	5
Other European	5
Outside Europe	5

Topic guides were developed for use in the interviews. They included key questions and a structured set of follow-up prompts, to allow natural conversation to flow. This method encouraged interviewees to elaborate on their answers in reflective dialogue. Specifically, the topic guide was structured around the research questions and asked interviewees about their perceptions of:

- Current thermal storage usage in their country and the benefits of thermal storage.
- Barriers they see holding back thermal storage integration.
- The future direction of thermal storage.

Additionally, the interviews sought insights on thermal storage costs and integration with the electricity system to access additional benefits on peak demand management and grid balancing.

Specific attention was paid to barriers and drivers related to thermal storage operation, economics, resilience (in terms of consistent supply to customers), energy security (at the national level) and emissions, highlighting areas of market failure and their underlying causes.

Focus group with Distribution Network Operators

The objective of the focus group was to gauge current understanding and views on thermal storage in heat networks from innovation and flexibility leaders in the UK electricity District Network Operators (DNOs) and the National Energy System Operator (NESO). Seven DNO participants and one NESO participant joined the focus group, with their organisations representing the majority of UK electricity network coverage.

The focus group differed from the interview content in that it specifically examined the relationship between heat networks and the UK electricity system and the role of thermal storage in connecting these. Discussions covered understanding of current thermal storage deployment, future grid capacity concerns, and the potential benefits of heat networks to the grid with and without thermal storage integration. Participants explored the impact on peak demand management and necessary market support. The focus group also addressed potential barriers to implementing thermal storage-integrated heat networks. The purpose of the discussion was to explain the complex dynamics of interconnected energy systems within the UK's evolving low carbon infrastructure.

Rapid Evidence Assessment (REA)

To comprehensively respond to the research questions, a Rapid Evidence Assessment (REA) was undertaken to evaluate the most recent and relevant academic literature on thermal storage in heat networks.

A long list of over 1,000 relevant documents was identified through academic databases and research institutions. This long list was condensed to 100 documents by applying additional relevance criteria, such as individual research questions, year of publication, UK context, etc.

The 100 shortlisted papers were evaluated and scored against each research question. The papers were then ranked based on their total score to identify 40 documents for detailed analysis. Papers offering more comprehensive evidence on a single research question, particularly those that included cost data for thermal storage technologies, were prioritised over those addressing multiple questions in less depth.

Current state of thermal storage technologies in UK heat networks

This section discusses the coverage and types of thermal storage in heat networks in the UK, the technologies under consideration, and the factors behind this.

For context, the modern form of heat network was established about 150 years ago. Heat networks have evolved through multiple "generations" over time, from the first-generation steam networks of the late 19th century to today's fifth-generation systems, with each evolutionary step responding to efficiency demands and the changing energy landscape. Thermal storage is recognised as a crucial facilitating technology in achieving the ambitions of today’s heat networks to reduce losses, decarbonise heat, integrate with the electricity grid, and deliver a lower levelised heat cost to customers.

Heat network design is diverse, especially in the UK compared to other countries where heat network infrastructure is more widespread, and a wide range of thermal storage options is available to accommodate each heat network's various architectures, circumstances and demands. Due to UK circumstances (as covered in the later section Barriers to using thermal storage in heat networks*),* short-duration sensible storage, in the form of small steel hot-water tanks, is the most common form of thermal storage. This form of thermal storage is commonly used to enhance the financial performance of Combined Heat and Power (CHP) units and occasionally gas-boiler-driven heat networks, managing peak demand on the network and providing system resilience.

At the time of writing, the research found no operational large-scale interseasonal thermal storage projects in the UK. International deployment also remains limited, with some exceptions like Denmark and the Netherlands. Outside of these markets, 93% of global storage capacity is under 10 hours’ duration (Bolton et al. 2023). This was generally seen to be a result of decisions shaped by the constraints of thermal storage integration, such as land costs (Bolton et al. 2023).

The higher prevalence of interseasonal storage in countries such as Denmark and the Netherlands was reported by interviewees as being due to the scale of district heating infrastructure, the relatively low cost of land (compared to the UK) and multi-utility ownership structures.

> “…in other countries like Denmark, you can only look in some envy at the scale of interseasonal storage they have, like pit stores. As far as I know, there isn't a project like that in the UK.”
>
> *UK heat network operator*

The reported efficiency of interseasonal projects varied according to the literature and depended on several factors specific to the project's local geological and hydrogeological conditions (Bolton et al. 2023).

UK interviewees frequently mentioned that they had investigated long-duration thermal storage, but that these discussions seldom advanced beyond the ideation stage. Public ownership, positive public perceptions, space availability, and more compatible planning regulations were reported as facilitators in markets where heat network infrastructure is more widespread than in the UK. Favourable geology, taxes on gas prices, and a skilled workforce may also play a significant role (these are explored further in the *Barriers to using thermal storage in heat networks* section).

Although there are currently no interseasonal thermal storage projects operational in the UK there are some forms of low-temperature (<50°C) long-duration storage, such as the 2.5MW aquifer thermal storage (a long-duration form of sensible storage) at Wandsworth Riverside Quarter in London (Jackson et al. 2024).

Case illustration: Wandsworth Riverside Quarter

The Wandsworth Riverside Quarter development in London showcases an innovative Aquifer Thermal Energy Storage (ATES) system integrated with a district heating and cooling network. This mixed-use development, comprising 504 apartments and commercial spaces, utilises a highly efficient ATES system with eight wells to deliver 1.80MW of heating power and 2.75MW of cooling. The scheme employs three ground source heat pumps connected to a common ground loop served by 2 boreholes, each 100 meters deep. The system operates by storing warm water (17°C) in one aquifer during summer and cool water (7°C) in another during winter, allowing for seasonal energy exchange. This approach significantly reduces carbon emissions, cutting approximately 450 tonnes annually. The network operates at lower temperatures for space heating (45°C) and higher temperatures for domestic hot water (75°C), optimising efficiency. By combining ATES with gas CHP, the system provides low-carbon heat, hot water, cooling, and electricity, demonstrating the potential of geothermal technology in urban environments (CIBSE 2023, Bordajandi & Brogan 2024).

Newer technologies, such as Latent Heat Storage (LHS) and Thermochemical Storage (TCS), face limited adoption in heat networks worldwide (Pompei et al., 2023). Thermochemical Storage is regarded as early-stage and requires significant Research and Development (R&D) before market viability.

The global PCM market is currently small, with few manufacturers (Energy Systems Catapult, 2020). Although PCMs provide increased heat per m³ and offer attractive space-saving benefits, recent trials suggest the technology is not yet mature enough to replace water-based thermal storage. A key limitation is that PCMs operate at specific phase-change temperatures (e.g., 60°C), unlike water, which functions effectively across the typical district heating range (40-90°C).

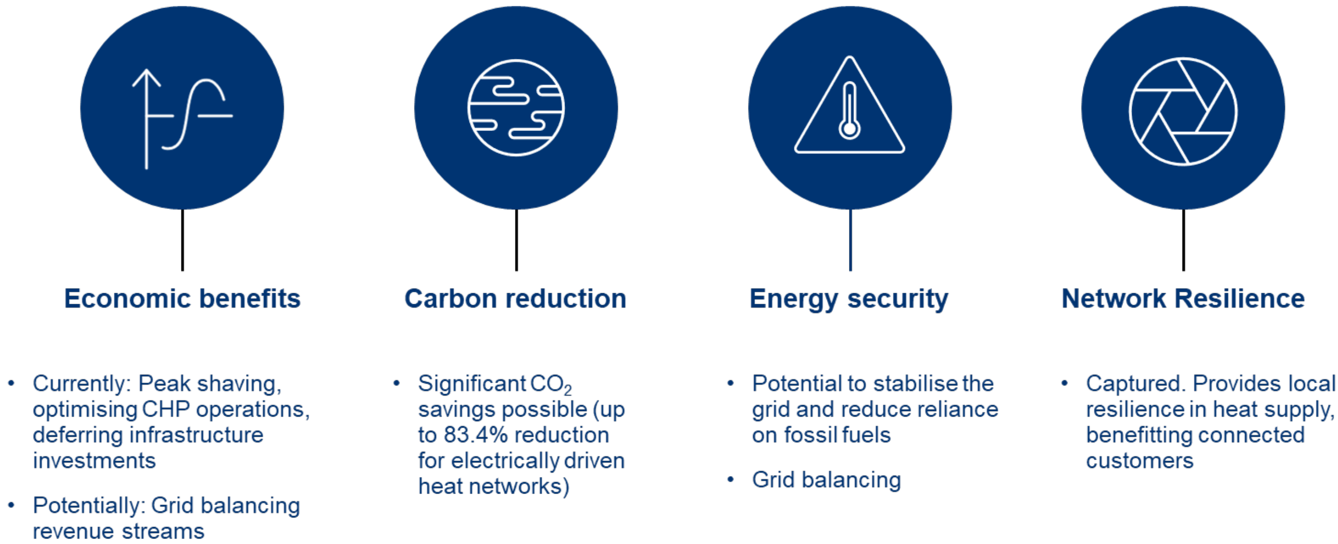
> "All of our thermal storage in the UK are water-based. I have been exploring PCMs, but …the PCM materials being put forward to us are very specific in their temperature ranges."
>
> *UK heat network operator*

UK interviewees expressed a wish for broader adoption of thermal storage to achieve decarbonisation, performance, and energy security goals, noting that integrating thermal storage in heat networks could improve performance and enhance future grid flexibility. This was also a baseline assumption across the literature reviewed.

Benefits of thermal storage technologies in heat networks

The benefits of utilising thermal storage can be generally classified into financial benefits, environmental benefits, network resilience (to operators and customers) and energy security (national and wider society) (**Figure 1**). Each benefit is described in detail in this chapter. Potential benefits that could further augment these headline benefits are discussed separately.

Figure 1: Benefits of thermal storage in heat networks



Alt text for Figure 1: There are four benefits of thermal storage, illustrated in this image: Economic Benefits, Carbon Reduction, Energy Security and Network Resilience.

Financial benefits

This research defines financial benefits as the operational cost reduction and revenue opportunities for heat network operators when utilising thermal storage. Financial benefits to heat network operators have been distinguished from broader economic advantages to energy consumers, such as lower electricity bills, as these depend on multiple factors beyond thermal storage adoption alone. Benefits that may have a financial aspect but for which there are currently no clear pathways for operators to realise those benefits, such as reducing electricity grid upgrade costs, are considered in the *Barriers to using thermal storage in heat networks* section.

The literature consistently cites the integration of thermal storage in heat networks to optimise the operation of CHPs, extend plant operating life, and therefore defer replacement expenditure, as well as participate in grid-balancing mechanisms (e.g., Behzadi et al., 2022; Espagnet, 2016). Interviewees (including UK and international operators and developers) had a strong understanding of the financial benefits of thermal storage, aligned to the evidence in the literature. For those heat network operators interviewed who used CHP systems as their primary heat source, thermal storage is deployed to optimise the engine's operation and reduce the need for expensive peak load capacity.

> "… in order of priority, we [firstly] use thermal storage to optimise the CHP's commercial performance. Our schemes are heat-led, so we don't dump heat. We're never power-led. We just want to run that CHP as optimally as possible. And when there's no heat demand, we'll drop the output from the CHP into the thermal store. There's the commercial driver…
>
> And then next up, resilience. You get loads, but [with thermal storage] you might get 10-12 hours of resilience in the worst-case scenario if everything in the energy centre has gone down, assuming you've still got some power for pumping. So those are probably the two main [reasons]."
>
> *UK heat network operator*

UK heat network operators who own or are developing electrically driven heat networks reported that they intend to utilise thermal storage to maximise access to cheaper off-peak electricity and reduce operational expenditure (OPEX). Interviewees also pointed out that the financial benefits of thermal storage for heat pump or electric boiler systems are not yet fully realised or optimised.

> "…sizing electric boilers to be able to cover normal steady state loads, and then having peak tanks, you can use the electric boiler to charge those tanks during periods of cheaper electricity and then discharge the storage vessels when you need a peak load."
>
> *UK heat network operator*

In addition to the current financial benefits, a point of consensus in the research was the importance of heat network operators gaining access to electricity market revenue streams such as the balancing and ancillary markets to further decrease OPEX. The *Financial incentives and funding* section discusses this in more detail.

Environmental benefits

There was clear evidence that thermal storage contributes significantly to carbon reduction in heat networks through improved system efficiency (IRENA 2020, Bars et al. 2021, Guelpa & Verda 2019, Kauko et al. 2022).

A recent study modelling the carbon emission reductions from a UK heat network in Loughborough, powered by a heat pump and integrated with evacuated-tube solar thermal collectors (ETSTC) alongside a long-duration thermal store, supported this finding for electrically driven systems. Results showed that CO_2 emissions and electricity costs could be reduced by 83.4% and 12.3%, respectively, compared to the same heat network without thermal storage (Pans-Castillo & Eames 2023). Thermal storage facilitates these savings by allowing the ETSTC to charge the thermal store and providing the flexibility to purchase electricity during periods of low grid demand when renewables constitute a greater proportion of the energy generation mix.

In the current UK context, interviewees reported the potential to reduce carbon emissions through power integration. One operator who is realising these benefits now, highlighted that carbon savings would be substantial if they could recognise the time-of-day carbon performance as opposed to the grid average or even marginal grid activity. Whilst the main motivation for this use of thermal storage is financial, interviewees highlighted that thermal storage can significantly reduce carbon emissions as a byproduct of the way these financial benefits are realised.

> “If you look after the cost, you look after the carbon. I spend a lot of my time discussing that ‘no carbon’ is not our primary goal. Our primary concern is cost. And if we look after the cost, we bring down the carbon.”
>
> *UK heat network operator*

Realising carbon reduction benefits depends on well-considered design and operating practices. The literature showed that various factors, such as system losses, the variability in system performance under different conditions, and the carbon intensity associated with the electricity-powered heat pumps, could affect thermal storage's carbon emission reduction potential. Some evidence even suggests that poorly designed and operated thermal storage can increase a heat network's carbon intensity (Delta Energy & Environment Ltd. 2016).

One interviewee referenced the potential for heat networks to improve local air quality as fossil fuels are replaced by low-carbon infrastructure. This benefit is relevant as thermal storage is an enabling technology that supports the growth of modern heat networks, displacing fossil fuel systems and their associated air pollutants.

The literature and interviewees suggested that thermal storage can also help minimise the wider energy system's reliance on fossil fuels by storing energy during low-demand periods when low-carbon electricity is more readily available (Behzadi et al. 2022, Espagnet 2016, IRENA 2020, Kallesøe et al. 2019, Barns et al. 2021, Morvai, Evins & Carmeliet 2017, and more). One of the interviewed UK heat network designers supported this view quite succinctly and forcefully stating. *“… you can't decarbonise your power grid without thermal storage.”*

Energy security

The research found that thermal storage technology enhances energy security by providing backup to help maintain critical provision of heat during supply disruptions (further discussed at the system level in the *Network resilience* section), reducing the dependence on imported fuels and addressing intermittency issues with solar and wind power by storing excess energy as heat.

Several papers noted the potential for thermal storage to support enhanced grid flexibility and contribute to energy security goals both at a systems level within the heat network and, when consolidated, at a national level (see, for example, IRENA 2020, Enescu et al. 2020, Sifnaios et al. 2023, Barns et al. 2022, Kauko et al. 2022, Kassem et al. 2021). Four ways were noted: flexible generation, increased transmission capacity, demand-side management, and energy storage (electricity, heat, and hydrogen) (Sifnaios et al. 2023).

A study that modelled sensible thermal storage found that district heating significantly alleviated pressure on the power grid in Norway, with peak power demand reduced by up to 31% with seasonal thermal storage installed (Kauko et al. 2022).

At a UK level, the three main contributors to energy security provided by thermal storage can be summarised as:

- Electricity Grid Stability: thermal storage is widely recognised for its ability to stabilise the grid, particularly in the context of increasing renewable energy penetration. “Thermal storage can help balance the electricity grid by using intermittent renewable electricity to supply heating and cooling when needed by coupling with other technologies such as heat pumps” (Barns et al. 2022, 17).
- Reduction of Fuel Imports: There is agreement that thermal storage can help reduce dependence on energy imports by maximising domestic renewable energy resources.
- Support for Local Resilience: Thermal storage is crucial for supporting decentralised and local heat and power infrastructure, contributing to overall energy security.

Network resilience

The final point on the energy security rationale above creates a bridge to a benefit that is more specific to heat network operators and connected customers. That is, thermal storage provides local resilience for any outages in the provision of heat. The larger the storage capacity, the longer the provision of guaranteed heat remains uninterrupted, even in the case of plant failure or maintenance needs. Interviewed heat network operators consistently referenced the use of thermal storage to cover maintenance requirements and unanticipated outages and protect the rights and needs of customers.

One UK interviewee highlighted that, for them, resilience alone (e.g., thermal storage used as a backup) drives the current business case for thermal storage. International interviewees operating town and city-scale heat network infrastructure never discussed resilience alone as a driving force for investment in thermal storage, although it was consistently referenced as a component of the rationale for investment.

> "We operate schemes with thermal stores, but they are not a big part of our operation. I'm not sure that the size of schemes and the sophistication at which those schemes… [operate now] really offer much benefit other than resilience. Often, that's because they're not fitted properly or have enough temperature sensors to have any real ability to use them."
>
> *UK heat network operator*

Other potential benefits

Specific to long-duration storage

The research found that long-duration storage offers significant system benefits beyond shorter-duration technologies. In Denmark, interseasonal storage is employed to improve network interconnection and integration with the power grid. This enhances network coverage, plant scalability and efficiency, flexibility, and access to power market mechanisms.

Benefits to the wider electricity system

A common view amongst interviewees and the DNO focus group was that thermal storage can significantly enhance electricity grid flexibility. Thermal storage systems were seen as crucial in helping to balance supply and demand, especially during peak times, and in smoothing out demand peaks, reducing the need for grid reinforcement. Interviewees expressed the need for greater knowledge exchange and collaboration between DNOs and the heat network market.

> "I would have said there needs to be more work together with electricity distribution. This needs to be a much closer collaboration."
>
> *UK heat network operator*

The literature recognises the growing importance of thermal storage as the grid experiences higher renewable penetration. Several studies noted the cost-effectiveness of thermal storage versus battery storage and how increased adoption of thermal storage could reduce renewable energy curtailment (see, for example, BNEF 2024, IRENA 2022, Hennessy et al. 2019, Denholm & Mai 2017). Sifnaois et al. (2023) projected that adopting seasonal thermal storage could reduce renewable energy curtailment by 53% in Denmark.

Interviewees understood the potential for thermal storage to store electrical energy from the grid as heat during low or negative electricity prices and release it during periods of high heat demand, likening thermal storage to batteries. They recognised that this would provide cost savings to the heat network operator and support the balance and stability of the electricity network.

> “If you can start diverting that excess energy to keep those turbines working into thermal stores, they act like batteries. And it's an environmentally cleaner battery system than having lithium cells … and because they are a battery, if you're producing electricity that goes into an electric boiler that goes into a thermal store, you're fundamentally doing the same thing as a lithium cell.”
>
> *UK heat network consultant*

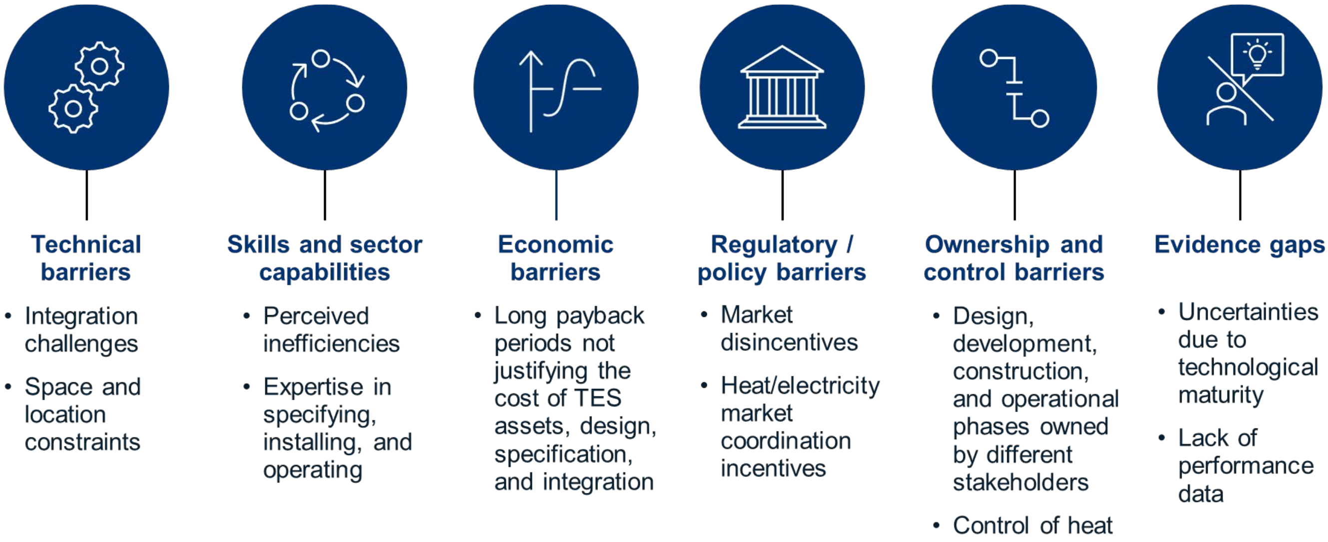
Interviewees and evidence from the literature reported that the UK had the opportunity to transition directly to the newest generation of heat networks, using advanced engineering principles incorporating integrative technologies, and design approaches tailored to enabling thermal storage.

> "The UK is in a fantastic situation because you're building heat networks in modern times, so you can skip to 4th Generation district heat networks already with low temperatures and well-designed hydraulics for diverse heat sources."
>
> *UK heat network consultant*

Barriers to using thermal storage in heat networks

The research identified six categories of barriers inhibiting thermal storage implementation, which are set out below in **Figure 2**. The most acute barriers to thermal storage adoption in the UK were high land costs, limited space availability, particularly in dense urban areas suited to heat networks and fragmented ownership models.

Figure 2: Key barriers to thermal storage uptake



Alt text for Figure 2: There are six key barriers to thermal storage uptake in the UK. These are: technical, skills, economic, regulatory, ownership and evidence gap barriers

Technical barriers

Technological maturity

There is significant variation in maturity across thermal storage technologies deployed in heat networks, ranging from the most mature sensible heat storage technologies to the least mature thermochemical storage technologies.

- **Sensible heat storage** technologies are well-established globally. However, long-duration storage solutions are limited to applications in Scandinavia and a small number of other European countries. In the UK, BTES, ATES, and PTES are currently in concept, trial, or early adoption phases.
- There was mixed evidence on **latent thermal storage**. There was consensus within the literature around the need for further development of PCMs, though there was some reference to their current applications (Pompei et al. 2023). In contrast, interviewees

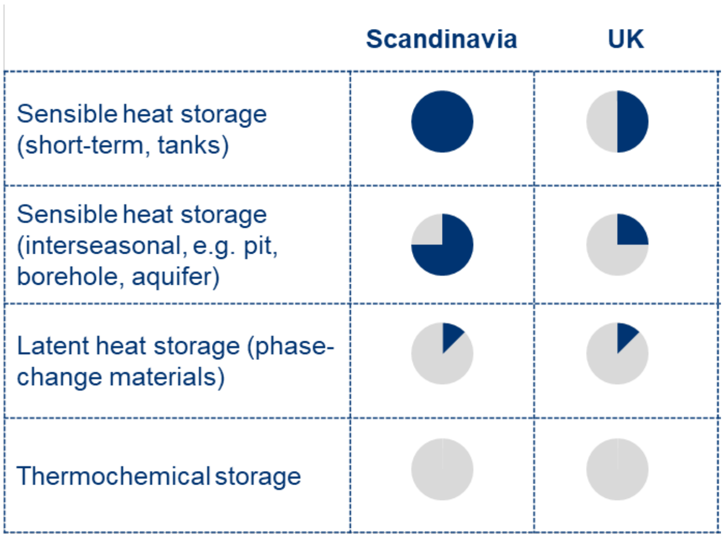
considered PCMs to be at the pilot stage, which implies that they have been tested in situ in heating and cooling applications but are not yet used commercially.

- **Thermochemical storage** is firmly at the research and development stage.

More mature thermal storage technologies are currently preferred, with interviewees citing their reliability, simplicity, and cost-effectiveness.

The circles in **Figure 3** represent technology adoption levels in Scandinavia compared to the UK, with the shaded portions indicating adoption levels. Scandinavia has a well-established market for long-duration sensible energy storage, which is relatively nascent in the UK by comparison. However, there is a significant research base in the UK for innovation on latent heat and thermochemical storage, and the trialling and adoption of these technologies are equivalent across all markets.

Figure 3: Market maturity of different thermal storage technologies, UK versus Scandinavia



Alt text for Figure 3: The graphic describes the market maturity of thermal storage technologies in the UK compared to Scandinavia. Harvey Balls (a grey circle where a contrasting blue is used to show percentage coverage) are used to show the relative adoption rates of short-duration sensible heat storage, interseasonal sensible heat storage, latent heat storage and thermochemical storage technologies.

The literature identified **interseasonal pit thermal storage** technologies as less mature within sensible heat storage technologies, particularly concerning lifecycle performance, which interviewees also highlighted as an issue. The cover in pit thermal storage must often be replaced during its lifetime. For example, Dronninglund thermal storage was upgraded in 2022 with a newer, improved lid due to the failure of the original lid. Bolton et al. (2023) claims that a 20-year lifetime without replacements has yet to be proven, and cost analysis rarely considers the costs of replacements and upgrades.

Temperature range was identified as a technical barrier across **latent and thermochemical thermal storage** technologies. Here, temperature range refers to the operating temperature limits, i.e., the specific temperature thresholds at which a system can store and release energy efficiently. In other words, different mediums used to store heat (such as water) can only “hold” heat up to certain temperatures, and therefore, matching thermal storage technologies to specific applications is complex. With heat networks supplying hot water to connected buildings at temperatures of 50-90°C, there is a need for the storage medium to have flexibility to meet both the operating flexibility of an individual network and the variability of flow temperatures between networks. This is currently a challenge for latent thermal storage with phase-change materials limited by the melting point of the PCM. The PCM would no longer be effective if the network ever needed (even briefly) to supply water at a temperature above the PCM’s melting point. The literature also highlighted other challenges with PCMs, particularly poor thermal conductivity, which limits heat transfer to and from phase change materials (Raine 2017).

Gaps in available performance data slow down, inhibit, and affect the final design and specification of less mature technologies. This includes latent and thermochemical thermal storage and large-scale and seasonal sensible thermal storage technologies such as Pit Thermal Energy Storage (PTES) and Borehole Thermal Storage (BTES), which are more prevalent in Sweden, Denmark, and the Netherlands but have yet to be deployed in the UK. Interviewees cited that there is a challenge accessing performance data and relevant case studies to support the business case for these technologies (described in the Evidence gaps section).

An international operator reported introducing new technologies (including thermal storage) as difficult, noting that "*[a culture of] innovation is not typical in the district heating industry*.” The interviewee observed that the industry is very comfortable with water tanks from a technical and operational perspective and that adopting early-stage technologies involves unnecessary risk.

Challenges of integrating with existing infrastructure

Research into the integration of heat networks with existing UK infrastructure identified three significant challenges: heterogeneous network design, incompatibility of existing heat network infrastructure and limited understanding of effective thermal storage design in both the heat network and DNO industries. Two medium-severity infrastructure integration issues were also identified: public perception risks associated with the visual, noise, and environmental impacts of large thermal storage systems, as well as regulatory misalignment between the heat and power markets regarding the integration of new infrastructure with the grid. These integration-specific findings emerged as the most prevalent concerns among interviewees and in the literature. The positioning of heat networks in dense urban areas in the UK often leads to additional installation requirements that may add complexity and cost when making changes to accommodate thermal storage infrastructure (Delta Energy & Environment Ltd. 2016).

Variations in design philosophy across heat networks in the UK are particularly significant compared to countries with more extensive heat network infrastructure, such as Denmark, Sweden, Iceland, and Finland. This variability in the UK can be attributed to factors such as the complexity of the building stock and navigating congested subterranean infrastructure. Consequently, retrofitting existing district heating infrastructure poses challenges, especially when integrating thermal storage into existing systems lacking storage capacity.

> "Commercially, it's difficult to retrofit something in [to district heat networks], even if we're just talking about simple traditional short-term storage."
>
> *UK heat network consultant*

Space and location constraints

UK interviewees see space constraints, particularly in urban areas, as a significant barrier to deploying thermal storage systems. Non-UK stakeholders did not share this view, even when prompted with the same questions. Specifically, UK interviewees consistently highlighted that high land costs, limited availability of large plots, and stringent planning regulations make finding suitable locations for large-scale thermal storage installations challenging. Interviewees reported that these space constraints directly affect the feasibility and scale of thermal storage installations. The research found that in densely populated areas, the limitations on available space has often led to suboptimal installations, such as smaller tanks or compact systems that may not perform as efficiently as larger, centralised storage units.

A fundamental challenge with thermal storage is that a dedicated space must be reserved for the installation, whether distributed or concentrated. The issue becomes more difficult when long-term storage is considered (Guelpa & Verda 2019). This problem is particularly pronounced for interseasonal storage, which requires space and specific subsurface characteristics that are rarely available in desired locations. Borehole and aquifer thermal storage systems, which store heat below the surface, require favourable geological conditions, including ground conditions suitable for wells, non-corrosive water sources, and accessible thermal storage media (Batista 2017).

Developers in the UK often resist allocating sufficient space for thermal storage systems, further exacerbating the space issue. This is particularly problematic in new developments, where the high cost of space frequently results in trade-offs with network performance, leading to compromises in the design and effectiveness of thermal storage systems. A UK Heat network operator stated in an interview that "*the main barrier [to optimised deployment] is ensuring we can allocate space, particularly in new developments*."

One Canadian interviewee also discussed how space concerns in design are driving the investigation of innovative solutions that provide a range of benefits:

> "Alternative types of storage are an emerging area for us. Water-based storage is great, but the issue is often space. We're interested in other technologies for three reasons: they're usually more space efficient [than water], which is important in urban areas. They can usually be stored at higher temperatures. And some technologies can go back to electricity with thermal storage."
>
> *Heat network consultant, Canada*

The aesthetic impact of energy infrastructure also emerged as a significant concern among UK interviewees, particularly regarding public acceptance in residential areas. Interviewees with international experience of district heating highlighted a notable contrast between British and Danish public attitudes towards large-scale thermal storage facilities, with the latter demonstrating greater receptiveness to visible energy infrastructure in urban settings. One interviewee spoke of the pride that some communities felt in Iceland towards their large storage tanks and the importance of trying to replicate this perspective in UK-based community projects.

> "We're trying to change the narrative to one of celebration…. why not have a big tank as a decorative item … it could be a work of art in the middle of your development."
>
> *Heat network operator, UK*

Repurposing heat network infrastructure has global precedent. A heat network operator from Iceland highlighted Perlan in Reykjavík, a nature museum situated among active large thermal storage tanks being used to support district heating requirements.

Case illustration: Perlan, Iceland

Perlan is a natural history museum in Reykjavík, Iceland. The site has been used as a geothermal storage facility (in the form of large hot water tanks) since 1939 and was used to supply hot water to homes and buildings in Reykjavík. The first tanks were torn down and rebuilt in the 1980s; today, six water tanks can hold a volume of 5000 m3 each. In 1991, a museum linking the tanks was opened to the public. The museum is an important cultural and educational part of Reykjavík, with the tanks still operating as stores for hot water heated by geothermal energy.

Operational inefficiencies

The literature highlighted a set of operational inefficiencies associated with thermal storage. For tank thermal energy storage (TTES), operational inefficiencies related to thermal losses, inefficiencies during charge/discharge cycles and system design were all mentioned but rarely quantified. Pilot studies on newer pit storage, described by (Sifnaios et al. 2023), have identified efficiencies ranging from 60-70%, depending on ground conditions and insulation lid performance, noting though that this was still considered generally good performance.

Research indicates that storage duration directly impacts operational efficiency, with extended storage periods leading to thermal losses and higher costs. Desguers et al (2024, 1) for example, found that short-cycle operation (days) of BTES can achieve recovery factors (the ratio of energy recovered from the storage system compared to the energy initially stored) exceeding 85%, while seasonal operation resulted in 50-60% recovery factors due to *“significant thermal losses during prolonged periods between consecutive charges.”*

Interviewees, in contrast, did not raise the operational inefficiencies of thermal storage as a barrier to deployment. UK stakeholders did not view inefficiencies as a problem, whereas interviewees from Denmark, Iceland, and Sweden went even further, strongly reiterating that thermal storage solves system inefficiencies rather than contributing to them. The difference in viewpoints from within the literature and the interviews may point to gaps in available information, discussed in more detail in the section on *Performance data availability*

The literature and interviewees agreed that using more sophisticated controls could be of benefit, suggesting that smart controls are an area for improvement and further study to optimise thermal storage performance (Behzadi et al. 2022). While this only came up in limited contexts, there is an additional brief discussion on these technologies in the *Smart control systems* section.

Skills and sector capabilities

Expertise and skills

The literature and interview evidence presented a nuanced picture of expertise and skills as barriers to thermal storage system growth in district heating. While some argue that the required skills are similar to those needed for general heating and power systems, evidence suggests specific expertise gaps persist, particularly for larger installations (Eames et al. 2014). These gaps span system design, installation and operational knowledge, with limited potential in these areas for skills to transfer from other sectors. The research identifies a particular shortage of experienced design consultants for thermal storage-integrated heat networks, as highlighted by staff at London's Pimlico District Heating Undertaking (PDHU) network (Eames, 2014). While this source is a decade old, the viewpoint remains consistent with UK stakeholders interviewed.

Interview data further indicates that skills requirements are evolving, with heat networks increasingly participating in electricity markets. A key emerging requirement is expertise in electricity market arbitrage - the practice of exploiting price fluctuations in the day-to-day electricity market to provide the lowest-cost heat through strategic scheduling of energy storage. This represents a shift from purely technical competencies to a hybrid skillset combining technical systems knowledge with market operation expertise. The persistence of these skills gaps first identified over a decade ago (in Eames et al. 2014), suggests structural challenges in developing the necessary expertise. This situation is particularly acute for larger-scale thermal storage projects, where operators must combine technical and market knowledge to operate the system effectively.

> “We're not used to building that sort of scale vessel in the UK, so there's a whole skills and development experience thing which needs to come on board with that as well.”
>
> *Heat network consultant, UK*

Some interviewees emphasised the need for specialised thermal storage apprenticeship programmes in the UK heat network sector. These programmes, they said, would develop technical skills that university education often overlooks, directly addressing current gaps in thermal storage manufacturing, installation, operation and maintenance. Interviewees also reported that similar programmes in Germany and Denmark have contributed to higher deployment rates and system longevity, suggesting the UK could achieve comparable benefits through targeted vocational training.

> “The UK needs something like Germany, where they have a sophisticated apprenticeship programme and where it’s socially completely accepted not to go to university to study but instead enter trades.”
>
> *Thermal energy storage manufacturer, UK*

An international heat network operator reported that it takes time to build operator confidence when using thermal storage to manage daily or hourly heat demand and supply imbalances. Some operators with less experience of working with thermal storage may be more hesitant to identify trends in heat demand and energy use and turn on the thermal storage systems. The interviewee mentioned that better data and automation have made this process more seamless.

A lack of specialised knowledge in less mature thermal storage technologies was identified as a barrier to their broader adoption. More specifically, the research identified a perceived lack of experienced consultants and designers who could confidently specify these technologies as a challenge. Interviewees referred to a need for a more connected ecosystem around relevant R&D in less mature thermal storage technologies and the support needed to commercialise and integrate them into supply chains.

The specialist skills required for drilling when implementing seasonal thermal storage projects using modern techniques such as BTES and ATES are one of the barriers to their adoption (Barnes, 2022). This specific challenge is recognised internationally.

As one interviewee mentioned when discussing the reasons behind the failure of an ATES project in Hamburg, where specialists were not contracted for the drilling:

> "Subsurface aquifer storage is quite a hot topic, but I'm only aware of Hamburg where they've tried it, but it was unsuccessful… they drilled in the wrong place. And I think that is just a lesson learned that district heating companies should not be [doing the drilling]. It is just not their core expertise."
>
> *Heat network operator, Denmark*

Supply chain capabilities

For more mature thermal storage technologies, such as TTES, one UK interviewee observed a lack of UK suppliers in the market and limitations in the supply chain. This has implications for the pace of UK thermal storage adoption, placing a potential reliance on international manufacturers and allowing them to benefit from an emerging UK market opportunity.

> "The supply chain is limited. I think we've only got two potential suppliers on our list. … Because the UK has de-industrialised so much, we don't have much of that capability … We've talked to European suppliers, but trying to move large tanks around the place is not sensible. So, we need to reinvigorate the UK supply chain."
>
> *Heat network operator, UK*

Economic barriers

Capital costs

The research found that accessing the benefits of most forms of thermal storage is restricted by long payback periods (except short-duration TTES). A lack of understanding exacerbates this issue, as heat network operators struggle to consistently identify and quantify the full range of revenue opportunities that can offset the high capital expenditure costs or are unwilling to speculate on as yet undefined future revenue opportunities. While thermal storage can relatively uncontroversially cover its costs over time, this depends on whether existing market conditions hold, as the payback periods are longer than required for industrial equipment (around 5 years is a typical threshold for industrial equipment). "In many cases, the break-even point is often within 10 years" (Kallesøe et al. 2021, 130).

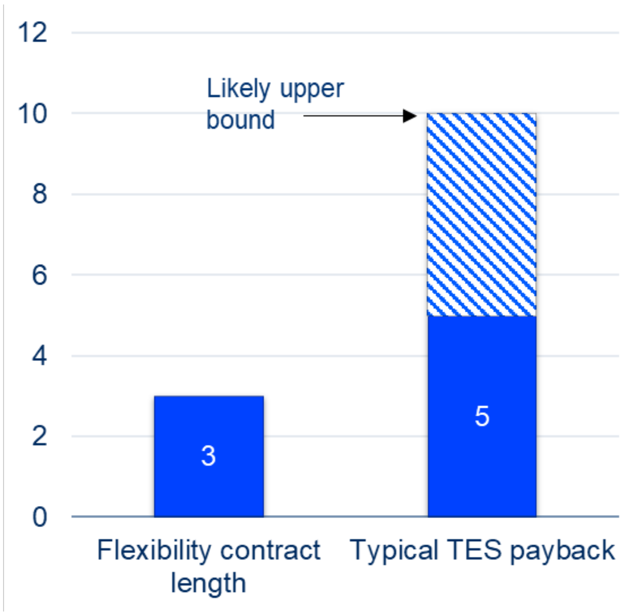
Interviewees emphasised that capital costs are particularly prohibitive in urban areas due to the complexity of retrofitting thermal storage systems into existing heat networks, as discussed previously in the *Technical barriers* section. Some interviewees mentioned that the high capital costs relate to materials, e.g., steel, as well as installation/integration. The high capital costs particularly affect the large and innovative systems required for seasonal storage.

The literature frequently highlighted the overall cost-effectiveness of thermal storage compared to electricity storage solutions, with sensible heat storage frequently highlighted as a cost-competitive option. However, the high upfront costs remain a barrier to broader adoption, highlighting the need for strategies to mitigate these, such as achieving economies of scale or integrating with planned infrastructure that could reduce capital costs.

Interviewees highlighted that construction uncertainty and identifying a contractor with a specific understanding of thermal storage were key barriers when retrofitting thermal storage into existing systems. This uncertainty also made it challenging for interviewees to make the commercial case for thermal storage, as construction risk needed to be factored into capital cost provisions, increasing the challenge for next-generation and larger thermal storage systems. UK interviewees also cited “construction uncertainty” as a direct reason for projects failing to progress beyond feasibility studies when discussing the commercial case of Aquifer and Borehole thermal storage systems.

A critical misalignment exists between thermal storage investment economics and flexibility contracts as a revenue opportunity for UK heat networks. The DNO focus group highlighted this fundamental disconnect, as illustrated in **Figure 4**. Thermal storage systems require substantial upfront capital with lengthy payback periods (5-10 years, according to interviewees and Kallesøe et al. 2019), while flexibility contracts typically only offer 3 years’ duration. As repeat flexibility contracts are not guaranteed, such mechanisms only provide a limited certainty of revenue over the investment period.

Figure 4: Misalignment of flexibility contracts to thermal storage payback (years)



Alt text for Figure 4: This is a bar chart comparing the length of a flexibility contract to the typical payback ranges for a Thermal Energy Storage project. The chart shows that the typical TES payback period is 5-10 years and the length of a flexibility contract is 3 years.

Operational costs

Thermal storage systems, particularly established technologies such as TTES, demonstrate lower operational costs than alternative energy storage methods. Within the thermal storage family, more sophisticated solutions incorporating Phase Change Materials or Thermochemical Storage tend to incur higher operational expenses than simpler thermal storage options due to increased maintenance requirements and the need for continuous system optimisation. Regardless of technology, storage duration plays an important role.

The evidence (see *Operational inefficiencies* section) points to a sensitive correlation between operational efficiency and costs within thermal storage systems: those with higher thermal losses require more energy input to maintain desired temperatures, driving up operational expenses. This relationship is particularly pronounced in long-duration storage applications, where even minor efficiency losses compound over time. Based on the available research, we can conclude that maximising thermal efficiency through proper system design and maintenance is crucial for controlling operational costs, with simpler thermal storage technologies generally offering the most cost-effective solution within the thermal storage category.

Financial incentives and funding

Some papers noted that access to market mechanisms such as ancillary services, e.g., payments from the flexibility markets, could provide additional revenue streams for thermal storage operators to improve the investment case. However, current market structures for heat network delivery in the UK have yet to widely implement or support opportunities for revenue stacking through the utilisation of thermal storage. UK interviewees reported that TTES is selected and designed based on access to established market incentives that are well understood, rather than speculating on access to existing and future electricity market incentives.

Some interviewees highlighted that the decarbonisation of industry presents a significant unrealised financial opportunity by integrating recovered industrial waste heat into district heating systems, enhanced by thermal storage capabilities. This opportunity could be further monetised through carbon credits, as industries that feed their excess process heat into heat networks may become eligible for carbon offset incentives, creating a dual revenue stream from both heat sales and emissions reduction credits.

> "What we can see is wrong in the UK is that people think about connecting buildings; therefore, we need a bigger energy centre. But in reality, the UK needs … to realise that we actually need to have a very large-scale harvesting of heat from where we have heat sources. We need to link heat networks to industry. If they can get carbon credits by connecting their waste heat to heat networks [industries would be incentivised to recover and share their excess process heat]."
>
> *Heat network operator, UK*

Interviewees stated that a significant barrier to industrial heat recovery revenue streams is the lack of coordination and alignment between industry and heat networks, encompassing physical, regulatory and investment timeframe challenges. Better planning could enable co-location between these systems, while in cases where co-location is not possible, the physical separation presents opportunities for innovation. Some industrial facilities are already exploring heat batteries as a transportable solution, illustrated by a major London waste incineration plant pioneering this approach.

Case illustration: Cory Group

The Cory Group in the UK takes waste heat from Cory's Bexley waste-incineration facility and captures it in Sunamp PCM heat batteries. The batteries are transported down the River Thames in London, with the heat sold to networks near the river. Cory believes this to be a new revenue stream for their business and an attractive new solution for heat networks. An interview with Cory Group suggested that there is an appetite among different industries with accessible pathways to urban centres and district heating networks. They believe that with sufficient demand for heat coupled with long-term contracts, the capital investment required to supply heat networks can be justified, making remote industrially recovered heat using thermal storage an increasingly attractive solution for urban decarbonisation in the UK.

Interviewees identified the potential of electrically driven heat networks to enable off-peak thermal storage charging but noted that current electricity prices prevent viable implementation. While operators could purchase cheaper off-peak electricity to charge thermal stores, the available electricity tariffs remain too high to create a compelling business case. This pricing challenge stems from high overall electricity costs relative to gas and heat networks' limited ability to access wholesale electricity rates, as illustrated in the quote below.

> "There's no real incentive for an operator to buy electricity to effectively buy and sell heat. The market doesn't exist in the UK: buying electricity at low, very low prices and selling heat at a higher price because those markets aren't joined up…As for market reforms, if the heat network could access the electricity prices closer to wholesale prices, then they could really start doing some interesting stuff."
>
> *Heat network operator, UK*

Outside of the UK, especially in Scandinavian countries, financial incentives to support greater use of thermal storage in heat network operations were spoken about mostly in terms of policy interventions. This includes effectively raising the price of gas through, e.g., carbon tax, to make purchasing non-fossil electricity and other energy cheaper by comparison and incentivise more investment into reducing the cost of electricity via renewables.

Regulatory and policy barriers

The regulatory and policy landscape for thermal storage in UK district heating networks necessitates careful analysis to differentiate between genuine market failures and perceived needs for government intervention. While interviewees consistently emphasised the significance of government support, the broader research found that it is not solely government backing that will resolve some of the identified barriers. Consequently, such perspectives should be assessed within the context of a framework that requires robust evidence of specific market failures or structural barriers and the government's role in addressing these.

Planning regulations

The planning landscape for thermal storage in the UK presents a complex picture. At the national level, heat networks operate within a framework characterised by notable gaps - they are absent from the National Planning Policy Framework, lack a dedicated energy planning statement, and are not classified as Nationally Significant Infrastructure Projects. In interviews, some heat network operators and consultants with national coverage suggested that this lack of clear national guidance may have resulted in local authorities making independent decisions about TES implementation.

Interviewees had mixed perspectives on how these regulatory conditions affect thermal storage deployment. While planning considerations consistently emerge as an early challenge in project development, particularly in urban environments where land availability is limited and height constraints become significant, they appear to be manageable barriers. A small number of interviewees with experience in attempting to develop larger-scale storage systems in the UK, typically either tall TTES or long-duration systems, suggested that securing planning approval becomes a more acute challenge.

When discussing possible areas of support for enabling thermal storage benefits in district heating, one interviewee said:

> "There are quite a few [areas of support needed to enable the benefits of thermal storage to the electricity system via integration with district heating]. I think planning is our first hurdle when we're developing a project. Obtaining planning approval for larger-scale storage systems can be challenging.
>
> From central government, we'd be looking for that intervention in using district heating schemes to improve energy security throughout the UK, helping to normalise its use across the country. Then, the storage would naturally flow and follow that process."
>
> *Heat network developer (investor), UK*

Planning was additionally highlighted as an issue by one interviewee, suggesting that industrial energy storage infrastructure requires strategic policy support, particularly through adjustments to permitted development rights to enable the installation of large thermal storage vessels at industrial sites where waste heat is generated. These policy changes, they believed, would facilitate more efficient heat network systems by allowing thermal storage to be deployed at the point of generation, maximising the capture and utilisation of industrial waste heat.

> "The largest stores we want to use [for] balancing are very large vessels. So, we're going to need some planning support on that. That might be adjustments to permitted development rights. Because quite often, we're going to want to put these large stores at the point of generation, and mostly that's going to be ideally from industrial waste [heat]. So, we'll probably install these thermal stores in industrial areas anyway."
>
> *Heat network consultant, UK*

However, the view that planning serves as a barrier to thermal storage was not universally recognised. One interviewee from a trade association mentioned that they had never encountered a situation where a thermal store was rejected on planning grounds.

Access to the wholesale electricity market

The research identified specific structural issues within the UK electricity wholesale markets, particularly concerning the integration of distributed energy resources (DERs) with thermal storage and district heating networks. Some interviewees noted a perceived undervaluation of thermal storage as a distributed energy resource, particularly given its capacity to provide flexibility for winter heating and accommodate reduced summer cooling loads.

This challenge is not unique to the UK and is supported by evidence in the literature and a review of international policies. For example, the US Federal Energy Regulatory Commission (FERC) Order No. 2222 (issued in 2020) has potential implications for district heating. This order aims to remove barriers for Distributed Energy Resources (DERs) to participate in wholesale electricity markets. FERC describes DERs as "any resource located on the distribution system, including thermal storage" (Zhou, Hurlbut & Xu. 2021, 1). The order allows DER aggregations to participate in regional grid operators' capacity, energy, and ancillary services markets. Kassem et al. (2021, 1) highlights that, "changing the energy production paradigm by encouraging alternative technologies was a key driver for FERC Order 2222". By allowing heat networks to shift electrical loads and provide grid services, thermal storage enables network operators to participate in these markets via the order.

Some interviewees highlighted specific concerns about the potential exclusion of thermal storage from important subsidy mechanisms for energy storage in the UK, e.g., the proposed policy framework to enable investment into long-duration electricity storage.

Countries with higher thermal storage adoption, such as Denmark and the Netherlands, benefit significantly from favourable policies, including subsidies and comprehensive regulatory frameworks. The Dutch ATES framework is explicitly recognised as a global leader (Jackson et al. 2024). In 2008, a Dutch Government task force was established to promote the ATES industry. It recommended legislative adjustments to support deployment, leading to the adoption of a coordinated national framework in 2013. The permitting process was streamlined, and a licensing regime was introduced, all of which facilitated the accelerated deployment of ATES storage (Bolton et al. 2023). The literature on BTES noted that the absence of a clear regulatory framework in many countries poses a critical barrier to deployment (Kallesøe et al. 2021). One interviewee suggested that the UK's limited deployment of large-scale thermal storage stems from both weaker policy enforcement compared to that in Scandinavia and societal attitudes that are less receptive to collective energy solutions.

> "In the UK, to develop large-scale thermal storage, we need to change the way [we think] …at the end of the day, it's a very societal project…it's not the same mentality as in Scandinavia…the state is very engaged and imposes policies on local communities so that they can develop their solutions. I think a lack of enforcing policies is why large-scale thermal storage doesn't exist yet [in the UK]."
>
> *Heat network operator, UK*

Energy pricing and subsidies

The combination of higher electricity base costs compared to gas in the UK, along with the absence of time-of-use pricing in gas contracts, currently limits the cost efficiency of thermal storage. This creates multiple challenges for its adoption.

A significant adoption barrier identified by interviewees was the lack of meaningful time-of-use pricing in gas contracts. While electricity offers variable pricing throughout the day, gas pricing structures generally do not provide similar differentials. This removes potential financial incentives for adjusting gas consumption patterns through storage mechanisms, thereby weakening the economic motivation to implement thermal storage in gas-based systems.

In addition, interviewees emphasised that, despite the greater price variability of electricity through time-of-use tariffs, the baseline cost difference between electricity and gas remains too significant for most thermal storage applications to yield robust investment returns within electrically driven heat network systems. Interviewees operating heat networks observed that even when charging thermal storage with off-peak electricity, the total cost (including storage inefficiencies) often surpasses the cost of using gas for direct heating.

Although thermal storage technology can effectively address the timing mismatch between heat supply and demand, these economic realities indicate that the financial case does not consistently work out favourably.

System alignment

The benefits of integrating thermal storage across heating and electricity systems are well-documented (Morvaj, Evins & Carmeliet. 2017, IRENA 2020, Barns et al. 2022, Kauko et al. 2022). In addition, research across multiple studies, e.g., Barns (2022) and IRENA (2020), indicated that a crucial barrier to widespread thermal storage adoption in the UK stems from institutional fragmentation between the electricity and heating sectors. UK stakeholders, including heat network operators and Distribution Network Operators (DNOs), reported that these sectors have historically operated and been regulated in isolation, with limited coordination and integration.

The research concluded that the UK's complex governance arrangements and institutional barriers continue to hinder such integration. While regulatory innovations like FERC Order 2222 in the United States provide potential policy solutions, similar frameworks for promoting cross-sector coordination still need to be improved in the UK context. Participants consistently highlighted this institutional misalignment as a fundamental challenge that needs to be addressed to realise the full potential of thermal storage technologies.

Ownership and control barriers

Fragmented ownership models

Heat network ownership structures in the UK present a mixed landscape with both public and private models, significantly influencing thermal storage adoption patterns. The research suggested that where the developer would ultimately own and operate the network to deliver heat to their customers, particularly in public sector schemes, there appeared to be more ambitious deployment of thermal storage systems. In these cases, the research found that design decisions balanced capital and operational costs to achieve lower overall heat costs for end users. In contrast, where developers were building networks which they would not ultimately operate, the research determined that thermal storage design decisions were primarily driven by minimising upfront capital costs, with less consideration given to how operational costs could be optimised to reduce long-term heat costs for customers.

The fragmentation of district heating development processes in the UK creates barriers to thermal storage adoption, as initial developers' priorities often differ from those of eventual operators and end users. Furthermore, this disconnect between developmental and operational perspectives has demonstrably led to sub-optimal thermal storage sizing compared to European counterparts. Separate design, development, construction, and operational phases across stakeholders create misaligned incentives that impact system optimisation. This challenge has long been recognised, appearing in literature as early as Hawkey (2009) (although it should be noted that this paper was not explicitly included in the Rapid Evidence Assessment for this report due to its age).

> "The consultants and contractors often decide on storage size, design and location, and not the ones operating the heat network and paying bills. The fragmented decisions are reducing uptake of thermal storage."
>
> *Heat network operator, UK*

A study sampling UK networks found an interesting correlation between the integration of thermal storage within heat networks and ownership, with the highest levels of integration occurring under local authority ownership. However, private companies often played a role in operating those networks. The fragmentation of heat networks' design, construction and operational stages has led to consistent sub-optimal scaling of storage systems (Barns 2022). Stakeholder interviews highlighted that there is often a stark difference in priorities: publicly owned projects emphasised minimising operational expenditure to deliver lower heat costs to customers. Conversely, many private developer-led schemes prioritised reducing upfront capital costs. This fundamental misalignment of incentives frequently resulted in undersized thermal storage systems that failed to capture long-term operational savings, ultimately leading to higher costs for end users.

The research highlighted a notable contrast between the UK and other European examples, particularly in Denmark and Sweden, where well-established community and municipal ownership models enabled integrated decision-making prioritising long-term heat cost efficiency for customers. These two markets demonstrate how centralised, or cooperative ownership models facilitate comprehensive system planning and optimal thermal storage sizing. As documented by Bertelsen, Paardekooper, and Mathiesen (2021), this unified approach has contributed significantly to their market maturity and successful heat decarbonisation efforts.

Evidence from Bolton et al. (2023) highlighted how successful Danish thermal storage projects, such as those in Marstal and Dronninglund, benefited from unified ownership models under municipal control with technical support from the Danish Energy Agency. This integrated approach enabled optimal thermal storage sizing decisions based on system-wide efficiency rather than individual stakeholder returns.

> “Here in Denmark, the consumers own the district heating company. They all own the production, storage tanks, and pipe system. But when you go outside Denmark, different companies own the plant.”
>
> *Heat network operator, Denmark*

Addressing ownership fragmentation could increase thermal storage implementation in UK district heating networks.

The research could not determine whether emerging private ownership models designed to address fragmentation - such as private equity ownership encompassing distribution infrastructure, connection infrastructure, and heat generation assets - can effectively resolve the fragmentation challenges currently faced in the UK. However, new private equity-owned heat networks (particularly in Scotland) are actively exploring integrated approaches, including a strong focus on thermal storage. These initiatives may provide valuable insights and contribute to bridging this gap in understanding.

Evidence gaps

The research identifies several critical evidence gaps hindering the adoption of thermal storage within UK heat networks. Most notably, there is limited availability of comprehensive case studies, detailed performance data and economic analyses for both established and emerging thermal storage technologies. This knowledge gap is particularly acute for interseasonal storage and novel technologies such as Phase Change Materials (PCMs), where translating international experience to UK conditions proves challenging due to differing technical and market factors. Interviewees highlighted a concerning disconnect between the heat network and electricity sectors, which limits the potential of thermal storage to serve as an enabler of integration with the grid.

> "The UK has started to…imagine how power and heat ownership and regulation might need to work together. That disconnect means the benefits of energy storage can't be realised…, if I step back, the biggest barrier is that lack of understanding of the necessity and importance of thermal storage."
>
> *Heat network consultant, UK*

The absence of a dedicated knowledge exchange platform for thermal storage presents a significant barrier to advancement in the UK market. Whilst European projects offer valuable insights, there is currently no formal mechanism—such as an International Energy Agency Technology Collaboration Programme (IEA TCP)—to systematically capture and share learning across borders for thermal storage. This gap is particularly acute given the UK's nascent market position and reliance on overseas operators for engineering innovations. The financial landscape remains equally problematic; without robust analyses demonstrating economic viability—including potential 'revenue stacking' approaches and benefits when paired with heat pumps—stakeholders struggle to develop compelling investment cases.

Targeted action to address these interconnected evidence gaps could substantially advance the developing UK thermal storage market in the near term.

Demonstration projects and case study availability

Both the literature and stakeholder interviews identified two related gaps slowing the adoption of thermal storage within the UK heat network sector. First, there is a limited number of demonstration projects and full-scale implementations available for analysis, and second, a resulting lack of case studies that provide data to serve as the evidence base for an investment case. For emerging thermal storage technologies, real-world demonstrations are essential for developing meaningful case studies that can effectively analyse performance, operational characteristics, and economic viability. The evidence indicated that this was particularly crucial for interseasonal storage systems and novel technologies such as BTES and PCMs, where practical demonstrations and subsequent in-depth analyses are notably absent. To address this gap, the global sector requires both an expansion of demonstration projects and systematic documentation of their implementation, alongside detailed monitoring and evaluation to establish the technical and economic performance and feasibility of these technologies in operational settings. (IRENA, 2020, Bolton et al. 2023).

Interviewees who were directly involved in developing investment cases for thermal storage, including some consultants and most operators, consistently expressed concern about the availability of evidence on the performance of larger-scale thermal storage systems throughout their operational lifecycle.

> "We're thinking about much larger-scale thermal storage; I guess mines or geothermal aquifers, [and the] engineering and technical considerations about the longevity of those heat sources and how they perform over 20, 30, 40 years."
>
> *Heat network consultant, UK*

Performance data availability

The research revealed significant gaps in publicly available performance data for thermal storage technologies, particularly regarding their operational effectiveness in specific contexts. Interviewees referenced this as a barrier, and the literature similarly highlighted a lack of relevant available data (Stevens et al. 2013, Zhang et al. 2016). While some performance data exists, it often lacks the granularity necessary to build robust business cases or to fully assess the long-term operational benefits of thermal storage.

Interviewees emphasised that the absence of comprehensive, accessible data creates fundamental challenges for both technical validation of performance and investment justification. This aligns with documented evidence highlighting significant gaps in quantifiable data regarding energy storage capacity, retention periods, and system losses (Stevens et al. 2013). The challenge is further complicated by the predominantly bespoke nature of existing cold climate installations, which, as noted in the literature, has resulted in limited standardised data on system efficiency, fuel consumption, and economic metrics (Stevens et al. 2013).

The literature underlined the need for improved standardisation around performance data related to more established thermal storage technologies, e.g., TTES. Current studies on thermal storage applications are case-specific and not easily generalised to different future conditions (Zhang, 2021). In addition, interviewees highlighted PCMs as requiring more detailed performance data, emphasising that their effectiveness varies significantly across different temperature ranges and operational parameters.

Variability in local market conditions, such as energy prices, regulatory frameworks, and regional infrastructure, influence thermal storage performance across different regions. This variability poses challenges for standardising thermal storage solutions across different regions and makes it difficult to generalise findings (Jackson et al. 2024). Interviewees pointed out that the performance variability across geographies hinders the use of international evidence. For example, PTES might be suitable for use when coupled with solar thermal generation in heat networks or with suitable recovered heat sources from CHP and Energy from Waste (EfW), but this is only the case where land costs, planning requirements, and other requirements are met to justify the business case. This means that PTES case studies from Denmark may have limited use as direct justification for business case development for similar installations in the UK.

The lack of publicly available performance data from live schemes, e.g., to compare operational performance before and after enhancement of thermal storage capacity and/or operation, presents a significant barrier to understanding and optimising the use of thermal storage technologies. Heat network operator interviewees also confirmed a lack of reliable performance data for thermal storage within their organisation, even across portfolio operations.

Interviewees did not specifically call on the government to address this barrier, though it could be addressed through coordinated action across government, professional bodies and trade associations.

Economic and financial impact analyses

Interviewees reported a lack of evidence regarding the financial impact of thermal storage on heat network operation, particularly concerning the long-term economic viability and financial benefits of thermal storage technologies. This includes an absence of examples around ‘revenue stacking’ approaches in the current market. Interviewees believed that guidance on creating consistent and impactful investment cases would enhance investment approval within their organisations and across the industry.

By comparison, the now withdrawn (2023) triad payments for electricity generation were well understood by interviewees. These payments supported the operation of CHP in a heat network alongside thermal storage to unlock payments for electricity generation during peak demand periods through electricity sales to the grid (N.B. Triad payments were replaced in 2023 with fixed flat rate payments following Ofgem’s Targeted Charging Review and no evidence suggests that similar revenue stacking approaches are viable for heat network operators under the new scheme). While time of use tariffs were not discussed in the research, by charging variable rates for energy consumption based on periods of peak and off-peak demand, they represent a potential mechanism for aligning the heat and power markets, particularly as heat is electrified. As the electrification of heat accelerates, these tariffs create price signals that could encourage consumers to shift their heat demand to periods of lower electricity or heat consumption, typically during overnight hours. This temporal flexibility inherently supports the business case for thermal storage systems, which can charge during low-cost periods and discharge during peak times, thereby reducing consumer costs whilst simultaneously alleviating grid stress.

With the increasing electrification of heat through heat pump integration in heat networks, there is a lack of clarity in the UK market regarding the financial benefits of utilising thermal storage alongside heat pump operation. This approach could capitalise on lower electricity prices during off-peak periods and prolong the plant's lifespan. This situation highlights a missed opportunity, as thermal storage could facilitate smoother operation of the heat pump and yield cost savings. However, there is a significant absence of guidance on how to design these integrated systems, understand UK electricity market mechanisms and procurement, and optimise storage sizing to realise these potential benefits.

Interviewees also identified that current analyses, primarily based on modelled expectations rather than actual data, do not account for potential benefits such as cost savings, carbon reduction, and grid balancing benefits, which are essential for justifying the initial investment in thermal storage. Furthermore, interviewees that had installed thermal storage were consistently unable to provide a detailed breakdown of installation costs or reference where estimates of these could be sourced (see *Costs and economic considerations* section).

The research found that evidence of the financial benefits of TTES was better understood than other thermal storage technologies. Several papers highlighted the need for economic and financial impact analysis around interseasonal and emerging thermal storage technologies. Stevens et al. (2013) argued that lifecycle cost analyses are essential for reducing the current uncertainty surrounding the installation of thermal storage systems, precisely due to the definitive information they provide on capital costs, maintenance costs, and the operational savings of thermal storage. Sifnaios et al. (2023), citing multiple other authors, describes a similar gap, emphasising that larger systems (such as PTES) need more studies on their specific impact.

In summary, the revenue opportunities (see *Financial benefits section)* that underpin the business case for thermal storage systems are not well understood in the UK, and where evidence does exist (from other countries), they are challenging to apply in situ. This is despite the fact that these systems have been “analysed in theory, demonstrated, and deployed in practice” (Sifnaios et al. 2023, 2), both in the UK and abroad.

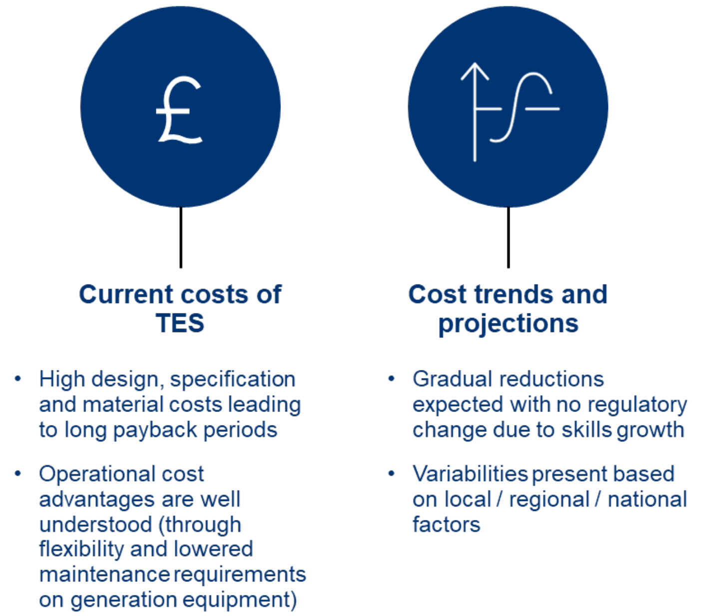
Despite the established technical viability of thermal storage systems in the UK, there is a lack of open-source financial benefit analyses. A variety of thermal storage pilot projects are underway in the UK, many of which receive government funding. It is crucial to collect data and develop case studies from this work to strengthen the evidence base for both policy and more consistent investment cases. Furthermore, we recommend establishing frameworks to effectively translate relevant international evidence into the UK context.

Costs and economic considerations

Current costs of thermal storage

While payback periods for the upfront costs of thermal storage remain a challenge, operational savings are viewed as more or less guaranteed after investment**. Figure 5** below outlines key takeaways from the cost research.

Figure 5: Cost and economic considerations of TES in heat networks



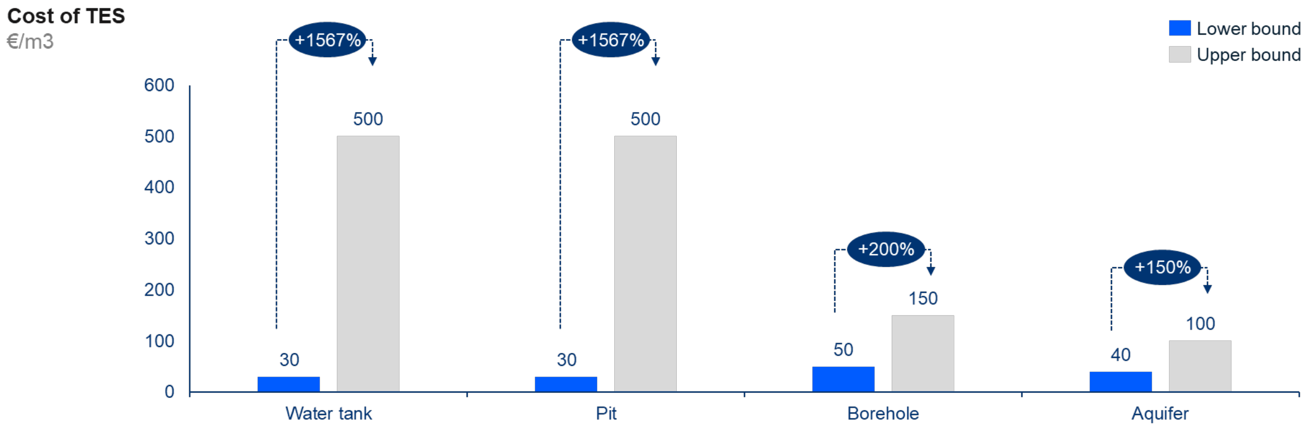
Alt Text for Figure 5: The graphic shows two blue circles - one with a UK pound sign inset in white and the other with a graph icon inset in white. The text describes current costs and cost projections for thermal energy storage

While interviewees acknowledged that installation costs represented a significant portion of the overall capital expenditure for thermal storage, they were unable to provide a detailed breakdown of these costs (also recognised in the Evidence gaps section).

indicating that this component was not well understood, as captured in the *Capital costs* section. UK respondents emphasised installation complexities due to planning and space requirements that contributed to higher capital costs, compared to interviewees from geographies where large-scale thermal storage is commonplace, such as Denmark.

The literature also contained only limited data on specific installation costs, and where they were cited, they were often reported in broad ranges on a per-kWh scale. Guelpa & Verda (2019) provide one example of Danish TES installation costs, as shown in Figure 6.

Figure 6: Thermal storage installation costs, Denmark (Guelpa & Verda 2019)



Alt Text for Figure 6: This is a bar chart that compares the upper (grey) and lower (blue) bounds for the cost of thermal energy storage in Euros per meter cubed in the Danish district heating market. The percentage difference between the upper and lower bound is captured in navy blue for each technology. The analysis is across water tanks, Pit, Borehole and Aquifer storage systems

The significant differences between the upper and lower bounds of installation costs, even when normalised to price per cubic metre, result from large differences across local, regional, national, and project-specific features, from technical limitations to customer demands and geography.

Regardless of these differences, the literature clearly defines that system scale significantly improves the cost-to-storage capacity ratio. “For interseasonal heat storage to become attractive, it must be very low cost. To achieve low costs, systems must be large” (Eames, 2014, 45). This is also true of borehole thermal storage, where the installation costs drop significantly with increasing storage size. “Storage volume should generally be larger than 20,000 m3 to be financially viable” (Kallesøe et al. 2021, 9).

Maintenance and operational costs

In the literature, maintenance and operational costs for thermal storage systems were generally reported as low once they were installed, especially for well-established technologies such as tank thermal storage. However, these costs can vary depending on the specific technology, with, for instance, PCM systems potentially requiring more ongoing maintenance due to material degradation or advanced control strategies. The cover in pit thermal storage must often be replaced during its lifetime but is rarely budgeted for (as discussed in *Barriers to thermal storage in heat networks*).

Thermal losses were identified as a significant factor, particularly in long-term storage systems, which can lead to increased operational costs (Guelpa & Verda, 2019).

There was no quantitative evidence from interviews on maintenance or operational costs. However, some interviewees mentioned that thermal storage, by enabling continuous operation of heat generation technology, saved significant maintenance costs on generating plant. In other words, the OPEX of the thermal storage systems is small compared to savings on the generating plant's OPEX.

Cost comparisons with alternatives

There is a range of possible alternatives to thermal storage that the electricity distribution and heat network markets could consider for energy storage, such as battery energy storage, pumped hydro storage, compressed air energy storage, and flywheel energy storage. Interviewees did not mention electrical storage being used within heat network systems or discuss it as a viable alternative to thermal storage, possibly because thermal storage is the most efficient route from electricity to heat, proven to be more efficient than storing energy as electricity until the moment of heat supply.

The literature consensus was that thermal storage is more cost-effective than battery energy storage technologies, particularly in large-scale applications and long-term scenarios. Hennessy et al. (2019) state explicitly that sensible thermal storage tanks are 50-100 times cheaper than electrical storage; this is corroborated by Guelpa & Verda (2019).

Cost trends

Historical capital cost trends

Interviewees had limited knowledge of historical cost trends in thermal storage. Some UK-based interviewees noted that the costs of thermal storage technologies, especially novel technologies like phase change materials (PCMs), have decreased in recent years due primarily to technology maturation and increased manufacturing scale, but remain high, which impacts their broader adoption. One UK heat network operator noted that the cost of TTES had risen in recent years due to the increased cost of stainless steel.

The literature provided minimal evidence of historical thermal storage cost trends, but it did recognise that “some cost improvements have been made based on learnings from earlier projects” (Delta EE. 2016, 20).

The situation is slightly different in Denmark. Interviewees with experience in the Danish district heating market noted that thermal storage capital costs have remained stable in recent years, and that high (and increasing) taxes on natural gas have supported thermal storage's economic viability.

Future cost projections

The research provided limited evidence or consensus on future capital cost projections for thermal storage and there were also conflicting views on future capital cost reductions. Some papers predicted that tank thermal storage, pit thermal storage, and borehole thermal storage are unlikely to see significant future cost reductions, given their relative maturity (Delta EE. 2016). In contrast, other papers suggested future cost decreases for interseasonal storage with technology improvements in materials and components and learning curve effects in construction and operation (Sifnaios et al. 2023).

Some papers noted that technological advancements and economies of scale, particularly for small-scale or community network systems, may reduce costs for emerging technologies. Delta EE. (2016) states that developers expect to see significant PCM cost reductions, potentially reducing by over 60% to £250/kWh of heat stored for residential applications. This implies cost competition with small and medium-sized hot water cylinders over the next five years.

One interviewee cautioned, however, "*that capital costs are difficult to predict and that flawed long-term projections have held back the development of the heat network industry in the past*", specifically citing previous incorrect biomass cost forecasts in Denmark.

Drivers of adoption and scale

The cost drivers discussed in the literature varied depending on the thermal storage technology. There was consensus around the importance of economies of scale for Sensible Heat Storage (SHS) technologies, particularly in interseasonal applications to drive down unit costs.

Interviewees highlighted a synergy between heat networks and renewable power markets that lies in sector coupling, demand-side flexibility, and integrating renewable heat sources. One interviewee noted that increased renewable penetration could drive thermal storage adoption by creating greater demand for storage, thereby potentially reducing costs through economies of scale.

A common view among interviewees was that subject to appropriate pricing and/or market reform, electricity costs would drive thermal storage as the market adopts a mentality of purchasing heat via off-peak electricity supply; otherwise, heat network operators will just continue to burn gas (in the absence of a carbon tax). In Scandinavian countries, the artificially raised gas price has supported the creation of these market conditions. In Denmark, interviewees directly correlated the tax on gas to their integration of thermal storage.

> "Before we had the [thermal storage] tanks, we had to deal with the peaks by burning natural gas. By implementing the tanks, we could stop firing natural gas to satisfy the demands, so the tanks were paid off very quickly. This is due to gas being expensive in Denmark. Because of the tax on the gas you burn, you must pay a tax per unit of heat you make. That's what paid off the tanks."
>
> *Heat network operator, Denmark*

By comparison, many UK interviewees identified the low cost of gas as a barrier holding back the ability of low electricity costs to drive thermal storage adoption. An example shared included foreign governments (such as the Dutch government) moving the levies from electricity prices onto gas prices with the potential to eventually drive thermal storage uptake.

> "The [UK] government is looking at levy rebalancing, potentially narrowing the gap between electricity and gas prices and making thermal storage more valuable. But that's fundamentally the problem: We currently have cheap gas, so the value of stored heat is finite."
>
> *Heat network consultant, UK*

One interviewee from the United States described how thermal storage would win at larger scales via an economic transition scenario (as opposed to a net zero transition scenario). In other words, economies of scale will propel thermal storage integration in heat networks.

> "Economies of scale do work in thermal storage. Where we find less success is when it's done on a building-by-building basis…Because that requires individual buildings to manage that asset with tools, staffing, and skills, I don't know that that can be properly managed on an individual building basis."
>
> *Heat network consultant, US*

Prospects and innovations in thermal storage

This section provides a brief overview of technological advancements, emergent demand, and market growth within the thermal storage technology ecosystem, specifically those related to district heating integration. Several innovations are focussed on addressing market failures that are covered in the *Barriers to using thermal storage in heat networks* section.

Technological advancements

The literature highlighted several potential technological advancements in thermal storage. Notable examples included developing new materials, adopting novel storage solutions (e.g., geostructures[1]) and smart metering and control systems designed to enhance efficiency and reduce costs. Interviewees also observed that innovation is moving away from hot-water-tank thermal storage towards longer-duration thermal storage systems such as borehole and aquifer thermal storage. One interviewee noted that these technologies require unique contractor expertise, with potential transferrable skills from geothermal engineering and gas exploration.

New materials

Significant research is dedicated to developing and refining advanced materials, including PCMs and thermochemical storage methods. These materials are being explored for their potential to improve energy density, thermal conductivity, and overall storage efficiency. Many of these materials are still in the early stages of development and require further research to overcome challenges such as thermal decomposition and low conductivity. Interviewees mentioned that these technologies could overcome space restrictions by using non-water heating elements that can hold more heat in less space. This can potentially address one of the significant barriers to thermal storage optimisation, space and land costs. Networks in dense urban areas where land values are likely to be highest would particularly benefit, where space-saving could be built into the investment case.

Whilst interviewees noted that a limitation of current PCMs was that they operate at precise temperatures, they were generally considered promising. Research & Development in this field is often focused on improving latent heat thermal storage's application and feasibility characteristics because it is considered an important option for future energy storage (Pompei et al. 2023). Several innovators with thermal storage or relevant thermal storage technologies are also operating in the UK. These include salt-based PCMs, heat batteries, microencapsulation and PCM-enhanced building materials.

[1] Geostructures (also known as energy geostructures or thermo-active geostructures) are underground structural elements that function both as traditional foundation components supporting buildings or infrastructure and as heat exchangers for thermal energy storage and transfer with the surrounding ground.

Nanotechnology (through nano-enhanced PCMs) was identified as a future innovation area in PCM research to increase the storage medium's thermal properties, specifically its thermal diffusivity. This enhanced thermal diffusivity allows for smaller heat exchange surfaces while maintaining performance, resulting in more compact and cost-effective latent heat thermal storage systems (Pompei et al. 2023).

The most significant thermochemical thermal storage innovations show promising commercialisation pathways, particularly Mg-based metal hydride systems (Sheppard et al. 2023) for district heating, whilst zeolite-salt composites achieving energy densities over 300 kWh/m³ (Zhang et al. 2022) demonstrate strong scale-up potential. High-temperature perovskite materials and metal-organic frameworks for CO2 capture (Liu et al. 2022) also represent emerging but promising technologies.

Further technological advances, including more temperature-resistant liner materials in pit thermal storage, could enhance the feasibility of interseasonal storage. At the time of writing, a leading technology explored in academia is HDPE (High-Density Polyethylene) material (Roy et al. 2023). While this innovation would strengthen the business case for pit storage, it does not resolve the fundamental barriers to deployment in the UK, which are access to electricity market mechanisms and high land costs.

Novel storage systems

The literature also discusses the use of geostructures as thermal energy stores, aimed at optimising energy storage and utilisation in urban environments. Examples of integrated geostructures include foundation piles, retaining walls, tunnel linings, and basement walls fitted with embedded pipe networks. Other examples of geostructures comprise transportation tunnels and wastewater heat recovery. “In the UK, initial calculations suggest that >50 TWh/year could be generated from a combination of a variety of new-build infrastructure and exploitation of heat from existing wastewater systems” (Loveridge et al. 2022).

Other novel storage systems covered in the literature include mobile thermal storage (Lin, Xiao & Wang, 2024) and energy stored from industrial recovered heat. A brief discussion of a specific case study on mobile thermal energy storage (M-TES) was presented in the *Financial incentives and funding* Section. Mobile energy storage efficiently captures and delivers waste heat from source to demand, reducing onsite storage requirements and infrastructure costs. While this offers space-saving benefits and enables industrial-to-urban heat distribution, our findings indicate that stationary thermal storage systems remain vital strategic assets for both electricity grids and heat networks. Thus, mobile heat represents a complementary solution to thermal storage challenges.

Smart control systems

Smart control systems could transform thermal storage operations through sophisticated monitoring capabilities and data-driven management. Real-time monitoring provides operators with continuous visibility of storage parameters such as temperature stratification, state of charge, and thermal losses, enabling immediate response to charge and discharge inefficiencies. Predictive analytics utilise historical storage performance data and machine learning algorithms to forecast optimal charging periods, manage storage cycling, and anticipate thermal degradation—critical capabilities for maximising storage efficiency and extending asset life.

Advanced control technologies in thermal storage are evolving rapidly. AI algorithms can process complex variables, including storage temperature profiles, energy prices, and discharge demands, to optimise charging strategies. Cloud-based platforms facilitate the integration of multiple storage units within heat networks, while digital twin technology creates virtual replicas of storage systems to simulate and test cycling strategies without risking thermal shock or the inefficient operation of live storage assets.

The adoption of smart controls in thermal storage demonstrates significant potential for improving storage performance, though implementation varies considerably across heat networks. Traditional storage control systems often rely on fixed temperature setpoints and simple timing loops, limiting their ability to adapt to dynamic network conditions. As highlighted by Behzadi et al. (2022), modern algorithmic approaches enable sophisticated optimisation by continuously adjusting storage parameters based on real-time conditions and predicted thermal demand patterns. This is exemplified by a Swedish district heating operator who reported that implementing electricity price forecasting analytics enabled less-experienced engineers to make more informed decisions about thermal storage cycling.

These system improvements can serve a dual purpose: enhancing storage control whilst building a comprehensive performance database. The systematic collection and analysis of storage operational data provide valuable insights into stratification behaviour, thermal cycling efficiency and optimal charging strategies. This evidence base not only supports individual storage improvements but also facilitates knowledge transfer across the sector. By establishing standardised storage performance metrics and operational benchmarks, operators can share experiences and best practices, accelerating the learning curve for new thermal stores and building sector-wide confidence in storage solutions. Such practical demonstrations of enhanced storage control and knowledge sharing are crucial for widespread adoption. However, these advanced control systems remain in early adoption phases across many district heating schemes, indicating substantial room for performance improvements as these technologies mature and become more widely implemented.

Stimulating demand and market growth

Policy and market incentives

Several existing and emerging market and regulatory mechanisms will likely drive the thermal storage market's development. Forthcoming policies such as the Review of Electricity Market Arrangements (REMA), Regulated Energy Storage Providers (RESPs), Smart Systems and Energy Programme (SSEP), and Heat Network Zoning could enhance the value proposition of thermal storage through better recognition of its grid benefits.

UK interviewees discussed the necessity of having thermal storage to access Green Heat Network Funding (GHNF) as a potential growth driver.

> “We are seeing more thermal stores now because all the large projects are funded by the Green Heat Network fund (GHNF), and DESNZ has decided, rightly, that thermal stores are important.”
>
> *UK district heating trade association*

None of the interviewees or literature evidence described a current direct policy mechanism specific to thermal storage. Current market signals remain primarily indirect, with thermal storage deployed to optimise heat generation assets or provide system resilience rather than responding to specific policy incentives. While flexibility and balancing markets exist within the electricity sector, these mechanisms remain largely inaccessible to heat network operators.

Projected increases in gas prices could accelerate market development, enhancing the economic case for thermal storage as a balancing tool. However, near-term growth may be constrained by rising land costs and labour shortages.

The research indicates that several policy mechanisms could support thermal storage deployment. Some papers suggest modifying existing incentive mechanisms, such as VAT relief on thermal storage installations, while others advocate for new targeted policy mechanisms. Bolton et al. (2023, 7) explicitly highlight that a high degree of system orchestration and planning is required for interseasonal storage given the evidence gaps and (im)maturity in the UK, arguing that national and local policymakers need to "recognise the value" of thermal storage.

Stemmle et al. (2024) research on aquifer thermal storage across 30 countries found that international stakeholders did not feel that there was any targeted policy support to increase interseasonal thermal storage uptake. The paper emphasised the need for thermal storage knowledge transfer programmes, as these are currently limited to academic research projects. Specifically, technical assistance and collaboration programmes were argued to address systematic transfer of thermal storage expertise, potentially through existing structures such as the International Energy Agency's (IEA) Technology Collaboration Programme on Heat Pump Technologies (HPT TCP).

Across the interviews, only one interviewee expressed concerns about incentivising thermal storage adoption, specifically related to making the right investment choices in capital-constrained circumstances. The interviewee, an innovator in thermal storage and controls technology, expressed concern that increased investment in thermal storage might divert funding away from building fabric retrofit. Their argument suggested that by enabling stable heat network performance and consistent home temperatures, thermal storage might inadvertently reduce incentives for improving building efficiency through proper insulation and draught-proofing.

Knowledge exchange and collaboration

The absence of a dedicated knowledge exchange platform for thermal storage presents a significant barrier to advancement in the UK market. To address this, the UK could consider the establishment of a dedicated thermal storage knowledge exchange platform and pursue formal participation in relevant IEA Technology Collaboration Programmes.

Existing innovation frameworks, including the Energy Systems Catapult and Innovate UK programmes, have yet to establish dedicated workstreams or funding mechanisms specifically for thermal storage. The Heat Network Technical Assistance Scheme (HNTAS) could play a pivotal role in addressing these gaps by expanding its technical and innovation support to include dedicated thermal storage knowledge exchange. This would help establish a centralised platform connecting UK stakeholders with international expertise while creating a structured collaboration environment between government, industry, academia, and local authorities.

Several interviewees emphasised the need for closer collaboration between district heating operators and the electricity grid. This collaboration was considered essential for thermal storage advancement by unlocking new revenue streams for heat network operators in the electricity balancing markets.

Conclusion

This research has examined the role of thermal storage in UK heat networks, identifying key barriers, opportunities, and evidence gaps that have significant implications for policy development. Drawing on international comparisons and stakeholder insights, we present the following evidence-based conclusions and policy considerations.

Current state and fundamental challenges

Thermal storage offers substantial benefits for UK heat networks, with robust evidence demonstrating improvements in operational expenditure, decarbonisation potential, and enhanced system resilience. While short-duration sensible heat storage (primarily tank thermal energy storage) is relatively common in UK networks, significant untapped potential remains.

The most acute barriers to thermal storage adoption in the UK are:

- **Fragmented ownership models that fundamentally undermine optimal deployment:** When developers do not operate the networks they build, they prioritise minimising upfront capital costs over long-term operational efficiency. This misalignment of incentives consistently leads to undersized thermal storage systems that fail to capture long-term operational savings. By contrast, the research shows that aligned incentives between development and operational stages lead to greater adoption and optimisation of thermal storage.
- **Space constraints and high land costs, particularly in dense urban areas suited to heat networks**: These constraints often result in compromised installations that cannot deliver their full potential benefits.
- **Poor integration between heat and electricity market regulations that actively blocks grid flexibility benefits for heat network operators:** This regulatory disconnection prevents heat networks from accessing substantial economic and environmental returns that could strengthen the business case for thermal storage.

Evidence gaps and innovation barriers

Critical knowledge gaps persist that prevent confident investment in thermal storage:

- **Limited UK case studies:** Few comprehensive UK demonstrations of thermal storage performance exist, particularly for long-duration storage. This creates uncertainty for new projects and limits knowledge transfer within the sector.
- **Performance data shortages:** The lack of standardised, reliable data on system efficiency and financial metrics for different technologies hampers effective decision-making. Current studies on thermal storage applications are case-specific and not easily generalised to different future conditions.

- **Financial impact uncertainty:** There is insufficient evidence regarding the long-term economic viability and financial benefits of thermal storage, particularly for heat pump integration and electricity market opportunities. Guidance on creating consistent and impactful investment cases would enhance investment approval within organisations and across the industry.

The UK has a substantial research base for innovation in latent heat and thermochemical storage; however, adoption rates remain low. Despite promising space-saving benefits, phase change materials (PCMs) are constrained by their fixed operating temperatures and early-stage commercial development. This represents a missed opportunity to address the space constraints that currently limit the implementation of thermal storage in urban environments.

Market structure and economic considerations

A critical misalignment exists between the economics of thermal storage investment and electricity market mechanisms. Thermal storage systems require substantial upfront capital with lengthy payback periods (5-10 years), whereas flexibility contracts typically offer only a 3-year duration. As repeat flexibility contracts are not guaranteed, such mechanisms provide limited certainty of revenue over the investment period.

Current market structures for heat network delivery in the UK have yet to widely implement or support opportunities for revenue stacking through thermal storage. UK interviewees report that thermal storage is selected and designed based on access to established market incentives that are well understood, rather than speculating on access to existing and future electricity market incentives.

Supply chain and skills limitations

The research identified significant supply chain and skills gaps that constrain UK thermal storage development:

- **Design expertise**: A lack of experienced consultants who can confidently design and specify large thermal storage systems, especially for newer technologies.
- **Manufacturing capability:** Limited domestic capability for manufacturing large thermal storage vessels, creating reliance on international suppliers.
- **Operational confidence:** Heat network operators often lack experience in realising the full current and future benefits of thermal storage to both access electricity markets and optimise operation, requiring better data and automation.

Policy considerations and future directions

To realise the full potential of thermal storage in UK heat networks, several interconnected challenges need to be addressed:

- **Enhance integration between heat and electricity markets** to harness grid flexibility benefits and optimise peak demand management, thereby achieving full economic and environmental returns. Current market structures have yet to widely implement or support opportunities for revenue stacking through thermal storage.
- **Address fragmented ownership models that lead to misaligned incentives between developers, operators, and consumers**: Design decisions should balance capital and operational costs to achieve lower overall heat costs for end users.
- **Encourage larger-scale systems to improve the cost-to-storage capacity ratio,** making thermal storage more economically viable. Research indicates storage volume should generally be larger than 20,000 m^3 to be financially viable.
- **Bridge evidence gaps by collecting performance data and developing case studies** from existing pilot projects to strengthen the evidence base for both policy and more consistent investment cases.

While thermal storage investment is expected to grow in line with heat network expansion, coordinated development can ensure that storage technologies are appropriately sized, selected, and implemented to maximise benefits. This coordination would support the alignment of heat networks with an electrified, low-carbon future, helping to unlock the full potential of thermal storage in the UK energy system.

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