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A niche technique overlooked in the Danish district heating sector? Exploring socio-technical perspectives of short-term thermal energy storage for building energy flexibility

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ABSTRACT

This research explores socio-technical perspectives of the demand-side management strategy of using the built environment for short term thermal energy storage. Here conceptualised as a niche innovation within the Danish socio-technical district heating landscapes, the research explores potentials and limitations of this building energy flexibility strategy from the perspective of district heating sector professionals, actors at the centre of the low-carbon energy transitions. Results of the mixed-methods abductive research enquiry suggest that this energy flexibility strategy facilitates (I) solving local network congestion challenges in smaller parts of existing networks and (II) reduces needed network capacity in new heat supply areas. Sector professionals assess this (III) energy flexibility strategy as most practicable in large-scale/commercial buildings and industries. Challenges include hardware balancing, service and maintenance, and the sometimes counterproductive incentive structures among stakeholders involved. Research evidence suggests that business models appealing to environmental values and priorities may incentivise sustainable heat-use behaviours more than economic benefit alone among some groups of end users. Building energy flexibility and demand-side management strategies may become integral to future 'smart' energy systems throughout the world. However, their successful implementation necessitates understanding the local socio-technical dynamics involved. Multidisciplinary research approaches as the one taken here facilitate these necessary insights.

1. Introduction

In temperate and cold climates, district heating systems provide the most cost-effective and sustainable solution for supplying heat to buildings located in urban areas [1,2]. District heating systems are flexible in terms of fuel use, technological solutions, and energy storage. They can integrate a wide range of renewable energy sources, harvest the waste heat from local industries and combined heat and power plants (CHPs) [3,4], and they may comprise short- and long-term thermal energy storage capacity. This may enable energy sector coupling, increase energy flexibility, and thus facilitate low-carbon energy transitions [5,6]. Research suggests that district heating systems facilitate energy flexibility at a markedly lower cost than alternative solutions [7]. For these reasons, district heating systems could become an important part of low-carbon smart energy systems in countries with high heat demands in the future [1,2].

However, district heating systems that are fuelled by intermittent renewables, for example wind power and solar power, may lead to an imbalance — or a mismatch - of heat supplies and heat demand. This challenges the security of heat supplies. Multiple demand-side and supply-side management strategies have been developed to reduce these mismatches. These strategies may include energy load shifting, peak shaving, valley filling, maximising the use of locally produced energy, and preparing end users for forecasted grid deficiencies [3] (see section 3).

Multiple innovative energy flexibility and demand-side management strategies are currently being tested. For example, activating the thermal capacity of the built environment for short-term thermal storage has proved a promising demand-side management

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strategy [8–11]. However, while novel demand-side management strategies may work in theory, they may not always be practicable due to multiple socio-technical factors and frictions. Sector professionals, the key actors who tackle these challenges in their everyday working lives have unique insights into these complex socio-technical dynamics. They may also have a keen sense of where – and how - systems optimisation might occur.

This research explores socio-technical perspectives of the demand-side management strategy of using the built environment for short term thermal energy storage. Specifically, the research sets out to explore potentials and limitations of this demand-side management strategy from the perspective of district heating sector professionals, the actors at the centre of the ongoing low-carbon energy transition processes. Here, use of the built environment for short term thermal storage is conceptualised as a niche innovation within the Danish socio-technical district heating landscapes [12–14] (see Fig. 1 and Text Box 1).

The research is guided by the following research questions: How does the demand-side management strategy of using built environment for short-term thermal energy storage work? How well-known is this demand-side management strategy among district heating professionals, and how do they view it? Given the above: What do sector professionals perceive as key limitations, challenges, and potentials of this short-term thermal energy storage demand-side management strategy within the socio-technical district heating landscapes in Denmark?

In terms of limitations, the empirical and analytical breadth and scope of the paper come at the cost of in-depth empirical and analytical detail, and alternative demand side and supply side management strategies are not discussed.

The paper is organised as follows: After the research methodology (2), the background section (3) describes the building energy flexibility strategy of using the built environment for short-term thermal energy storage, also noting key contextual factors that may inform the viability of the method are outlined. Section (4) presents the mixed research data results. In view of the above, section (5) discusses socio-technical limitations, challenges, and potentials of using the built environment for short term thermal energy storage within the Danish socio-technical landscapes.

Textbox 1
The Multi-Level Perspective

*The Multi-Level Perspective (MLP) has proved a popular heuristic for socio-technical transition studies [13,17,18]. There are three analytical levels in the MLP: the landscape, the regime, and the niche [17,19]. **Niches:** allow for experimentation with emergent technologies, practices, and regulation. Niche innovations are generally bottom-up phenomena. Niches are protected spaces [13,20].*

***Regime:** represents the conventional approach – dominant ideas, established interests, technological paradigms or regimes, rules, common practices and cultural influences. Regime-level phenomena are institutionalised. Within the regime, economic actors respond to market signals and to macro-political dynamics. The regime is relatively stable and resistant to change [21,22]. **The Landscape:** within this three-level view of the world, the landscape is at the macro level. The landscape is an area of slow change. Slow-moving cultural, social, structural, political, economic, and technical change processes are located conceptually within the landscape [17,23], (Textbox adapted from Ref. [24]).*

2. Methodology

The abductive and exploratory research enquiry draws on mixed data from an extended case study [15,16]. The research is underpinned by the pragmatic research paradigm, and it is informed by the Multi-Level Perspective conceptual framework (MLP) [12,13] (see Fig. 1 and Text Box 1). This mixed methods abductive research strategy serves a double purpose: a) It harvests socio-technical (localised) knowledge, professional insights and perspectives from the sector professionals, and b) provides conceptual insights into the frictions, fractions, dynamics, *and energy flexibility potential* of the socio-technical Danish district heating landscapes.

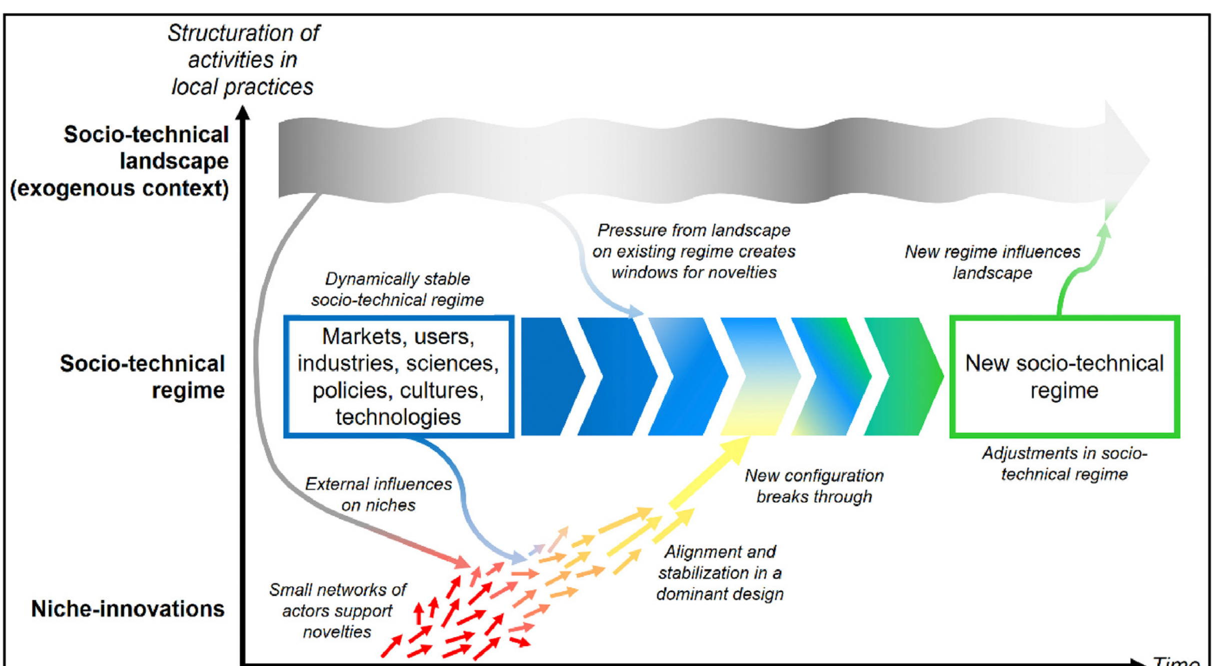

Fig. 1. The multi-level perspective on transitions. Adapted from Ref. [13] for this research by Hicham Johra. Printed with permission.

The research benefits from multidisciplinary collaboration, knowledge-sharing, and inspiration.

2.1. Data collection, survey sample and coding process

The qualitative data were collected from district heating professionals, consultants, government experts, and researchers. These data com-prise informal- and semi-structured interviews, insights from sector webinars, seminars, and workshops. The research also draws upon academic literature, sector reports and legal texts. The exploratory qualitative data collection process informed and inspired the survey instrument. To ensure validity and reliability in the survey, district heating professionals from various types of district heating companies were asked to contribute with comments, suggestions, and to correct/refine the technical terminology used. The final survey design allowed for testing and validating analytical assumptions and hypotheses generated by the lead author during the initial exploratory research process.

The survey respondents are district heating sector professionals. The sampling frame comprised the 534 district heating companies and CHPs throughout Denmark. This list was generated by combining information from the Danish Utility Regulator (Forsyningstilsynet, 2021) and the Danish surveying business, LIFA [25]. The largest companies were invited to provide contact information for several employees, while only one employee was invited from the smallest companies. Diversity in professional outlooks and perspectives was ensured by inviting respondents with different professional titles and responsibilities. The recruitment- and data collection took place during the spring of 2020 and in accordance with the GDPR criteria set out by the Danish Data Protection Agency. A professional data collection platform handled the data collection process.

The final survey sample comprised respondents from a wide range of the diverse Danish district heating companies (see Table 1, Fig. 2, and section 3.5). Most respondents were senior males with many years of work experience within the district heating sector. This tendency mirrors the working population within the Danish district heating sector. The respondents completed the survey meticulously, and many of the 1161 open-ended responses were long and rich in reflective detail. The qualitative survey data were coded using a rigorous inductive process of content-coding. This resulted in descriptive, thematic, and analytic codes. The lead author translated the open-ended responses included here from Danish to English. Statistical significance is reported with.

Table 1
The survey sample. Notes. Respondents in total: 187. Final sample: 175. Privately/industrially owned district heating production plants that sell surplus heat wholesale only (i.e., with no end users) were coded missing in the final sample. Coded missing: 12. Total string responses: 1161. Total number of utilities/companies represented in the survey: 148. For a sense of the complex nature of the Danish district heating sector, see Fig. 2.

Utility size compared to other companies in the Danish district heating sector	
Small	62
Medium	67
Large	46
Total	**175**
Utility type	
Combined heat and power plant (CHP), centralised	22
Combined heat and power plant (CHP), decentralised	47
District heating plant only	63
Distribution and/or transmission only	15
Bare field plant, a decentralised CHP	12
Privately/industrially owned district heating production plant	04
Other ownership: ‘Other’ large mixed utilities, centralised CHPs (7) privately/industrially owned district heating production plants (4) and other (5)	16
Total	**175**
Ownership type	
Cooperative ownership, typically AMBA.	110
Municipal and public ownership, typically I/S.	59
Other ownership: Includes private DH plants (3) and housing associations (1)	06
Total	**175**
Respondents' professional title or occupation within the company	
Production manager or other management position	67
Operations manager/machine engineer or similar	66
Engineer, technical advisor or similar	06
Craftsmen with different roles and specialities	10
Energy planner, energy consultant or similar	11
Communication/administration or similar	05
Other	10
Total	**175**

standardised chi-square values of $p < 0.01$***, $p < 0.5$** and $p < 0.1$*.

3. Background

3.1. Technical background

This section explains how the demand-side management strategy of using the built environment for thermal energy storage works. It out-lines key socio-technical factors that inform how practicable it may be, and it considers to what extent these can be changed or adapted. The technical background for this niche innovation is described first. In recent years, engineers have referred to a new paradigm when considering building stock. Previously, buildings were considered merely passive recipients of energy. However, new research shows that buildings can become an active part of the energy system by using energy flexibility- and demand-side management strategies [27,28].

Building energy flexibility strategies are defined as the adaptation or modulation of energy use in a building *without* jeopardising: (a) the technical capabilities of the operating systems in the building[1] or (b) the comfort of its residents/users [27]. The energy demand profile of buildings can be moderated via peak demand shaving, valley filling and load shifting (see Fig. 3). Building energy flexibility strategies can — potentially - improve the operation of energy grids. Moreover, buildings can also *produce* energy that can be re-injected into the energy system in different forms.

Among the different building energy flexibility strategies, direct storage of heat inside the built environment has shown great potential to perform load shifting over time, from a few hours to a couple of days [30–33]. This is beneficial when operating a district heating grid with an increasing share of renewable energy sources. Far from the ‘norm’ or ‘standard procedure’, this building energy flexibility strategy is conceptualised as a niche innovation here (Fig. 1; Text Box 1) [13,24,34].

Research suggests that this niche innovation may help: (I) solve local congestion challenges in isolated sections or ‘pockets’ of a given district heating system (II) and reduce the minimum district heating network capacity required to meet growing heat demands in older heat supply areas. (III) Sector professionals assess this building energy flexibility strategy as most practicable among larger-scale end users, for ex-ample in commercial buildings, industrial buildings, and in multi-family buildings (see section 4). The

[1] Examples might include: the continuous start/stop of heat pumps, heating up the water tank more than necessary, running ventilation too high, increasing, or decreasing the local voltage or frequency of the electrical grid, which will damage electronic systems, etc.

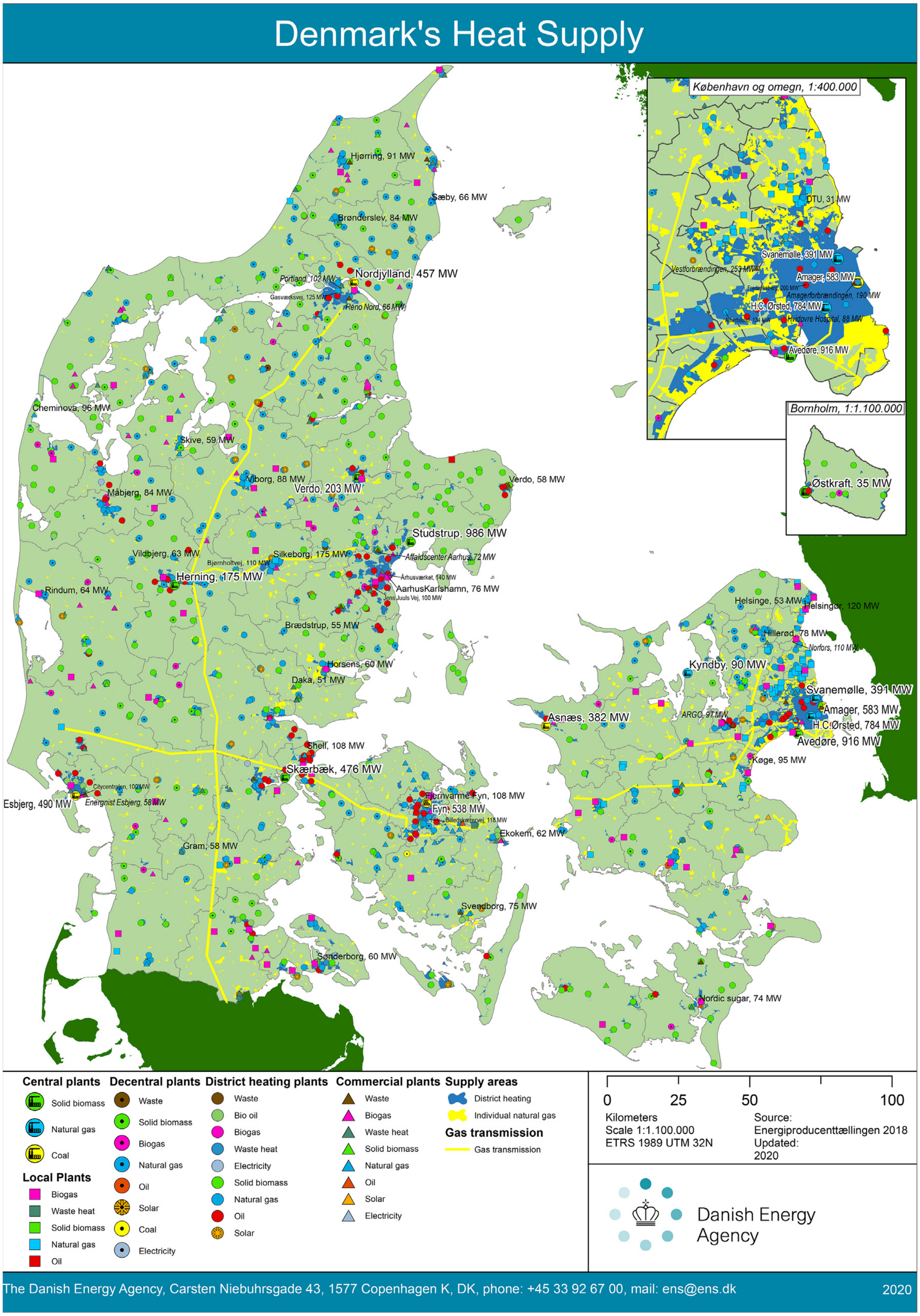

Fig. 2. Heat supply in Denmark. Source: [26].

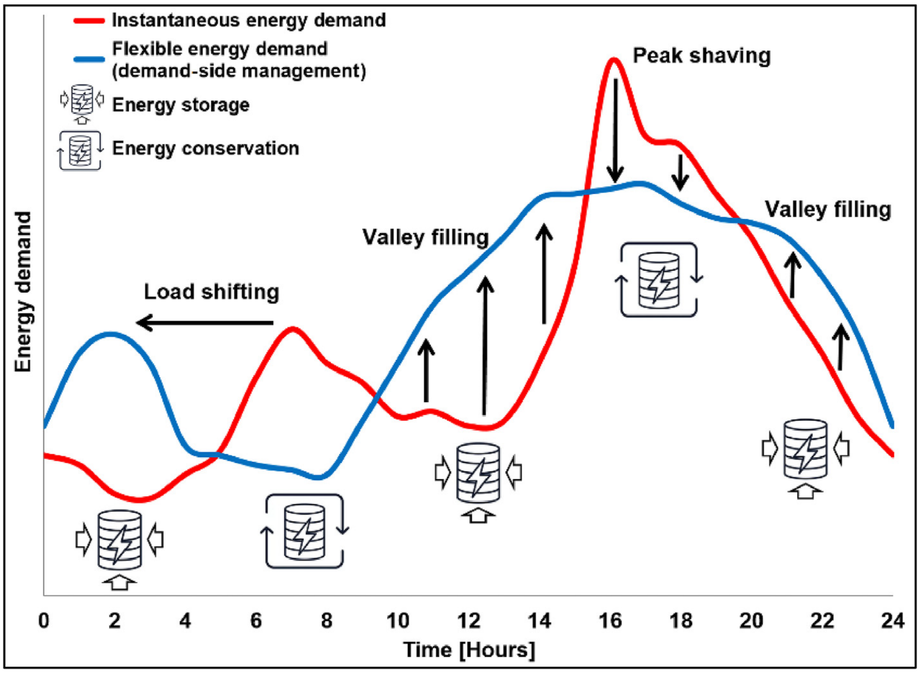

Fig. 3. Demand-side management illustrated (modified from Ref. [29]). Notes. Peak shaving: Reduction of energy peak demand. Load (time) shifting: Anticipate or delay energy use. Valley filling: Increase energy use over a short period of time when the energy demand is low, and the renewable energy production is high. This energy can be stored for a predicted/known period of energy shortage or peak shaving need. Valley filling can also be the result of a rebound effect following peak shaving.

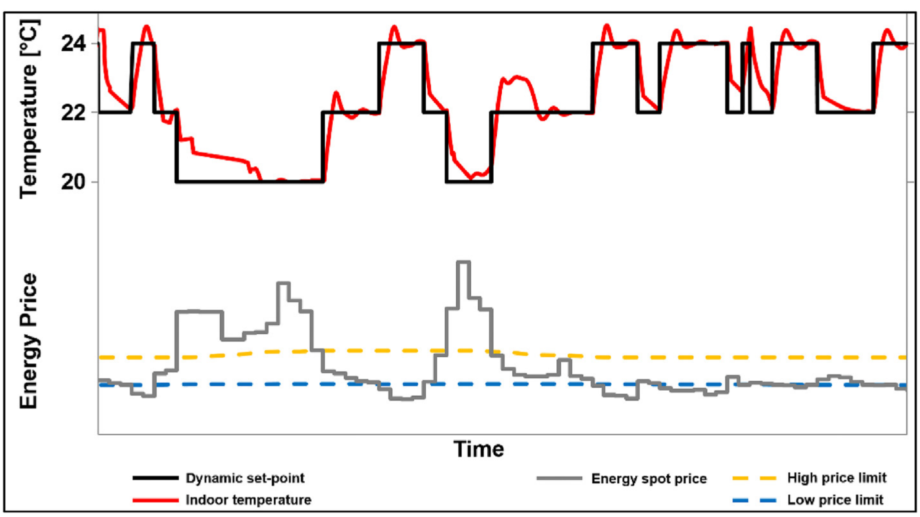

Fig. 4. Example of demand-response by means of an indoor temperature set-point modulation according to an energy spot price control signal.

following sections describe how the built environment can be used for short-term thermal energy storage.

3.2. Thermal energy storage using the built environment: how does it work?

Lowering the temperature set-point[2] at night, i.e., when commercial buildings are empty and when occupants of dwellings typically sleep, leads to energy savings without jeopardising the thermal comfort of the users of buildings/occupants. This is referred to as a night-time indoor temperature setback. Re-heating the now colder indoor environment in the morning then creates a morning peak in heat demand. In Denmark, morning showering *and* re-heating the indoor space after the night-time temperature setback are common causes of morning peaks in heat demand. To tackle this challenge, demand-side management strategies, for example thermal storage by activating the thermal inertia in building stock, can be employed. This can be done via an indoor temperature set-point modulation control for the heating system.

Fig. 4 shows an example of demand-side management by means of indoor temperature set-point modulation. Here, the chosen control signal, i.e., the incentive for the energy end user, is the electricity spot price. When the price of electricity is low, and the production of renewable energy resources is high compared to the demand, the temperature setpoint is increased to 24 °C. The

[2] The temperature set-point is the desired temperature.

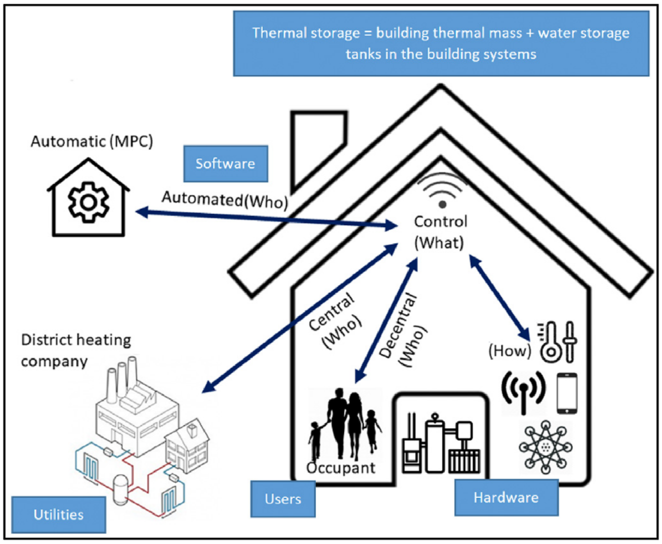

Fig. 5. The How, Who and What of smart home technologies for demand-side management in buildings connected to a district heating system. Adapted from Ref. [36] by Hicham Johra for this research. Printed with permission.

controlled according to another incentive or penalty signal, for example the CO_2 intensity of the energy mix in the grid, or the congestion status of the local network.

The thermal storage capacity and the correlating load-shifting capacity of dwellings or buildings vary. This load-shifting capacity depends on the indoor thermal mass of the building, and on the thermal performance of the building envelope. For light buildings, or for older buildings with poor insulation, load shifting may only be possible for a few hours. For well-insulated buildings, and for buildings with high thermal inertia, load-shifting may last up to a day or two. After a full heat accumulation period, a low-energy/passive house may maintain a comfortable indoor temperature - without any heating demand - for more than 24 h [33].

Energy accumulation in the indoor environment is a cost-effective solution compared to hot water storage tanks [35]. It does not require installation of expensive indoor equipment that takes up valuable space in expensive urban housing. Rather, it relies on smart home technologies, smart meters, building automation and building management systems (see Fig. 5). Increasingly common in our lives, these may also be used for automated billing, energy use monitoring, optimisation of in-door comfort, fault detection, security, etc. [37].

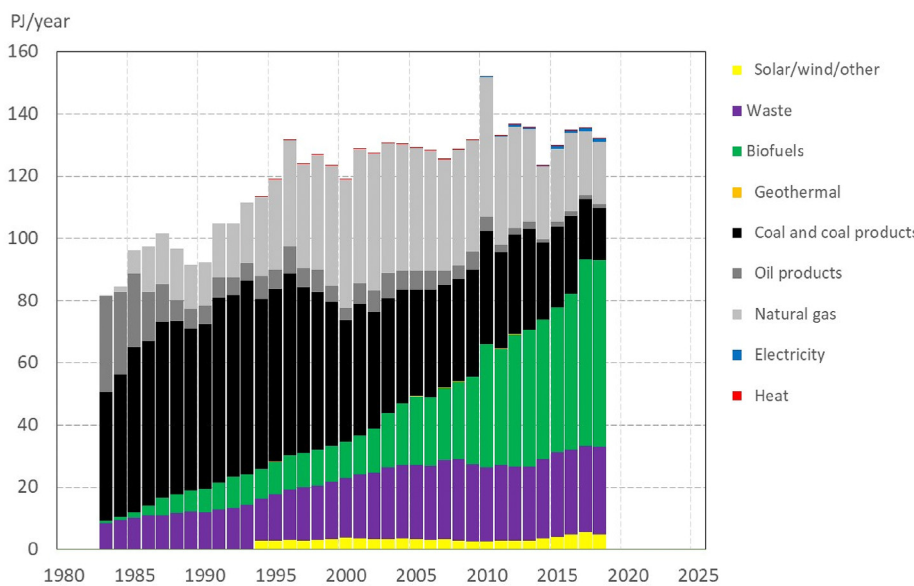

Fig. 6. Fuels used for district heating in Denmark from 1980 to 2018. In PJ/year.

building energy demand increases, and part of this heat is stored in the thermal inertia[3] of the indoor space. When the electricity spot price is high (and the production of renewable energy sources is low compared to the demand), the temperature setpoint is decreased to 20 °C. The building energy demand decreases, and some of the heat stored in the thermal mass is released into the indoor space. This slows down the temperature drop. When the price of electricity remains between the higher and lower limits, the temperature set-point is maintained at 22 °C. That way, indoor temperature set-point modulation effectively performs load-shifting from high price periods to low price periods [33]. In Fig. 4, the indoor temperature set-point is modulated according to the electricity spot price. However, it could also have been

3.3. Policy context and existing heat supply infrastructures

The policy priorities security of supplies, energy equity, fuel diversification and energy independence were integral to the first Danish Heat Supply Act from 1979 [40–44], and in the 1990s they easily integrated the notion of sustainability [40,41,41–43,45]. The policy criteria for heat supplies in Denmark is still energy equity, fuel diversification, energy independence, and 100% security of supplies [45–47]. District heating systems throughout rural- and urban Denmark are highly heterogeneous, varying in terms of technical solutions, network capacity, short-term- and long-term thermal storage solutions; fuel use and fuel supplies, utility types, heat supply density and heat supply area characteristics (e.g., rural, suburban, or urban, single-family houses, apartment blocks or commercial buildings) (see Figs. 2 and 6 and Fig. 7) [14,49–51].

[3] Thermal inertia: the amount of energy that a system (e.g., a building) can store for a specific increase in temperature.

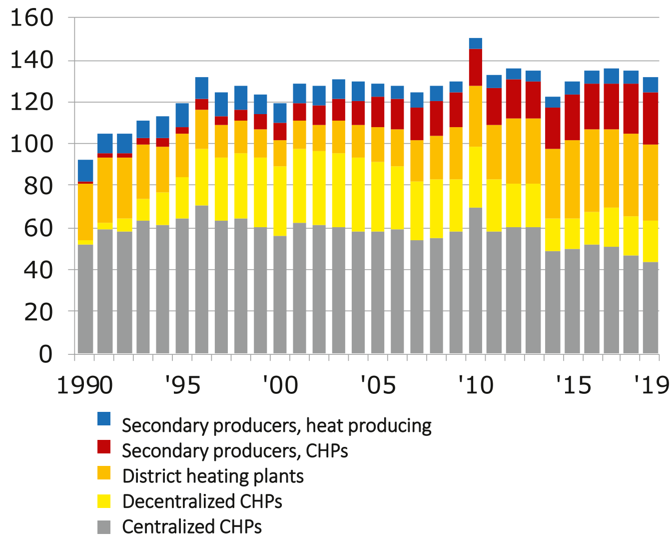

Fig. 7. Production of district heating in Denmark from the year 1990–2019 by type of heat generation plant. In PJ/year [48].

3.4. Boundary conditions, buildings, and their users

Multiple socio-technical factors and boundary conditions inform how viable and practicable use of the built environment for thermal storage is (see Textbox 1 and Fig. 1). Boundary conditions can be understood as external variables or factors with great impact that a) cannot be changed, or b) as factors that can be changed, but only at a cost - or with other changes in the socio-technical system (see Fig. 1; Fig. 5; Text Box 1).

Boundary conditions could be the 'types' building stock (e.g., single-family houses, apartment blocks, office space or industrial building), climate/outdoor conditions and geographical location; thermal performance of the building envelope, the effective indoor thermal mass, and types of heat supply systems [33]. Other important socio-technical factors could be maintenance- and supervision of the heat supply infrastructures in buildings, indoor thermal comfort preferences of the occupants, their willingness and ability to (or lack thereof) to provide flexibility services to the grid, acceptance of smart home technologies, etc. How intelligibly users/building occupants interact with these technologies has been identified as an important *barrier* to their implementation [38].

While some of the socio-technical factors and boundary conditions mentioned above are fixed, e.g., the local weather, climate and the existing heat supply infrastructures, other factors and variables may be adapted or changed. For example, heat supply infrastructure maintenance may be improved, and perhaps existing heat supply infrastructures can be used in different ways. Building regulations can change. Policy priorities and the legal framework for heat supplies can be adapted. Notably, norms, traditions, and expectations of indoor temperatures (or indoor comfort) among the end users/consumers of heat can be moderated or adjusted. History tells us that these have, indeed, changed radically throughout the decades. We also know that they vary greatly throughout the globe [39].

4. Results and analysis

The mixed data presented below is collected from district heating sector professionals, the people and the experts who tackle low-carbon energy transition processes in their everyday working lives (see section 2; Table 1). These data reflect the plethora of demand-side management strategies and technical solutions used throughout rural and urban district heating landscapes in Denmark. Informed by these data, the next sections discuss socio-technical factors that prove relevant for the demand-side management strategy of short-term thermal energy storage using the built environment. The language and the technical terminology used among the sector professionals themselves is also used here.[4]

4.1. Policy priorities: security of supply and energy equity

Variations of the historical energy policy priorities: security of supplies, price, and sustainability often appear in utility slogans. They also emerged as key concepts in the exploratory process of this research.[5] In the survey, respondents were asked to rank security of supplies, price, sustainability, and comfort by how they felt these were currently prioritised at their companies.

The results in Fig. 8 show that security of supply is the top priority for most, while the notion of comfort is the lowest priority. From a utility perspective, however, 'comfort' is ensured with supply security as supply security allows the customers/end users to adjust their indoor temperatures according to individual temperature preferences.

Fig. 9 illustrates the diversity of technical solutions and combinations of demand- and supply-side management strategies that are currently used within the Danish district heating sector. While Fig. 9 shows how common these demand- and supply-side management strategies are, it does not reflect their relative capacity or effect. For example, seasonal thermal storage solutions represent considerable thermal storage capacity *and investment*, but they are not very common.

4.2. Peak-load management challenges in the Danish district heating sector

Survey data suggest that morning-, evening- and winter/seasonal peak-load challenges are not pressing for most of the Danish district heating companies (see Fig. 10). 20.6% of the respondents in the final sample did report yearly peak-load management challenges, however. Thus, Fig. 10. suggests that most district heating systems in Denmark already have the network capacity to manage seasonal peak demands. While this could be viewed as a general tendency of *over-dimensioning* the district heating networks, this excess (or ample) network capacity also ensures meeting the heat supply policy criteria — and, indeed, political mandate - of ensuring 100% heat supply security for the end users (see section 3.3).

4.3. Demand- and supply-side management strategies in the Danish district heating sector

The politically determined heat supply policy criteria can be met through an array of demand- and supply-side management technologies *and* strategies.[6] These can be combined in various ways to meet the specific local needs/challenges in a specific local district heating system.

In Denmark, the most common strategy for short-term thermal energy storage in buildings is use of domestic hot water storage tanks. These are sometimes installed with space-heating or

[4] For information about the history of heat-supply infrastructure planning and policy in Denmark, see Refs. [40–42]. For an in-depth overview of the Danish district heating sector, see Ref. [14].

[5] For many years, the slogan of Greater Copenhagen Utility (HOFOR) was 'Grønt. Sikkert. Billigt'. Or in English: 'Green. Stable/Safe. Inexpensive'. See: HOFOR.dk.

[6] See e.g., Ref. [3] for an overview of these.

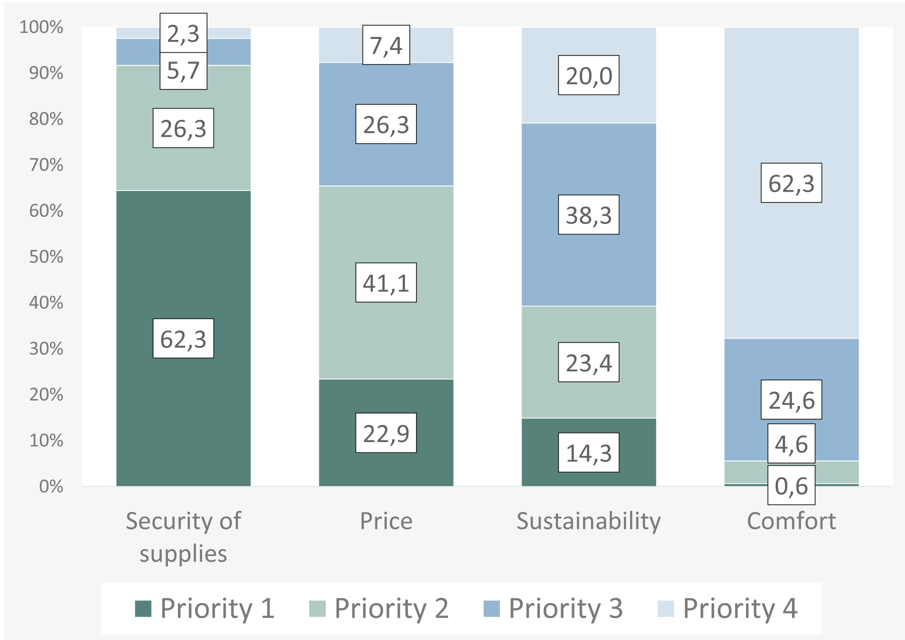

Fig. 8. Policy priorities at the district heating companies. Notes: The respondents ranked the concepts of security of supply, price, sustainability, and comfort in order of assessed prioritisation at their companies. Ranking: From highest priority to lowest priority. The terms were presented in a randomised order to the respondents. N = 175. This order of prioritisation is the same across the various utility types.

sanitary hot water production systems in single family dwellings, apartment blocks and multi-family housing. Some utilities also experiment with demand-response strategies that target behavioural changes among energy end users. This could be economic incentives that reward users for reducing or offsetting their heat usage during times of peak demand or when renewable energy resources are in short supply.

For many utilities, managing seasonal peak-load challenges entails activating reserve- or peak-load boilers (see Fig. 9). These are usually powered by fossil fuels. Thus, activating reserve-load boilers often results in higher CO_2 emissions/bigger CO_2 footprints for the individual utilities. Typically, reserve-load boilers also have higher operating costs [3].

4.4. Building energy flexibility: knowhow and reflections among sector professionals

Niche innovations (see Textbox 1) continuously emerge within the Danish district heating socio-technical landscapes. Some of these are well known, while others are less so.

Fig. 11 illustrates knowledge about the emerging niche method/technique of using the built environment for short-term thermal energy storage among the sector professionals by self-reported utility size. Ac- cording to these survey data, only 45.1% of the smaller district heating companies know of/have experimented with this short-term thermal energy storage solution, compared to 87% of the larger companies.

While the results in Fig. 11 may not be surprising, they also emphasize that keeping up to date with technical advances and knowhow may be particularly challenging among the smallest utilities.

Fig. 12 maps recurrent topics and themes in the open-ended response option on experiences and/or thoughts about the demand-side management strategy of using building stock for short-term thermal energy storage among the district heating professionals. These data highlight the importance of unique local district heating infrastructure characteristics. Some respondents describe why this strategy is *not* relevant in their district heating system, some respond by highlighting excess/surplus capacity in their district heating network, and others list thermal energy storage solutions they have already implemented in their district heating systems. See illustrative examples in Table 2.

Fig. 13 maps recurrent topics and themes in the open-ended response option on utility strategies for managing heat consumption challenges among end users. These data highlight the keen focus on customer service among the sector professionals. They also show that maintenance of domestic district heating hardware *and* non-optimal return temperatures among end users are recurrent challenges throughout the sector. Many sector professionals mention the general lack of knowledge/interest in optimising - or merely maintaining - heat supply infrastructures among the end users - private as well as commercial (see Table 2).

According to these data, district heating professionals are *positive* towards use the indoor built environment for short-term thermal energy storage overall. The sections below summarise their key reflections and rationales vis-à-vis limitations, challenges, and *potentials* of this building energy flexibility demand-side management strategy. They are organised by end user types.

4.4.1. Single family dwellings

Some district heating professionals highlight the array of potential legal- and technical complexities associated with domestic electronic devices (e.g., smart meters). This scepticism is informed by their professional experiences with/perceptions of private end users as generally disinterested, unwilling to, and in some cases perhaps *unable to* maintain even their current in-house district heating hardware. Many reported that most private end users have little or no interest in - let alone knowledge of - their heat consumption and their heat supplies.

Some respondents anticipate that end users will be open to

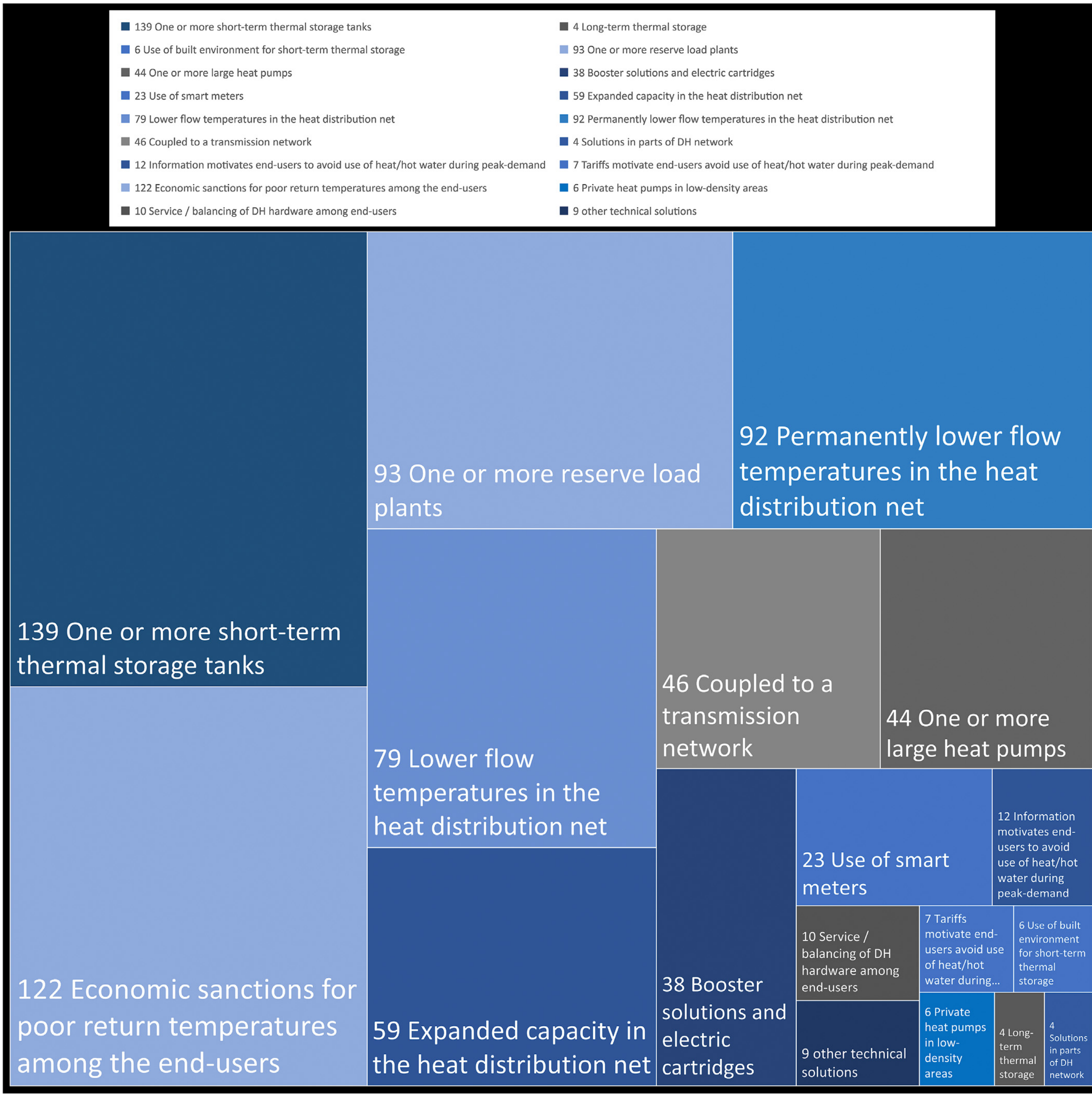

Fig. 9. Variance of demand-side and supply-side management strategies in the Danish district heating sector. Notes: This Figure presents common and less common demand- and supply-side management technologies/strategies in the Danish district heating sector. This highlights the technical diversity that characterises this sector. The numbers in the graph represent only self-reported data from the survey sample. These numbers do not show or refer to the relative infrastructural size/capacity of the different strategies and technologies. The list of demand- and supply-side management strategies used within the Danish district heating sector was created through a two-stage process: (I) Exploratory research enquiry by the lead-author resulted in the initial list. (II) This list was then refined, corrected, and supplemented through semi-structured and structured interviews with district heating professionals from various types of utilities (see also section 2.1). Survey respondents were also free to add to the list via an open-ended answer option, yet lesser-known demand- and supply-side management strategies may still be added.

novel district heating innovations. Drawing upon their knowledge of the end users/costumers, they asses that the costumers/end users will not mind if: these innovations work, do not jeopardise their security of heat supplies, or demand too much (indeed any) effort from the costumers.

4.4.2. Large buildings: non-commercial

Data show challenges in the non-commercial larger buildings (e.g.,larger public buildings, office buildings, multi-family housing/ apartment blocks). Here, grievances concern mostly stakeholders responsible for/somehow linked to the district heating

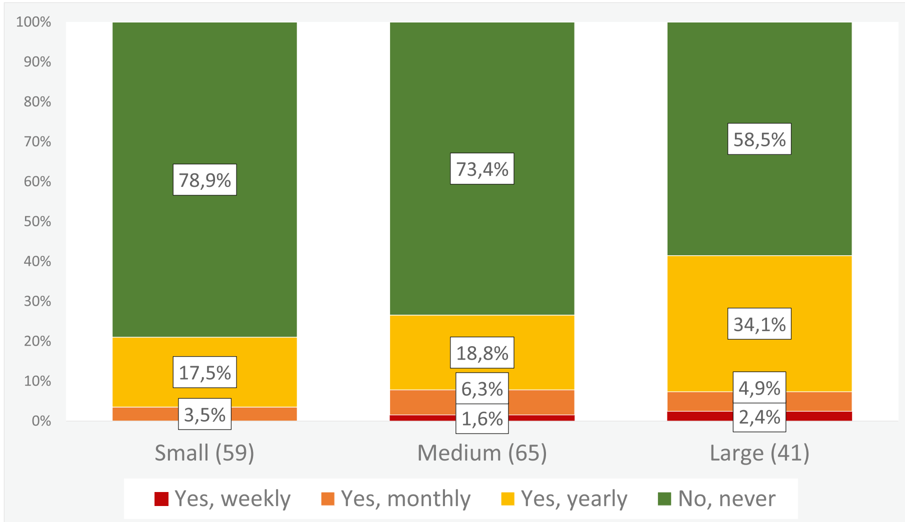

Fig. 10. Self-reported winter peak-load management challenges among utilities by utility size. Notes. Valid sample: N = 175, p*** Coded missing: "There are no peak loads in heat demand from our end users" (2 responses); "do not know" (8 responses). Many district heating suppliers overcome (potential) seasonal challenges in peak-load management by activating peak or reserve load boilers during those coldest days or weeks of the year.

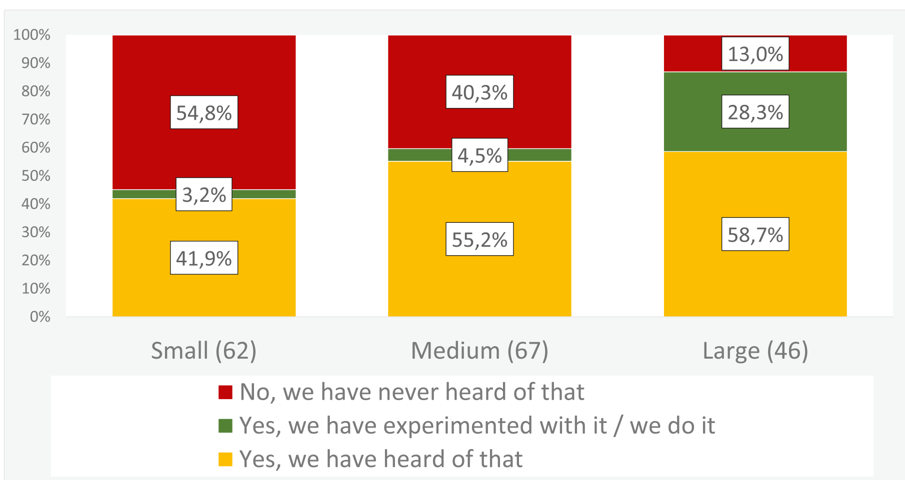

Fig. 11. Knowledge about the emergent niche method/technique of using building stock for short-term thermal energy storage among sector professionals by utility size. N = 175, p*** This tendency is approximately the same across all utility types.

infrastructures, for example, property janitors, plumbers, and other craftsmen. Challenges mentioned include balancing of the district heating hardware (or lack thereof), sometimes counterproductive incentive structures among stakeholders involved and lacking expertise/knowhow among them. Sector professionals see most potential of building energy flexibility demand-side management strategies in the larger building stock, and particularly in cities where growing populations challenge the capacity of existing heat supply infrastructures.

4.4.3. Large buildings: commercial and industrial

Commercial- and industrial end users represent the largest potential for short-term thermal energy storage using built environment according to the sector professionals. Such end users may have economic incentives to do so. Importantly, they have professional staff that can maintain the necessary technical infrastructures. Surprisingly, sector professionals report that even some commercial/industrial end users fail to maintain their district heating hardware and lack the motivation to reduce their heat consumption/heating bill.

4.5. Future energy transition challenges in the Danish district heating sector

Fig. 14 shows how respondents anticipate future changes in peak-load management challenges at their company as more intermittent renewable energy sources are integrated into the grid. 68% of the respondents anticipate no change. 8% anticipate that peak-load management will become easier. 14.3% anticipate it will become more difficult, and 9.7% do not know. 34.8% of respondents

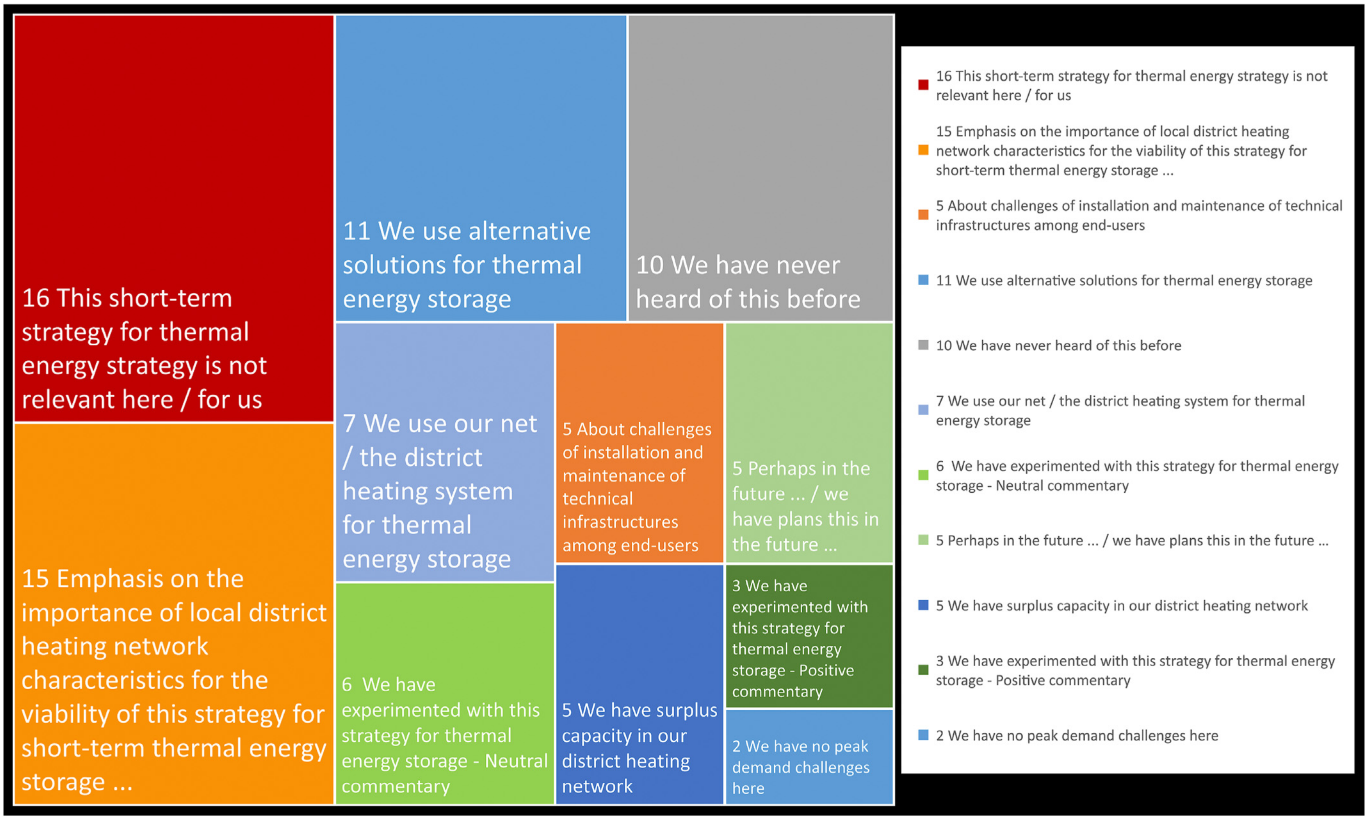

Fig. 12. Coding results from the open-ended response option: “Please elaborate on your experiences with and/or thoughts about the technique or method of using indoor built environment for short-term thermal energy storage”. Notes. 79 comments in total. Fig. 12 captures emergent themes and topics in the responses to this question - each described via the short phrase or sentence in Fig. 12 The numbers show how many times these were identified in the total responses. In this way, Fig. 12 is indicative of the relative importance ascribed to each identified theme/topic among the survey respondents. See Table 2 for illustrative examples.

Table 2
Illustrative examples of the open-ended responses that were coded in Figs. 12 and 13. The examples are translated by the lead author. The translation seeks to mimic the words/phrasing used by the informants themselves in the best possible way.

not interesting for us as we have a thermal storage tank and as our pumps have more than substantial capacity. It doesn’t look like our heat supply area will become bigger either.

requires agreements with a lot of costumers and that they should be located together in the same heat supply areas ...

Interesting. Particularly for a city like Aarhus whose population increases by approximately 5000 inhabitants a year. This challenges the infrastructure.

We have no appropriate building stock [in our supply area].

For sure, there is potential in regulating heat use in public buildings in the future.

we’ve used our district heating network for short-term thermal energy storage...

The effect is good. But incentive structures lack as all costumers are treated equally. Should be easier to create common investments/tariffs ensuring that the investments are optimal from a socio-economic point of view. Building regulations are also a barrier as effects in the district heating network are not attributed specific properties.

(...) [research we’ve been a part of suggests] it is hard to change the habits of the end-users: They are usually positive towards participating in projects (...), but it should be easy (...), preferably automatic, and not jeopardize their comfort ...

We offer regular service for customers high volumes of heat use, typically industry, (...) a subscription for the District Heating Service Scheme for private end users, (...) and Heat+ which is a district heating unit via subscription ...

As much as possible should be automatic. It’s just a problem when the automatics don’t work.

We go to costumers with [problematic return temperatures] and through try to improve [it] through dialogue. We assist in (...) balancing the system, but [the costumer should] solve the technical challenges. We plan to introduce a ‘motivational tariff’ before long.

We aren’t challenged by the heat consumption among our cooperative members. [Heat consumption] is what keeps the business going! Reductions of heat loss in new houses is the challenge. How much district heating is needed in a 0-energy house?

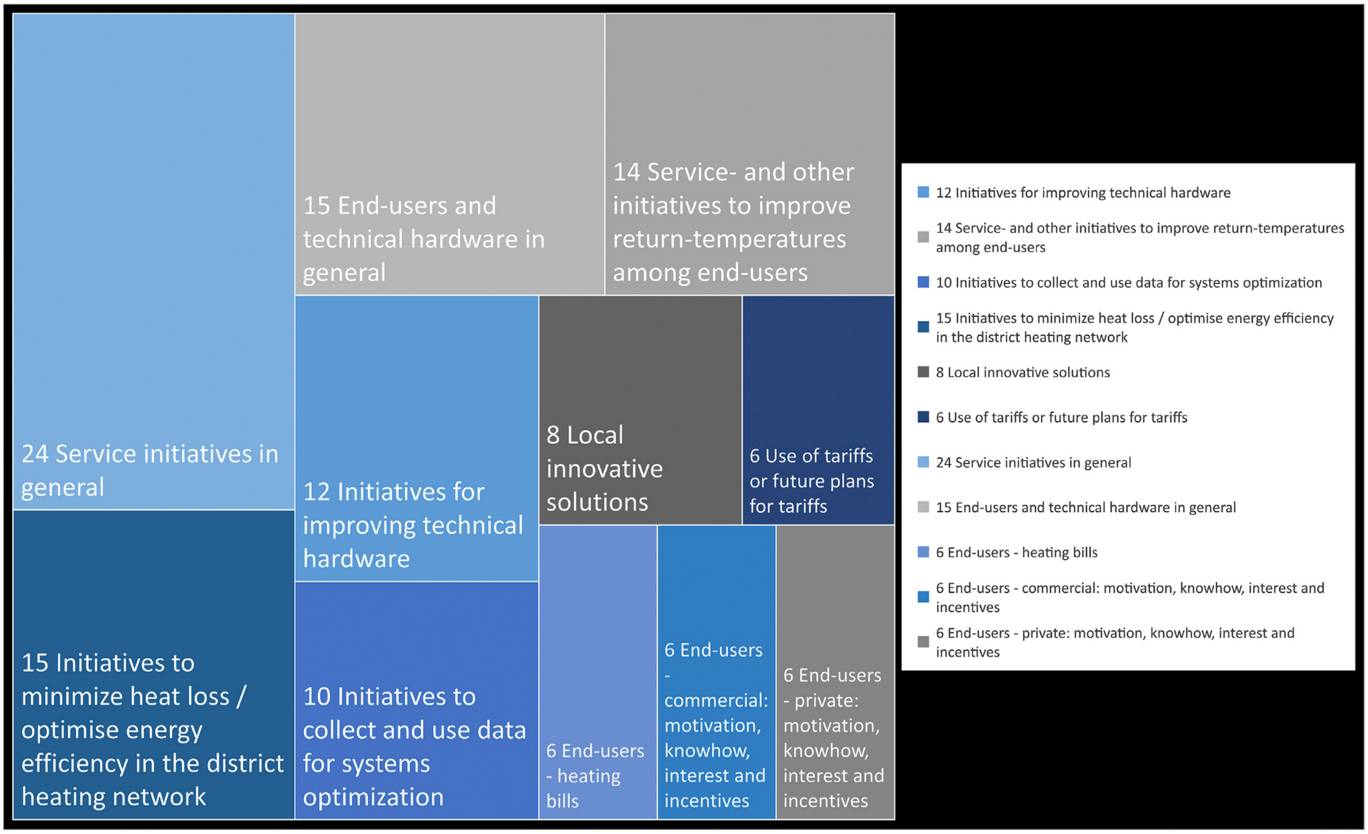

Fig. 13. Coding results from the open-ended response option: "Feel free to elaborate on how you have tackled challenges (if any) with heat consumption among your customers, and also on your general experiences in this regard". Notes: 44 comments in total. Fig. 13 captures emergent themes and topics in responses to this question. These are represented via short phrases or sentences. The numbers indicate how many times these themes and topics were identified in the responses. In this way, Fig. 13 provides an indication of the relative importance ascribed to these themes and topics among the sample population. See Table 2 for illustrative examples.

from the larger utilities anticipate more peak-load management challenges in the future compared to only 4.8% of the respondents from the smaller utilities.

These responses may be explained in various ways: Firstly, the Danish district heating sector is not heavily dependent upon fluctuating renewables such as wind and solar, but more upon other fuel-types, most notably biofuels and waste (see Fig. 6) [14]. This may change in the future as more large-scale heat pumps are integrated into the grid. Secondly, demographic changes inform heat use. Currently, the general trend is that populations decrease in rural heat supply areas but increase in more urban areas. Less heat consumption in old heat supply areas creates surplus network capacity, while growing populations in the larger cities challenge the capacity of those existing heat supply networks. Thirdly, the utilities that serve larger Danish cities are commonly centralised CHPs (see Figs. 2 and 7), and the role of CHPs is changing as the Danish energy system is - increasingly - electrified [14]. Due to this change, lower electricity prices challenge the business models of the CHPs. management systems (see Fig. 5).

Many of the centralised multi-utilities continuously expand and diversify their technology portfolio and fuel mix.

5. Discussion

This section discusses where and when thermal energy storage using the built environment may prove viable considering various socio-technical limitations, challenges, and potentials.

5.1. An alternative to domestic hot water tanks and thermal storage capacity

Heat accumulation in the indoor built environment may prove a cost-effective solution compared to domestic hot water storage tanks [35]. This building energy flexibility strategy does not require installation of expensive equipment, but relies entirely on smart home technologies, smart meters, building automation and building.

Notably, short-term thermal storage in a domestic hot water tank may be *combined* with thermal storage in the indoor environment. These solutions are not mutually exclusive. However, if hot water tanks are recently renewed, or if they are expected to remain functional for many years to come, there will be fewer economic- and/or sustainability incentives for that change.

Thus, activating the short-term thermal storage capacity of the indoor environment as an alternative to the use of reserve-load boilers will *reduce* fossil fuel consumption during seasonal peak loads. Moreover, additional thermal storage capacity allows for absorbing more of the intermittent energy from renewables into the electrical network, especially when the electricity spot price is low or negative.

5.2. Solves local congestion challenges in parts or 'pockets' of a district heating system

Building energy flexibility strategies can be applied in local areas

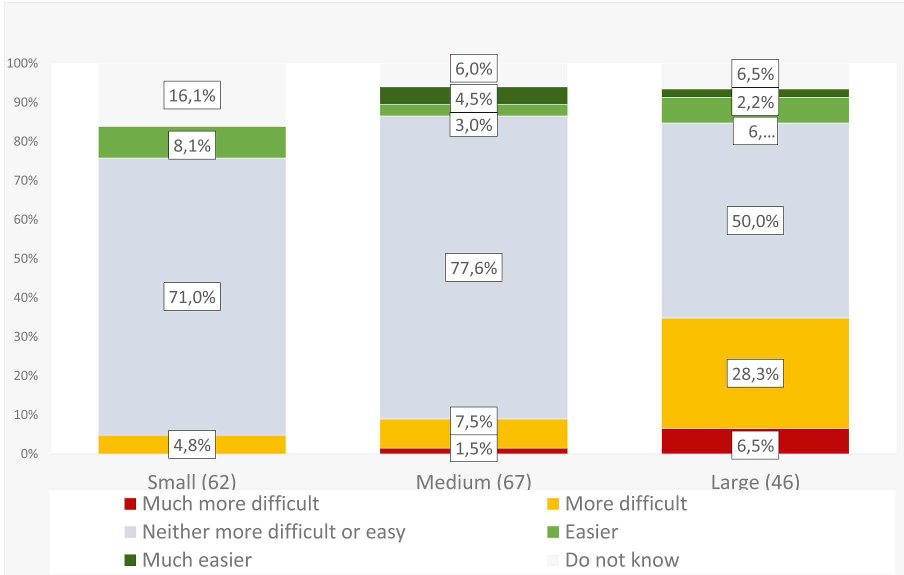

Fig. 14. Anticipated future changes in peak-load management challenges due to the increasing share of intermittent renewable energy sources in the energy grid. Notes: N = 175, p***.

(or pockets) of a district heating system to mitigate local network con-gestion problems [3].

Many district heating companies have peak load boilers or large thermal storage systems as backup capacity for seasonal peak loads. Conceptually located in the MLP regime (Fig. 1), these represent a 'typical' tried-and-tested solution to peak-load management. They also represent a relatively small and simple investment [3]. However, peak- or reserve-load boilers are typically powered by fossil fuels.

Local network congestion challenges in district heating networks that serve older heat supply areas could arise due to, for example, a) newly built suburbs in old heat supply areas, b) increasing housing density in general in old heat supply areas, c) emergent industrial production in older heat supply areas, or d) other newly built large-scale end users in old heat supply areas. In such cases, activating the thermal storage capacity of buildings may minimise the need for remedial action. Currently, well-known ways of solving local congestion challenges in existing district heating networks could be a) expanding the existing network capacity or b) adding temperature booster substations to existing heat supply infrastructures. But these solutions are costly. Multiple decentralised district heating systems that require local booster substations can be more expensive in total cost per kWh than centralised district heating systems. This is because more sites that require maintenance and supervision also leads to higher costs of operation and maintenance.

5.3. The role of incentive structures and business models

Lack of appropriate business models may challenge the future application of building energy flexibility strategies. In most cases, the control signal for use of short-term thermal energy storage is the energy spot price.[7] For short short-term thermal energy storage to be economically beneficial for the end user, however, the control signal from the grid should have significant variation over the course of a day. Currently, district heating networks *do not* provide a signal with substantially small temporal resolution and variability to create this economic benefit.

But do tariffs or variable pricing provide sufficient incentives for the end users to shift their energy use at all? Insights from behavioural economics show that end users and consumers rationalise and prioritise in multiple meaningful ways. Indeed, sometimes, economic benefits may be outweighed by alternative individual- or social prioritisations and valuation schemes that cannot be explained by the rationale of monetary value alone (see, e.g., Refs. [52,53]).

Control signals from a smart grid could respond to multiple variables. For example, the electricity spot price, the CO_2 intensity in the grid, the ratio of renewable energy sources in the energy mix, or similar (see section 3).

Some of these variables may appeal to other rationales or incentives than monetary value among (some groups of) end users/consumers. Indeed, perhaps some end users would quite happily tolerate/accept slight instability of heat supplies during the coldest days of the year if they know this facilitates more sustainable heat supplies. This might hold particularly true in this Danish case where - currently, and all things being equal, the energy bills constitute a relatively small part of the average household budget [55] (see Textbox 2).

5.4. Socio-technical flows, frictions and change inertia

Within the socio-technical Danish district heating sector, regime-level resistance to change may sometimes result in discrepancies between regime-level dynamics and landscape-level flows (see Textbox 1; Fig. 1). Here, conceptualised as a niche innovation, use of the indoor environment for short-term thermal storage proved an illustrative case exemplar of regime inertia and change resistance within the Danish socio-technical district heating landscapes.

What may be seen as excess or superfluous infrastructural capacity has become almost a norm or a paradigm throughout the

[7] In the Scandinavian electricity market (Nordpool), the electricity spot price.-decreases with increasing wind power generation. Due to the intermittent nature of wind power and the large ratios of wind power in the grid, the electricity price is sometimes negative due to the overproduction of electricity [26].

Textbox 2
Economic incentives and electricity use in Denmark

> *Recent research suggests that dynamic electricity pricing only has little to moderate mitigating effect on energy consumption among end users* [53–55]. *In* Ref. [55]*, Hansen and Trotta show that electricity tariffs in Denmark are mostly fixed costs - in the form of taxes and subscription* fees*. The authors hold that - at best - 30% of the electricity bill in Denmark is variable. Consequently, they question the effect of economic incentives related to electricity use. Their research suggests that members of Danish households are not very interested in or worried about their electricity bill, security of supplies or peak-demand challenges* [55]*.*

socio-technical district heating landscapes in Denmark [14]. As a result, peak-load management challenges are not a pressing issue for most Danish heat-supply companies (see Fig. 10). In the language of the MLP, this norm for excess infrastructural capacity may be due to the firmly embedded historical regime-level policy priority of 100% security of supplies (see section 3.3). Additionally, and moving to the landscape-level of the MLP, this may be also seen as due to the landscape-level ideological flows of the Danish welfare state [41,45,56] (see Textbox 1; Fig. 1).

Even where the emergent niche innovation of short-term thermal energy storage using the indoor environment *does* prove technically and economically viable in the future, 'sticky' regime-level routines, practices, professional norms, and service-ideals (see Fig. 1; Fig. 8) [17,23,24], among sector professionals may still result in socio-technical regime-level frictions and change inertia. In other words, institutionalised and firmly embedded norms for how things should be done - and how they should be done well - may prove a barrier to implementation of this niche innovation.

But perhaps some end users are open to changing norms for heat service provision? After all, the focus on sustainability and sustainability and climate change has increased in recent years, and particularly, and particularly so among younger generations.

In this light, some groups of end users might warmly welcome heat supply provision service standards that *prioritise* renewables integration, sustainability- and energy flexibility *more* than security of supplies and low prices. Such a paradigmatic shift of heat supply service provision standards would call for radical policy adaptation and change, however (see section 3.3). For the sector professionals, prioritizing energy flexibility and sustainability more than security of supplies would challenge their firmly embedded service-ideals and sense of professional pride (see Figs. 1 and 8) [6].

Niche innovations need protected innovative spaces to develop, mature, and, perhaps over time, to enter the socio-technical regime. In Denmark, the natural gas heat supply infrastructures face decommissioning [57]. District heating may take in some of these newly freed heat-supply territories, affording opportunities to test and develop niche innovations such as building energy flexibility demand-side management strategies further. As other countries engage in low-carbon energy transitions, the global trend is a rise in the district heating market share. Given these national and global developments, technical advances and the test of time are yet to reveal the future fate of building energy flexibility strategies.

6. Conclusion

This research described the demand-side management strategy of using the built environment for short term thermal energy storage. The research also explored knowhow and perceptions of this building energy flexibility strategy among district heating sector professionals, the actors at the centre of the low-carbon energy transition processes. Use of the built environment for short-term thermal energy storage was conceptualised as a niche innovation within the Danish socio-technical Danish district heating landscapes.

Research results suggest that use of the indoor environment for short-term thermal energy storage may (I) help solve local network congestion challenges in smaller parts of an existing network and (II) reduce the network capacity needed in newly built suburbs/new heat supply areas. Sector professionals assess (III) this niche innovation as most feasible and practicable in larger-scale commercial buildings and industries. They also emphasize the potential challenges involved, notably those of hardware balancing, service, and maintenance, and the sometimes counterproductive incentive structures among some stakeholders involved. These are just some of the many socio-technical factors and boundary conditions that inform how practicable and viable this niche innovation may be in specific socio-technical contexts.

Noting the general growing environmental awareness and concern, it is suggested that alternative business models for this demand-side management strategy may prove beneficial. Among some end users or costumers, both economic benefit and appealing to environmental values and priorities may encourage more sustainable heat use behaviour.

In the future, use of the built environment for short-term thermal energy storage may be added to the list of well-known regime level demand-side management strategies within the Danish district heating sector. It could also become integral to future smart energy systems that serve other societies with high heat demands or indoor space conditioning throughout the world. Successful implementation of such 'smart' energy systems in diverse technical, political, legislative, social, and cultural contexts necessitates understanding the complex and interrelated socio-technical dynamics and phenomena involved. Multidisciplinary research approaches, such as the one taken here, facilitates these necessary insights.

Author statement

Katinka Johansen: Conceptualisation; research design, Methodology; qualitative and quantitative data collection; data Formal analysis; data Visualisation; Writing – original draft; writing - reviews; rewriting and editing; proofs and editing; Hicham Johra: Conceptualisation; technical support; feedback and technical ideas; writing – technical sections; technical analysis; illustrations; Writing – original draft; writing – reviews.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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