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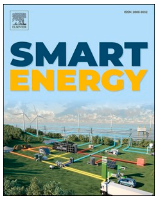

Strengths, weaknesses, opportunities and threats of demand response in district heating and cooling systems. From passive customers to valuable assets

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ABSTRACT

Buildings can deliver short-term thermal energy storage by utilising the thermal capacity of the building construction and/or by activating the water tanks included in the heating/cooling installation. The flexibility potential of demand management using decentralized thermal energy storage has been quantified in many theoretical modelling studies, and it is considered an essential technology for an affordable energy transition. We have investigated the drivers and barriers to the adoption of demand management in buildings in district heating and cooling systems via a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis and presented 17 elements that shape the current and future application of this concept. The results indicate that the application of the DR concept has left the theoretical studies and moved towards real-life applications. Yet, there is a lack of feasible business models and regulatory frameworks supporting the large-scale application of the concept. Utilities and their customers do not fully understand the benefits of the DR concept; therefore they are reluctant to adopt it outside of the research projects where the test environment is fully controlled and with limited impact and timeline. Therefore, the regulatory framework must be adjusted to allow DHC operators to develop new business models and DR tariffs that will incentivise the customers to deliver flexibility to the system without compromising their comfort and everyday practices and increasing energy poverty.

1. Introduction

Space and water heating accounts for 45% of the CO_2 emissions of the building sector, representing 12% of global energy and process-related CO_2 emissions [1]. Space cooling currently accounts only for 15% of the energy used for heating [1]. Together they account for the largest share of the building sector's carbon emissions. With the expectations of building floor area to double by 2070 and cooling demand to grow 3% per year for the next three decades, these two energy end-uses are identified as the main target areas for interventions for a fast and effective transition to zero-carbon energy systems [2].

District heating and district cooling (DHC) systems are considered the most sustainable way to meet the heating and/or cooling demand in densely populated areas where individual heat pump installations are impractical [2,3]. In the IEA strategy report "Net Zero by 2050" [4], DH systems are estimated to provide more than 20% of the final energy demand for space heating globally. This share could be up to 50% in the European Union in 2050 [5]. In 2021, DH systems delivered nearly 8% of the global final heating need in buildings and industry [6] and in

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Nomenclature:

DHC – district heating and cooling
SWOT - strengths, weaknesses, opportunities and threats
DC – district cooling
DH – district heating
DHC – district heating and cooling
DHW – domestic hot water
DR - demand response
GDPR - General Data Protection Regulation
RES – renewable energy sources
TES – thermal energy storage

2018, the DHC systems provided 6% of the global heating and cooling demand [7].

The planned decarbonisation of the energy system requires a revolution in all energy sectors and a transition towards smart energy systems, markets and social reconfiguration [8–11]. For decades, the reduction of the supply temperature was the main target indicator for qualifying improvements and new developments in the DH systems [12–14]. A high share of renewable energy sources (RES), such as geothermal, solar and wind energy, integrated directly at the DH production units or indirectly from the electricity grid by sector coupling via large-scale heat pumps (HPs) may lead to fluctuating characteristics of the production [15]. In short, the DHC system provides a buffer for intermittency in the energy system. Therefore, this variable heat production imposes additional challenges in the operation and planning of the DH systems, and thus the demand for flexible end-use of heat increases. As an example, the future decarbonized low-temperature DHC systems have a cost reduction gradient [euro/(MWh °C)] that is 6–7 times higher than that of current DHC systems using traditional heat sources and high-temperature technologies, such as CPHs and boilers [16]. Thus, the DH systems are undergoing major upheaval to meet the decarbonisation objectives and to build control over the intermittent heat supply sources to ensure meeting the heat demand at all times. Thermal energy storage (TES) is one of the promising solutions to enhance the controllability of the DHC systems during short- and long-term operation challenges [17,18]. According to [19], the TES in DHC systems can be classified according to a) physical phenomenon: sensible, latent and chemical storages; b) storage duration: short-term and long-term storages; c) location: distributed/decentralized and localised/centralized storages; and d) transportability: fixed and mobilised storages. The TES can be located at the primary side either integrated in the production unit or located at the strategic points in the distribution network and controlled centrally by the DH operators. The water circulating in the DH network pipelines has also been explored as a source of thermal storage [20,21]. These TES solutions involve actions and investments on the primary side. The other TES solution is located on the building level and allows for a heat flux to the building higher than the current heat demand. The stored heat can be used at a later point [22]. This concept is well known as energy flexible building or demand response and has been investigated by international experts for more than a decade, with a focus on the initial concept definition formulation and simulation studies [23], general discussion on the application of the concept and current challenges [24,25], or an extensive review of the evaluation matrixes [26].

However, these studies are limited to the academic perspective, the definitions are very generic, and the evaluation matrixes have diverse applications across different scopes with the majority of them being applied in the electricity sector and not accounting for the hydronics in the thermal DHC systems.

The smart energy systems call for the active participation of all energy sectors in the green transition [27,28]. The whole energy chain (i.e. production, distribution and demand) must interact and contribute if the Paris Agreement conditions are to be met [29]. In the recent energy crisis, resilience and the demand response in the DHC systems have gained international interest [30]. However, despite its potential, the practical and large-scale implementation of DR, also called end-use flexibility, in the DHC systems is not happening and DHC utilities are reluctant to apply it in everyday operation. Integrating flexibility solutions with existing DHC systems and building installation configurations while ensuring customer satisfaction, economic viability and compliance with regulatory obligations is a complex task that requires cooperation among different stakeholders that have different focus and objectives sometimes contradictory to each other. All this limits the implementation of DR concept at large-scale.

1.1. *Contribution*

This paper contributes to the topic of demand management in DHC systems. The scope of the paper is the demand response (DR), which focuses on encouraging customers to reduce or shift heating and/or cooling demand in response to real-time activation signals or individual contract agreements. Therefore it addresses short-term energy fluctuations. It aims to narrow the gap between the building and district heating/cooling sectors, which currently operate in silos, by providing a comprehensive overview of the challenges facing these sectors when utilising energy flexibility delivered by buildings in the daily operation of the DHC systems. By application of the Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis it systematically investigates the internal and external aspects that shape the current and future state and developments for the successful large-scale adaptation of the demand management concept in DHC systems. To the authors' knowledge, no previous study investigated this topic holistically from technical, economic, social, digital and regulatory perspectives. The weaknesses and opportunities were broadly discussed in previous studies, however, existing strengths and threats were not highlighted. Therefore, the full overview of DR potential in DHC systems is still missing. Moreover, this paper provides an overview of DR case studies from various locations including different generations of DHC networks, DR characteristics (i.e. various building typologies and customer types). This work does not provide an explicit solution on how DR should be implemented in DHC systems, yet a clear and objective presentation of the concept using the SWOT analysis as a scientific approach.

2. Methodology

A SWOT analysis is a commonly used technique in various types of analysis, starting from strategic planning and management of businesses to identifying key elements, such as strengths (S), weaknesses (W), opportunities (O) and threats (T) related to a specific scientific domain [31]. This technique is primarily used in decision-making processes as a tool to identify the factors, either internal or external, that may lead to the provision of added value. The SWOT analysis goes beyond identifying the technical challenges and opportunities as it was done in recent publications on this subject [31]. It also provides more than a classical literature review by analysing the existing pre-knowledge and grouping the key elements from the topic into the strengths, weaknesses, opportunities and threats or internal and external factors, which have either positive or negative impacts. This analysis and a subsequent evaluation of the results by the involved stakeholders and decision-makers may lead to concrete and targeted actions, either to overcome weaknesses by applying strengths or by using strengths to mitigate threats.

The demand response is a multidimensional concept and involves an interdisciplinary approach. It requires that building installations are fully integrated into the operation of the DHC systems, digital control solutions are in place, end-users are engaged, and finally, the regulatory framework supports the new collaboration/business models mutually beneficial for customers, utilities and involved stakeholders. Therefore, this SWOT analysis identifies the key elements and groups them into the technical, social, digitalisation, economic and regulatory aspects resulting in a compact and more focused overview of the application of DR specifically in DHC systems.

In the case of this investigation, the internal factors represent the impact of DR-relevant abilities and concerns on DR applications. External factors influence the impact of the DR-relevant environments and not of DR strategies themselves. The factors rated positively provide current and future possibilities for the successful expansion of DR strategies in DHC systems, whereas the factors rated negatively are detrimental to realizing DR potential and full-scale adaptation of this concept by DHC operators.

The information related to the application of DR in DHC has been gathered through an extended literature study and discussions with experts from research institutes and the building, heating and cooling sectors conducted during IEA EBC Annex 84 “Demand Management of Buildings in Thermal Networks” meetings and workshops. The information was analysed and boiled down to the SWOT analysis presented in the following section.

3. Results

The SWOT analysis identified 17 key elements of the DR in DHC systems: three strengths, eight weaknesses, seven opportunities, and three threats, see Fig. 1. 10 elements relate to a single topic and seven elements are evaluated to belong to more than one topic, which indicates that these elements are more complex and cannot be addressed solely in one domain. The distribution of elements between topics is 38% technical-, 18% social, 15% economical, 12% regulatory, and 17% digitalisation-related. Table 1 supplements Fig. 1 and briefly describes each element. The full elaboration of each element is provided in the

Table 1
Description of SWOT analysis elements.

Group	No	Description	Cat
Technical	1	Well-grounded state-of-the-art knowledge	S1
Technical	2	Great variety of DHC system types	W1
Technical	3	Great variety of building systems, lack of interfaced interaction, control possibility	W2
Technical	4	Lack of DR good examples; low penetration of best practices	W3
Technical	5	Accelerating the shift from high to low supply temperatures DH systems	O2
Digital	6	Lack of data sharing and DR follow-up check	W5
Digital	7	Accelerating digitalisation of the building and the DHC sectors	O1
Social	8	Lack of collaboration models to support DR implementation in real-life	W4
Social	9	Reluctancy to apply academic research results in real-life application.	T3
Regulatory	10	Intermittent and inconsequent application of policies to support DR, RES, DHC	T2
Technical Digital	11	Real-life examples of DR in the DHC systems supported by digitalisation	S2
Technical Digital	12	Lack of consistent evaluation matrix for DR actions/ strategies	W7
Technical Economic	13	Fault detection and diagnostics at the demand side in DHC systems	O3
Social Economic	14	New customer-tailored collaboration models and energy pricing mechanisms	O4
Social Economic	15	Customers’ increased awareness of energy consumption, flexibility potential and energy cost savings	O5
Regulatory Economic	16	Lack of regulatory framework and DR tariffs	W6
Regulatory Economic	17	Low penetration rate and period between planning and commissioning of DHC systems	T1

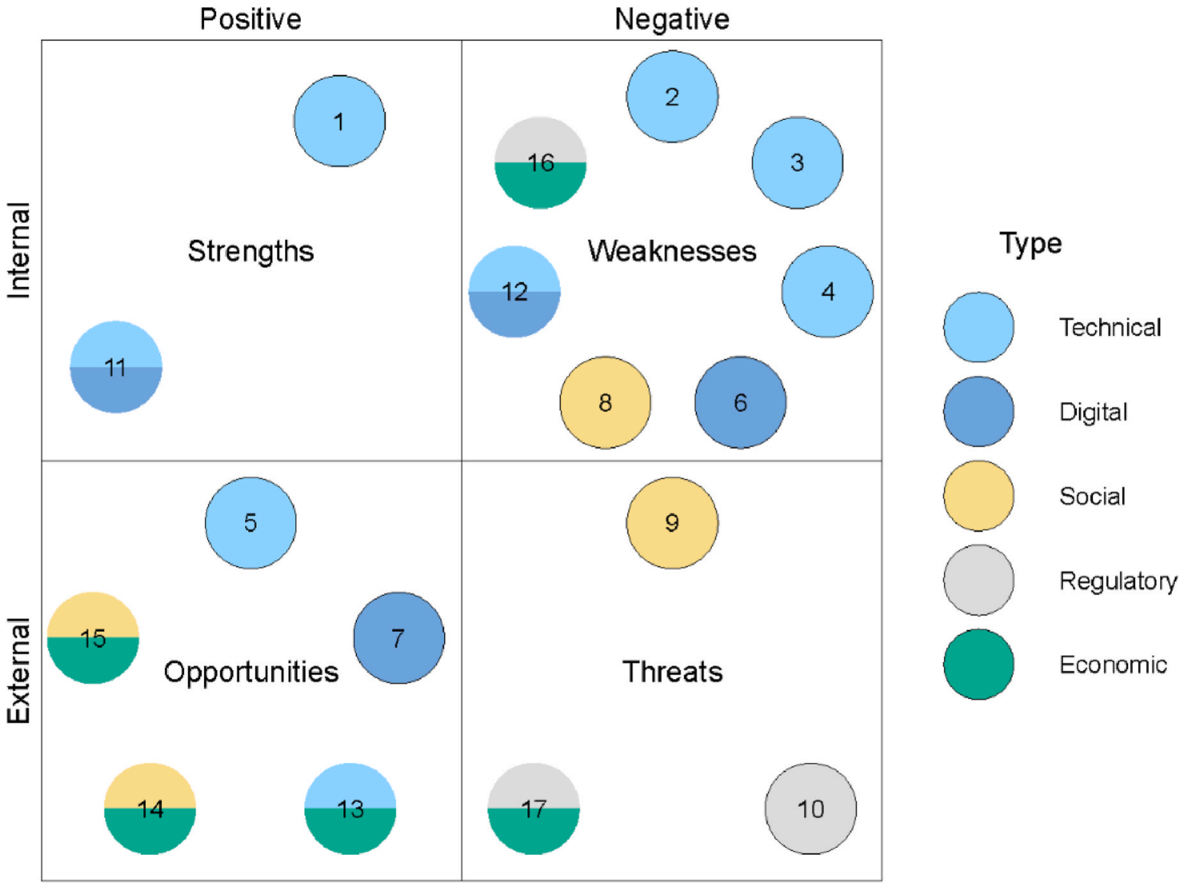

Fig. 1. Visualisation of the SWOT analysis.

following sections strengths, weaknesses, opportunities and threats.

3.1. Strengths

3.1.1. Well-grounded state-of-the-art knowledge (S1)

The concept of energy flexible buildings, which deliver short-term load modulation and storage to the energy system has been studied since 1988 [22]. As indicated by the extensive reviews [30,32] and during workshops and surveys with DH professionals [33,34], the theoretical knowledge about energy flexibility accessible by the application of demand response strategies in DHC systems is present, mainly in the form of state-of-the-art academic research and primarily modelling work [35–38]. Multiple benefits have been identified, including peak shaving in the building and thereby in the network by up to 30% [37], buildings' thermal inertial delivers significantly more flexibility than the network pipes and depending on network configuration the difference can be up to factor 570 [20], and increases the share of wind energy in the Chinese DH system with CHP unit by 35–47% [21] while running cost of DHC system decreases by 9–11% [39]. The knowledge of the state-of-the-art control strategies for flexibility utilisation in DHC systems is described in [40,41], where the authors introduced "advanced controls" of three categories.

1. "Central control" with one intelligent central point that receives all information and makes all decisions based on operational optimization criteria
2. "Distributed control" based on a multiagent system (MAS) where several agents control the local actions based on information received from external sources
3. "Hybrid control," which combines the features of central and distributed control

In theory, the DR application in DHC systems has great potential and can mutually benefit the building and heating/cooling sectors. Building stock has a high thermal storage potential, which when activated and coordinated well - can solve partly the challenges of the current and future DHC systems.

3.1.2. Real-life examples of DR in the DHC systems supported by digitalisation. (S2)

In most cases, the optimization of DHC systems focuses on the system (production and distribution) side and does not integrate the building installations [30]. Solving the challenge of DR is mainly technological, yet the success of new solutions is also hinged on building users and the associated regulatory framework. Adapting the new concepts requires mutual engagement, acceptance and cooperation of end-users, engineers, facility managers and utility operators [33]. The process is known to be very time-consuming, and evidences from the electricity sector show that the real-life DR demonstration can deliver the needed findings [42]. So far only a limited number of real-file applications of DR in DHC systems are available in literature.

The oldest DR field test known to the authors is from 1982 [43], where in eight residential and office buildings located in Stockholm, Sweden, the delivered heat was remotely reduced to increase the security of supply for the customers located farthest away from a heating plant. The magnitude and duration of the DR events were estimated from assumed time constants of the buildings and the maximum drop in indoor temperature of 3 °C. The longest DR event was for 24 h. Kärkkäinen et al. [44] conducted a field test in office and residential buildings with water-based heating systems in Jyväskylä, Finland and one office building with an air-based heating system in Mannheim, Germany in the winter of 2002. The DR events were centrally controlled to identify maximum peak load reduction without compromising indoor comfort. The domestic hot water was out of the scope. The tests showed a peak cut of 25–30 % and heat load reduction of 20–25 % during a 2–3 h DR event in the Finish buildings. In the German case, the building's daily peak was reduced by 4.1%. The difference in the heating systems showed that the time constant of the air-heated building is shorter than of the buildings with radiator heating and thus DR control strategies must account for buildings' HVAC characteristics. Similar conclusions were reached by Kensby et al. [45] in the field test in five multi-story residential buildings with radiator heating systems in Gothenburg, Sweden in the winter of 2010/11.

Sweetnam et al. [46] described a field test in 28 homes in England during the winter 2015/16. In this DR field trial, no DHC utility was involved as the aim was to demonstrate an active demand-shaping technology and its ability to reduce the building's peak demand by 15% by utilising building inertia to avoid simultaneous space and hot water heating. The peak reduction led to a demand increase of 3%. Additionally, the survey with the occupants revealed that the majority would be willing to participate in a commercial DR scheme for a small financial reward. The same approach to the DR concept and control technologies were applied in the 72 single-family houses located in Middelfrath, Denmark during the winter of 2013/14 and 2014/15 [47,48]. In the Danish demonstration, the energy-saving reach by activation of DR events, primarily the night-set-back strategy, was on average 7% with big variations among the houses. The customers used the DR control strategies in the following winter season and not only during the heating season when the technology was installed. Thereby, the demonstration showed that end-users might have a long-term interest in and acceptance of DR strategies.

Mishra et al. [49] conducted a field test in a 2014 refurbished campus building in Aalto, Finland, where 11 DR control strategies were demonstrated during the winter 2017/18. The DR events were centrally controlled at the BMS and executed by either a decrease or increase in the temperature of inlet water, which was correlated with the price signal (i.e. high price leads to temperature decrease and opposite for low price). The demonstration showed that DR events did not greatly alter occupant satisfaction levels, yet during DR events few rooms came up to feature in the list of non-compliant rooms. Therefore, the authors suggested that future DR strategies should be more decentralized and executed at room level.

Ala-Kotila et al. [50] described a DR field test in 27 residential blocks divided into eight case buildings occupied by students in Finland, in February–March 2018. The objective of the DR strategy was to reduce the power peaks, without negatively affecting the tap water temperature and the indoor temperature. The demonstrated DR events illustrated the peak reduction in every case building by 14%–15% on average, with a maximum decrease of 30%, and a decrease in total energy demand of eight buildings by 11%. The DR events led to the total cost savings of 26 000 €. These results were achieved for buildings already using heat optimization services therefore as highlighted the expected output would be ever greater for traditional buildings.

Christensen et al. [51] described a DR field test in a low-energy multi-storey residential building located in Copenhagen, Denmark in the winter 2018/19. The building has an underfloor heating system and mechanical ventilation and is constructed as a heavy thermal mass building. The objective of the DR strategy was the load shifting from the morning peak of 6 h to off-peak hours by application of the price signal to the local controller at each apartment. The local DH utility defined this DR window. The demonstration showed that heat load during the peak period was reduced by 85% during the DR events when comparing the energy use with similar apartments without DR events. In this demonstration, the residents objected to the DR events in bathrooms and toilets. This indicates that end-users have valuable inputs for the design of DR strategies.

Hagejärd et al. [52] described a DR field test in eight multi-residential buildings located in Malmõ, Sweden during November–December 2019. The main objective of the demonstration was to investigate occupants' acceptance and satisfaction of thermal conditions during DR events, which included five DR control schemes of heat supply reduction by 25, 50 or 100% for periods of 0.5–3 h and one DR event of heat supply increase by 25% for 1 h. All control strategies aimed to reduce peak generation at DH production units. The results indicated that a successful DR strategy should account for a) the condition of the building insulation and ventilation, b) the perception of indoor temperature by the inhabitants at different times of day and heating-related activities, c) the need for individual control and d) communication of the upcoming load shifts to the end-users.

Christensen et al. [53] described a DR field test in three low-energy one-story houses located in Aalborg, Denmark in February 2021. The objective of the DR strategy was to shift the space heating demand during the two peak hours in the morning using the local control of the radiator valves in the kitchen, living room and hallway. The quantitative measurement data were supported by the thermal perception votes of the residents. The main finding was that without a proper explanation of control strategies and potential benefits of DR events, the residents do not accept the DR control strategies and the non-standard behaviour of the heating system (i.e. pre-heating during night-time in houses when residents use the night-set back). In the house where residents vent their spaces in the mornings or use a night-set back heating strategy, the benefits from the preheating DR strategy are lost and occupants' dissatisfaction increases due to lower indoor temperatures.

Van Oevelen et al. [54] described a new control strategy, called "STORM controller", in which the thermal capacity of buildings is used to satisfy system objectives. Three DR control strategies were tested a) reduction of heat load peaks, b) shifting the load according to electricity prices, and c) increase of thermal energy exchange in grids providing heat and cold. The first and second STORM control capabilities were demonstrated in the Rottne DH network, Sweden in winter 2018/19, where 3.1% reduction of peak heat production was achieved and 96% of heat load was moved by charging the buildings. In the 4GDH network in Heerlen, the Netherlands, STORM controller was able to increase the system capacity by 37–49% and reduce peak by 7.5–34%. The same controller was further tested by Van Oevelen et al. [55] in Brescia, Italy in the winter 2021/22. A case study is a branch of the existing DH system (supply temperature up to 130 °C) delivering heat for space heating and production of domestic hot water for residential area including one multi-family house and 34 single-family houses. The main objective of the DR control strategy was to decrease the daily peak loads at the mixing substation point by control of the supply water temperature and utilisation of the building thermal inertia. In this demonstration, the effect of DR were monitored at the mixing substation level, where depending on the outdoor temperature the peak load energy supply was reduced by 30–40%.

Guelpa et al. [56] described a DR field test in a branch of an existing DH network in Turino, Italy for three days with an outdoor temperature of 10 °C. In the experiment, only 32 out of 104 substations/buildings had shiftable loads, which were remotely rescheduled with a maximum DR event window of 20 min to limit the impact on the indoor temperature. In all three days, the peak was reduced by more than 5% despite the significant constraints.

The described demonstrations show that DR application can be initiated by different stakeholders (i.e. DH utilities, technology providers or developers, researchers). An evaluation of the demonstrations can be done using different criteria.

a) Technical, as the subset of theoretical potential, including only controllable devices
b) Economical, as the valuable potential resulting from the application of DR on the technical potential
c) Practical, as the useable potential composed of the interventions accepted by stakeholders as well as the restrictions involved in the contacts between stakeholders and privacy considerations.

During the IEA EBC Annex 84 project, about 20 demonstrators were collected. From this group, seven case studies, indicated in Table A1, will be analysed in detail.

3.2. Weaknesses

3.2.1. Great variety of DHC system types. (W1)

The development of DHC systems is very diverse across the globe [2]. The period of establishing the DHC systems varies from one country to another. The older thermal networks were used only for heating or cooling purposes, while newer types of collective thermal networks provide both heating and cooling. The age of DHC networks often determines the heat/cold carriers and the operation temperatures. Table 2 provides the characteristics of different generations of DHC systems proposed in Refs. [2,57–59]. Moreover, each DHC system has a unique local signature through the components' geographical spread and technical characteristics, the mix of buildings with various heating/cooling installations and end-consumers. The recent reports [60,61] on DHC systems digitalisation show that the technologies are evolving fast towards new management technologies with opportunities for reaching higher performance and flexibility.

The DC systems are not yet as well established as DH systems. However, they can play a major role in mitigating the environmental impacts in a cost-efficient manner (lower environmental impacts than individual solutions, higher energy efficiency, enhanced flexibility for the electricity grid, cross-sector synergies, and reduced heat island effect [58,62]). They primarily deliver space cooling to commercial buildings in a few big agglomerations in Europe, the Middle East, Asia and Canada [63].

Parallel to this development, there is a growing interest followed by real-case evolution of 5GDHC systems aiming to provide both heating and cooling demand, depending on the season, in the local neighbourhoods [64]. The technological revolution in the DC systems is not at the same stage as in DH systems [58], yet with the growing cooling demand in the building sector, the DC systems gain international interest and their development proceeds rapidly.

Table 2
Features of the DH and DC system generations developed using information from [2,16,57,58,64,65].

	Period	heat/cold carrier	Supply Temp. (°C)	Extra features
DH system				
First generation (1GDH)	>1880	steam	>200	concrete ducts
Second generation (2GDH)	>1930	pressurised water	>100	in-suit elements
Third generation (3GDH)	>1980	pressurised water	<100	prefabricated elements
Fourth generation (4GDH)	>2008	pressurised water	<70	2-way DH
Fifth generation or Cold District Heating (5GDH&C or CDH)	>2010	water	<25	Combined heating and cooling; individual heat pumps or boosters
DC system				
First generation (1GDC)	>1890	refrigerant or brine	−4 to +7	centralized chillers
Second generation (2GDC)	>1960	cold water	2 to 8	large mechanical chillers
Third generation (3GDC)	>1990	cold water	0.5 to 8	diversified cooling technologies and cooling sources; storage; coupling to DH
Fourth generation (4GDC)	>2020	multi-source	4 to 24	Centralized and decentralized solutions; integration with Electricity, DH, and gas systems

Table A2 provides the DHC systems characteristics collected among the IEA EBC Annex 84 participating countries.

Additionally, the DH stakeholders/components map introduces additional complexity to the application of the DR concept, as illustrated in Fig. 2. In some cases, such as the Danish DHC systems, one public entity owns both the production units and distribution network. In contrast, in countries like Sweden, Germany, and Poland, different public and/or private entities own the production units and distribution network. Due to these national and/or local variations, there is no uniform strategy for implementing the DR concept, necessitating customized solutions.

3.2.2. Great variety of building systems, lack of interfaced interaction, control possibility. (W2)

Buildings are purposefully designed and operated to create comfortable living and working environments for human activities. However, there are inherent limitations to achieving energy flexibility due to factors such as building physics, usage patterns, indoor conditions, and the human experience. Across Europe, multiple generations of DHC systems operate concurrently, each imposing different requirements on heating/cooling installations within buildings.

The diversity in DHC systems generations results in varying demands placed on building installations. In some instances, refurbishing these installations becomes necessary, often undertaken in conjunction with the overall renovation or retrofitting of the building—a process known for its extended duration, high costs, and complexity, that is still estimated to progress at an average rate of only 2% per year. Conversely, certain local customers may either be unable or unwilling to invest in the refurbishment of heating/cooling installations. This poses a challenge for DHC operators, as they must adeptly navigate diverse customer needs and demands, making it challenging to formulate an effective DR strategy for the entire DHC system. Similar to the diverse compositions of the primary side, the demand side of the DHC systems is equally diverse. The variables found on the demand side include the building topologies (i.e. residential and non-residential, new-built and renovated), the technological status of the heating/cooling and domestic hot water (DHW) installations in the building (i.e. type, age, used components, IoT readiness, smartness level), the DHC substation’s characteristics, the monitoring sensors and control units. The minimum equipment is usually.

1. A heat meter for recording the thermal energy necessary for cost accounting and balancing of the supplied heat and cold
2. A temperature sensor on the secondary side of the house station for recording the controlled variable
3. A control valve on the primary side of the house station changes either the primary-side volume flow (throttle valve) or the primary-side flow temperature in the station (mixing)
4. The ward controller coordinates all control circuits on the primary and secondary sides of the house station (time programmes and setpoint temperatures are stored there).

In addition to the building envelope properties and user behaviour, the suitability of a building to carry out DR is strongly influenced by

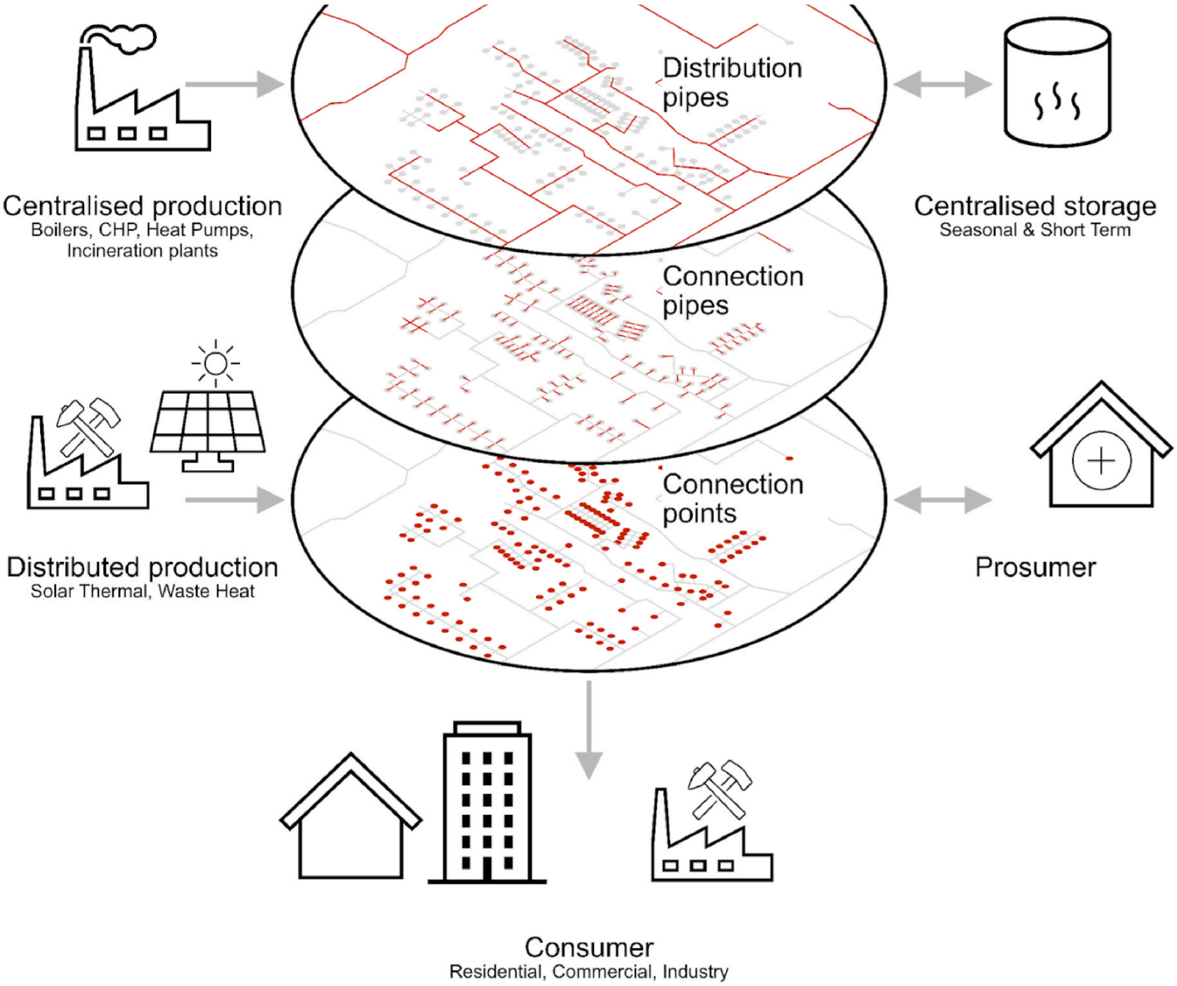

Fig. 2. Structure of the DHC system.

which technologies are present in a building to supply, store and distribute heat, cold and domestic hot water. Locally produced heat and electricity at the building level (e.g. roof-mounted solar thermal installations) can be utilised to alter the thermal demand profile needed to be supplied from the thermal grid. Furthermore, active storage devices such as hot water tanks or PCM storage can further enhance a building's ability to store heat over many hours, thus mitigating peak load periods. For these more complex system configurations, more attention has to be paid to the installation and control of appropriate monitoring and control devices within the building as well as their ability to communicate with signals coming from the thermal grid, see Fig. 3.

Furthermore, the impact of DR is contingent on network dynamics influenced by the topology and components of the network, as well as their interdependencies. To implement effective indirect and/or direct DR actions, it is imperative to choose an appropriate control strategy that involves continuous data uploading for real-time decision-making, swift and frequent computation of results, and the ability to manage different periods. The preliminary review also indicates that this interaction requires a new type of control software that goes beyond the classic feedback control mechanism variables proportional (P), integral

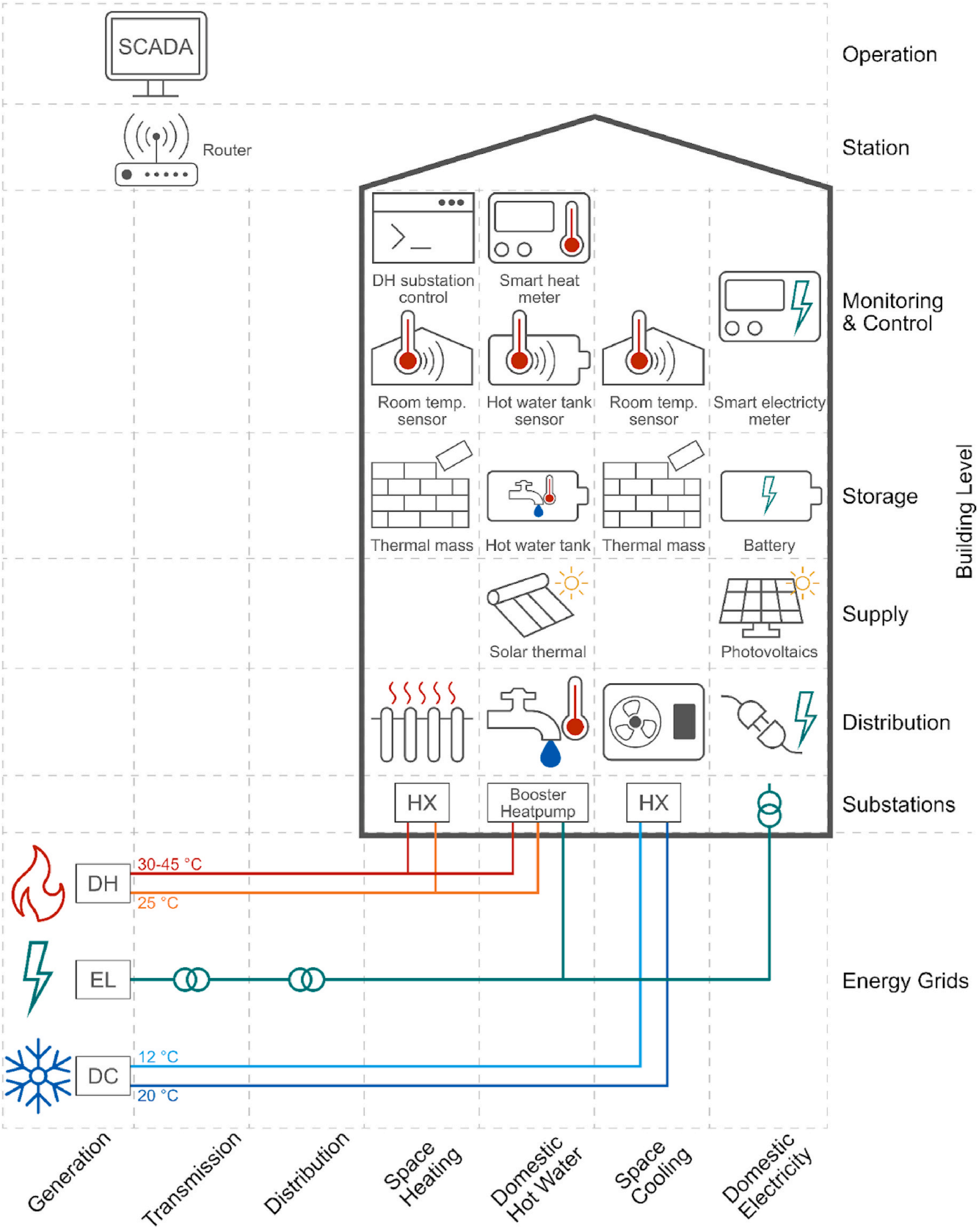

Fig. 3. Example of hardware present in a building connected to an ultra-low temperature DHC system to enable DR.

(I), and derivative (D) – or short PID. PID is excellent for set point tracking based on measurements "now" and in "the past". However, it does not consider "the future", which is key to the smart operation of the system. Studies [52,99] have indicated that software that makes use of economic model predictive control (*E*-MPC) as a higher-level controller that determines the set point for a lower-level controller realizing the set point – typically a PI controller – can be used to exploit the inherent thermal mass of building constructions and their interior for DR purposes.

Individual buildings being smart about their energy use (e.g. using *E*-MPC that optimizes the energy cost over a certain prediction horizon) may end up as a sub-optimization for the urban-scale DHC networks. Previous studies from the electricity grid have indicated that if large groups of buildings optimize on the same cost signal, it could lead to a peak shift rather than a peak shaving [100]. This indicates that cost signals must be tailored for the desired DR. In theory, the DR application in DHC systems has great potential and can mutually benefit the building and heating sectors. Building stock has high thermal storage potential, which activated and coordinated well can easier the challenges of the current and future DHC systems.

These demands underscore the necessity for DR to address varied requirements. However, practical implementation often faces challenges without a comprehensive understanding of the demand side characteristics that influence the DR potential. The DR demonstrations discussed in the previous section highlight that the current application of DR is confined to a scale ranging from a single building to approximately 30 buildings within a specific District Heating branch. This limitation is intentional to safeguard the overall network performance.

3.2.3. Lack of DR good examples; low penetration of best practices. (W3)

The practical implementation of theoretical knowledge on DR is still not common. The application and the long-term monitoring and evaluation of such DR strategies are still missing (academic research state-of-the-art is far beyond the practical implementation 'state-of-the-practice' of DR strategies). The DR real-life applications take a few day experiments [56] up to a few weeks during a single heating season [55] and thus present only a snapshot of the whole year operating conditions without accounting for the potential seasonality and/or long-term benefits of DR application. There is a lack of practical and varied best-practices cases (living labs or DHC systems) to cover a large range of DR strategies in various types/sizes/generations of DHC systems to show and qualitatively evaluate the similarities, differences and possible upscaling of these DR strategies in other DHC networks.

There is also a lack of scientific literature examining the long-term effects of DR on real existing buildings associated with large DHC networks and their occupants. Marszal-Pomianowska et al. [48] showed that in 72 Danish single-family houses 81% of residents can maintain the DR control strategies in the following heating season when the benefits are clear for them. However, the analysis did not present the long-term benefits of the DH utility and thus was incomplete and limited to the boundary conditions of the described experiment.

3.2.4. Lack of collaboration models to support DR implementation in real-life. (W4)

According to stakeholders' surveys and interdisciplinary workshops [33,34], the DHC network operators aim to sell more energy, still increasing the network efficiency and heat supply from renewable energy sources and lowering the production and distribution costs while the customers aim to reduce their energy bills while maintaining thermal comfort and/or DHW needs. For end-users, thermal and electrical energy is mostly invisible and consumed while performing activities in their everyday life and/or at their workplace. DR relates to the questions of thermal comfort, control of space heating and cooling, and patterns of DHW use.

The indirect and direct DR techniques proposed in Ref. [30] are developed from the perspective of the DHC grid operator. In the indirect DSM, the change in the demand profile is expected to be the response to the variations in the heat/cold tariffs. It is activated by the end-users (e.g. building owner or building management staff). It does not require any implementation and/or investment in the control systems. However, it requires customer engagement and reaction to the tariffs, and thus the results of the indirect DR technique have high uncertainty. When seen from the end-user perspective, this DSM technique is also called implicit DR strategy since the end-user is the actuator of the DR measure. In the direct DR, the change of demand profile is directly controlled by the DHC grid operator; thus, the DR effects are easier to predict and execute. On the one hand, the direct DR strategy is more reliable and preferred by grid operators. On the other hand, it requires investment in hardware and software to control and orchestrate the load modulation. The direct DR strategy also called an explicit solution, is driven by incentives to engage end-users in the DR campaign, yet with limited involvement in the DR event activation.

One valuable short-term solution to bridge this gap could be indirect DR [30]. The idea of indirect DR is to use an appropriate tariff structure, to financially motivate users to shift or lower their peak demand and thus lower the network peak. Consequently, this can reduce the operation cost of the DH network, thus lowering the overall DH price while increasing operational efficiency. Given that it does not require material and investment-intensive retrofitting, it is easy to implement, and investment costs are negligible [30]. Thus, allowing for a fast application in large areas with expected good social compatibility.

Limited demonstrations of DR activation in residential buildings have proven that the implicit participation is often forgotten by the residential customers after a short time [66] or the once-defined settings do not change [48], the monetary gain is not effective and cannot stand alone when the customers' habits and interactions with the technology are not included in the DR solution design [67].

Moreover, the adaptation of new communication and collaboration models is often confounded by significant split incentive barriers and information asymmetries between end-users (building owners, engineers, facility managers) and utility operators of DHC systems [33]. In principle, the established, incumbent district heating companies do not directly oppose the proposed DR concepts to be associated with future carbon-neutral DHC systems. However, they want a slower-pace transition towards new technologies by, for example, using their fossil fuel combustion plants until they reach the end of their natural lifetime to avoid a drop in the profitability of conventional energy generation. At the same time, new energy firms are entering the energy sector with various solutions, including renewable energy, excess heat recovery systems, ambient heat pump systems, energy efficiency, building automation and DR services. These firms claim that it is extremely difficult to introduce changes to the business models used by incumbent district heating companies since they control most of the distribution networks as local monopolies. However, these new energy companies are also expected to promote and apply novel technologies and services (including DR) to buildings associated with established DHC, causing them, in the end, to disconnect from the local district heating networks and disrupt the business model of the incumbent energy companies [68].

A conceptual co-creation process, based on the interviews, analyses and stakeholders' observations and dialogues during DR real applications, is thus needed (1) to enhance the positive perception of the utility of the DR actions and to convince the stakeholders further to invest and act in DR (2) to provide appropriate business cooperation models and services and (3) to improve the penetration rate of DR independent of the core technologies and the associated barriers, such as technology novelty.

3.2.5. Lack of data sharing and DR follow-up check. (W5)

The DR programs are defined as the ability of customers to change their consumption patterns in response to market/system signals which are either directly executed by customers by adjusting the thermostats and/hot water usage or indirectly by utilities by remote control of the customers' substation settings. Digitalisation of the DHC systems [60,61,69] may allow the stakeholders to attain their DR objectives more easily through data sharing and external or automatic control of heat and cold delivery equipment in individual homes. However, in any of the described DR real-life demonstrations an accurate measurement and verification approach is present. Yet, it is needed to assess them successfully since the evaluation of the real potential of a DR program that is enabled during a DR event depends on an evaluation method deployed to estimate the customers' consumption behaviour if they have not participated in DR. Hence, the customer base load estimation is critical for the further assessment of the difference between the estimated baseline and measured load data. Since various factors (such as load type, weather conditions, day of the week, etc.) could affect this estimation, more effort should be put into data selection, computation and eventual adjustments to show the real potential of DR measures.

3.2.6. *Lack of regulatory framework and DR tariffs. (W6)*

In 2020 the EU increased the target for the reduction of greenhouse gas emissions from 40% to 55% by 2030, and the following "Fit-for-55" package from the EU Commission is a set of proposals to revise and update EU legislation to realize this goal [70]. The building sector should even strongly mobilise energy-efficiency efforts through legislation and incentives, e.g. financial measures and administrative support, to encourage renovations of all types of buildings and installation of solar systems at the buildings if technically suitable and economically and functionally feasible. All these efforts should lead to stepwise energy reduction with the aim of zero-emission EU building stock by 2050 [70], which is in line with the recent Renovation Wave for Europe plan [71].

Since 2018 the Energy Building Performance Directive (EBPD) [72] has targeted obligatory energy performance requirements and voluntary smart readiness, which is evaluated by the smart readiness indicator (SRI) and is designed to evaluate building systems' technological maturity to interact with occupants and energy networks. It is a static evaluation scheme including 54 questions aiming to determine a building's intelligence capability [73]. To the author's knowledge, the SRI is the only regulatory framework which encourages building owners to integrate solutions enabling demand response both for the electricity grid and DHC systems.

There are two main types of DH market, namely the regulated and deregulated [74]. In the regulated market the price is regulated by the government, all DH plants and distribution networks are owned and operated by municipalities, and the companies do not make profits. The price of DH should cover the sum of operating cost, annual depreciation and permitted profit "cost-plus" pricing method. In the deregulated market the marginal-cost pricing method is frequently used. This method encourages the DH provider to reduce costs, promote efficiency and invest in new technology infrastructure and advanced solutions. Therefore, the "marginal-cost" pricing method is more DR-supportive than the "cost-plus" method. However, to the authors' knowledge, there is no DHC supplier with a pricing method enabling the demand response and active participation of the buildings in the DHC market by delivering energy flexibility.

In the context of DH tariff structures, recent research has focused on the effect on the profitability of building renovation. Their results show that a fully flexible tariff representing the actual heat supply costs and guaranteed low-interest rate loans for heat conversation measures create a strong economic incentive for retrofitting for most existing buildings [75–78]. However, an important aspect only mentioned on the side is the social compatibility of such flexible tariffs, which "penalise" energy-inefficient buildings. Considering that dwelling and apartment prices, respectively, rents are positively correlated with energy efficiency [79,80], a successful introduction of variable DH tariffs with a consequent retrofitting wave can contribute negatively to housing affordability [81]. Further, such tariffs can penalise low-income households for which it is more difficult to save energy [82], and low-income house owners who have a lower retrofit adoption share than high-income building owners [83]. Thus, while such tariff structures can be an essential tool to increase the notoriously low retrofitting rate of buildings, they require substantial accompanying political changes to make them socially compatible [82], making them a medium to long-term solution and not a short-term fix.

3.2.7. *Lack of consistent evaluation matrix for DR actions/strategies. (W7)*

There is no consensus on how to evaluate and compare the performance of DR in DHC systems. The work on methodologies to evaluate the energy flexibility of buildings, which is the precondition of the DR concept, has already been part of IEA Annex 67 [84] and is still an ongoing task in the IEA Annex 81 [85]. Nevertheless, many of the analysed methodologies and key performance indicators (KPIs) limit their application to energy as the main evaluation unit.

In the described DR demonstrations, the authors have used multiple matrixes that are related both to the building and network performance. The most commonly used is the peak load reduction during the high load periods (i.e. morning and/or afternoon peaks) achieved by the building and thereby also in the network [50–56]. Kärkkäinen S et al. [44] added to the peak reduction the share of the shifted load during the peak period. DR events could also contribute to the reduction in the temperature of the supply water [49] or in the customers' energy bills [46,47] as well as control of load according to electricity prices, and increase of thermal energy exchange in grids providing heat and cold [54].

Since, in the DHC systems, the energy is the output of changes in temperature and flow, the DR evaluation matrix must account for and visualise the variations in these two parameters. Finally, the DR event should also be evaluated for the impact on the energy efficiency of the overall DHC system (e.g. the increase of the return temperature from the building to the distribution network).

3.3. *Opportunities*

3.3.1. *Accelerating digitalisation of the building and the DHC sectors. (O1)*

The evolution and large-scale application of digital solutions in all energy sectors have opened up new possibilities for smart energy systems and interaction between energy sectors [86] The digitalisation of the DHC system is a fact [60,61] and similar trends also reach the building sector with the roll-out of smart heat meters [87] and installation of the "smart home solutions" [88–90].

These ongoing energy and digital transitions bring the possibility of real-time energy resource management to building owners/managers and energy system operators, with potential benefits for consumers, producers and the environment. To tap into the energy efficiency and demand response potential, stakeholders must be able to assess the performance of building energy systems and appliances continuously and hereby identify areas where energy efficiency and demand response can be achieved. Implementing this assessment capability requires real-time monitoring, data collection and analysis as well as smart control of building equipment and major energy-consuming appliances. Internet of Things (IoT) enabled sensors and devices that communicate with the cloud and execute control actions (thereby becoming smart devices) can effectively perform this functionality. Although modern smart devices and systems allow for remote monitoring and control, most residential buildings and systems are not equipped with such capabilities. Therefore, DR solutions and their large-scale application could enable the upgrade of low-tech buildings, appliances and technical building equipment with real-time monitoring and control capabilities. Hence the entire building stock is smart-grid ready.

The following issues must be addressed to seize this opportunity while developing and implementing DR strategies in practice.

a. GDPR for data collection, storage, use and ownership

b. Customers' willingness and trust in sharing their confidential/private information with utilities and/or third parties involved in DR control and execution
c. Efficient real-time monitoring, data collection and analysis, as well as control capabilities
d. Varying capabilities for remote monitoring and control of building devices and systems
e. Missing data either due to GDRP reasons or due to failure of data collection/management systems and recommendations for the minimum set of needed data to apply a certain DR strategy

3.3.2. *Accelerating the shift from high to low supply temperatures DH systems. (O2)*

The operation temperatures (supply and return) in the DHC distribution network depend on the temperature preferences of the customers. As the primary objective of the vast majority of DHC utilities is the reduction of supply temperature and the core of the demand response concept is the close interaction between the supply and demand side, there is a great potential that utilisation of DR will accelerate the ongoing transformation of the DHC sector [14].

3.3.3. *Fault detection and diagnostics at the demand side in DHC systems. (O3)*

To activate demand response through remote heating control in buildings the heating systems must often be modified to enable DH utilities additional functionalities, such as collection of real-time data for the demand side. This constant insight into the buildings' installation performance creates new possibilities for the detection and diagnosis of faults [91,92] since 50–60% of all building heating systems have faulty operation leading to higher volume flows and return temperatures and creating large barriers for DHC systems optimization [93,94].

3.3.4. *New customer-tailored collaboration models and energy pricing mechanisms. (O4)*

In the DHC systems, the relationship between the utility and the customer differs from that in the electric systems. The DHC utilities directly provide thermal energy that has to match the requirements for thermal comfort and DHW production of individual customers. The DHC systems are more local (i.e. their distribution area is limited due to the hydronic/pumping/energy losses and limitation of the distribution pipes). Depending on the DHC system structure, all components of the primary side (i.e. production units, distribution network) and even the substations located in the buildings can be owned by one stakeholder [60]. These characteristics provide the DHC utilities with an opportunity to build a close relationship with their customers and thereby create various, maybe even customer-tailored, collaboration models with their customers. In consequence, the success rate for the DR strategies application in DHS systems is expected to be higher than in the electric systems. However, due to the local characteristics, the developed cooperation models might have reduced spread and international application.

The introduction of variable energy tariffs, dynamic pricing, is an opportunity both for DHC network operators as well as for the consumers to establish new collaboration models (business models) able to valorise flexibility options through DR. Thus, while such tariff structures can be an essential tool to increase the notoriously low retrofitting rate of buildings, they require substantial accompanying political changes to make them socially compatible [64], which makes them a medium to a long-term solution and not a short-term fix.

3.3.5. *Customers' increased awareness of energy consumption, flexibility potential and energy cost savings. (O5)*

In the context of higher energy prices, the customers' awareness of their heat consumption can be increased by installing smart heat/cold meters, as obligatory metering instruments in the EU from 2027 [87], and intelligent appliances related to heating and cooling distribution and storage. Smart heat metering, robust communication and cybersecurity systems are essential for the successful application of DR strategies [30]. These technology solutions enable the network operators to collect information for load monitoring, the billing process, online control and management of the delivered heat/cold. They also empower customers to recognize how much heat/cold they are using and, accordingly, their flexibility potential to be utilised during DR events.

3.4. *Threats*

3.4.1. *Low penetration rate and period between planning and commissioning of DHC systems. (T1)*

Despite the effort to enhance the uptake of DHC systems, the current level of penetration of DHC systems is still low. One reason for this is probably the long period (3–10 years) needed from the first idea of developing a new DHC system until the real commissioning and operation of the new DHC system [65,95]. The slow development of DHC in operation forms a threat to the further uptake of DR. Development of DHC systems at a higher pace will trigger more DR actions in the new DHC systems. Nowadays, it is possible to mobilise a large spectrum of RES and waste energy sources in DHC systems, but understanding and forecasting the key technical features of such sources and assessing their long-term compatibility with the DHC network and connected buildings is still needed to develop reliable, flexible and cost-efficient DHC systems.

DC systems must gain higher visibility at the policy level leading to more practical applications as cooling demand rapidly increases worldwide [1]. As newer types of networks where cooling has a considerable share in the thermal energy circulating in the network, DH network operators also become DC network operators, and DC can be seen as an additional source of thermal flexibility that can be accounted for in DR actions. The DHC network operators in newer low-temperature networks (5G DHC) will have more ways to strengthen their thermal energy offer, remain competitive against individual heat pumps, and have a new source of revenue in the context of decreasing heating consumption [96].

3.4.2. *Intermittent and inconsequent application of policies to support DR, RES, DHC. (T2)*

The future scenario in the EU envisages the need to enhance and increase DR; however, not specifically associated with DHC and thermal energy. The European Directive 2019/944 established in article 17 that "*States shall allow final customers, including those offering DR through aggregation, to participate alongside producers in a non-discriminatory manner in all electricity markets*" [97]. While the electric energy market has national, transnational and global implications due to the relatively simple (standardized, well-accepted and long time in place) and interconnected manner of operation of the electric grids, the local, varied (non-standardized) and fragmented (isolated) nature of the existing DHC networks makes difficult the creation of a self-regulated, competitive thermal energy market with national, transnational or global coverage.

A closer look at the policymakers responsible for the proposal of measures to support DR, RES and DHC reveals that they are a particular group of stakeholders, including civil servants from ministries, members of parliament and representatives of various political parties with ties to the government. Interviews with policy makers in Finland [11] showed that, in their view, the main barrier to implementing proposed clean DH concepts was and still is energy security, as the concepts underestimate the need for developing enough power capacity that is crucial during high demand periods. In the path towards clean DH thermal energy provision, the closing of CHP plants may increase energy security risks, while the proposed low-carbon district heating concepts strongly rely on large-scale electrification, which implies a high share of intermittent energy production. This example concludes that the policy makers do not have all the needed science-based information backed-up by enough best-practices from other countries to propose consequent and long-term policies and measures to support DHC. As a consequence, the DR-actions that could be applied in future DHC networks are still not considered.

Some countries where DH plays a more prominent role in the heating/cooling sector (e.g. Denmark) already have many coherent laws and regulations that have also shaped the DH governance and ensured a high level of transparency and consumer protection. 95% of the DH systems are owned by municipalities or consumer associations, the latter representing 35% of the total. The Danish Utility Regulator (Forsyningstilsynet) oversees the sector and carries out a national benchmark voluntarily to incentivise cost-effectiveness [96].

3.4.3. Reluctancy to apply academic research results in real-life application. (T3)

In many DHC networks, there is a lack of trust between the network operators and the customers to directly apply in existing DHC systems the results of academic/theoretical research on the DR concept. There are not enough guarantees for continuous and increased advantages mutually beneficial for all the stakeholders (not only for the network operators or only for the residents but for both).

The DH and DC professionals are aware of the DR concepts and recognize the possibility of buildings providing short-term thermal storage to the system [32]. Nevertheless, they indicate that other short and long-term TES options, which have less operational uncertainty and are easier to load and discharge (e.g. boreholes, tank-pit or thermochemical storage located in the perimeter and connected to the distribution network), might be more robust in delivering long-term flexibility benefits and do not break the autonomy of production and demand sides [19,98,99]. Therefore, the DHC professionals see a very narrow opportunity for DR application in DHC systems.

4. Conclusion and future work

The present research aimed to gain a better understanding of the demand response concept in the district heating and cooling systems. The SWOT analysis was applied as a methodology to identify key elements, such as strengths (S), weaknesses (W), opportunities (O) and threats (T) related to this topic. The results of this study indicate that the application of the DR concept has left the theoretical studies and moved towards real-life applications. There is still a domination of weaknesses, seven out of 17 elements, however, they are not any more related to the lack of technology but rather to the social, economic and regulatory aspects. The described DR demonstrations have shown that technology solutions are accessible but the diversity of building installations and the variety of DHC systems configurations and generations hinder the possibility of easy replicability of solutions between DHC systems.

On the one hand, the interviews with DHC professionals, the theoretical studies and the real-life demonstrations confirmed that DR has the potential to solve the challenges of the DHC operation of today, such as the reduction of supply temperature, and of the future, such as phase-out of fossil fuel peak boilers and increase share of RES. Yet, the real-life demonstrations are primarily parts of research activities, where the optimistic modelling work is challenged with real-life conditions, not always clear to the academic community. On the other hand, this concept requires more sophisticated control and data exchange/storage and analytical solutions, involves multiple stakeholders and is in competition with centralized thermal energy storage solutions [100].

Moreover, the SWOT analysis findings have identified that to proceed with the further development of this concept the regulatory framework must be adjusted to allow DHC operators to develop new business models and DR tariffs that will incentivise the customers to deliver flexibility to the system without compromising their comfort and everyday practices and increasing energy poverty.

The insights gained from this study may be of assistance to DHC operators, policymakers, potential flexibility aggregators and DHC customers as the demand response in DHC systems requires simultaneous top-down (utilities towards customers) and bottom-up (customers towards utilities) strategies of information processing and knowledge/experience transfer.

CRediT authorship contribution statement

Anna Marszal-Pomianowska: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization. **Emilia Motoasca:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ivo Pothof:** Conceptualization. **Clemens Felsmann:** Writing – review & editing, Conceptualization. **Per Heiselberg:** Writing – review & editing, Conceptualization. **Anna Cadenbach:** Writing – review & editing, Conceptualization. **Ingo Leusbrock:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Keith O'Donovan:** Writing – original draft, Visualization. **Steffen Petersen:** Writing – review & editing, Conceptualization. **Markus Schaffer:** Writing – original draft, Visualization.

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.

Data availability

No data was used for the research described in the article.

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Appendix

Table A1
Summary of the metadata of the seven case studies.

	Buildings	Network	Storage	DR
1. Application of DSM in Turin	Existing/renovated buildings with mixed-use	SH only, 2GDH T > 100 °C	centralized & decentralized thermal storage, water-based short-term buffer, building mass	Active, direct DR for Load shed, Grid operator anticipates peak by substation control with no involvement of customer

(*continued on next page*)

Table A1 (*continued*)

	Buildings	Network	Storage	DR
2. Rural DH network in Austria	Existing/renovated buildings with mixed-use	SH + DHW, 3GDH ($70 < T <$ 100 100 °C)	centralized & decentralized thermal storage, water-based short-term buffer, building mass	Active, direct DR for Load shift and Load Shed, Grid operator uses flexibility by substation control, Implicit involvement of customer (acceptance of DSM)
3.100 % Renewable District Heating Leibnitz	Existing/renovated buildings with residential use	SH + DHW, 3GDH ($70 < T <$ 100 100 °C)	decentralized thermal storage, water-based short-term buffer, building mass	Active, direct DR for Load shift and Modulation, Grid operator uses flexibility by substation control, Implicit involvement of customer (acceptance of DSM)
4. Data-driven approach for a rural DH network	Existing/renovate d buildings with residential use	SH + DHW, 3GDH ($70 < T <$ 100 100 °C)	decentralized thermal storage, building + heating system mass	Active, direct DR for Load shift, Grid operator uses flexibility by substation control, Implicit involvement of customer (acceptance of DSM)
5. Customers-driven approach for DR Denmark	Existing/renovate buildings with residential use	SH + DHW, 3GDH ($70 < T <$ 100 100 °C)	decentralized thermal storage, building mass, SH and DHW system	Active, indirect DR to increase efficiency by activating Set Back (reduce set point temperature)
6. Office building in Dresden	Existing/renovated building with non-residential use (offices, labs, lecture rooms)	SH only, 2GDH ($T >$ 100 100 °C)	decentralized thermal storage, building + heating system mass	Passive DSM to increase efficiency and also active, direct DSM for Load Shed and Load Shift, Load Shed at particular hours, Load Shift for pre-heating thermal mass
7. Experimental and test recentre District LAB		2G to 4GDH possible (10 … 120 °C)	decentralized and centralized thermal storage	On a lab scale, single buildings and whole districts can be investigated regarding passive and active DSM measures, all DSM purposes are possible (Increasing efficiency, Load Shed, Load Shift, Modulating power demand and On-site generation)

Table A2
Overview on national characteristics of DHC systems

	Capacity MW/MWh	DH and DC status	Share of building stock connected	Legal framework for DHC and DR in DHC	Experiments of DR initiatives in existing DHC systems	Customers approach to DHC utilities
Austria 2018 status	23.1 TWh/y production with 19.6 TWh/y Fuel Mix: bioenergy 44.3%, natural gas 36.7%, waste 10.3%, oil 3.8%, coal 4.0%, other 0.9%) – 59.5% of all heat from co-generation plants.	DH: Backbone is 2nd and 3rd generation system. Over 2400 DH networks, the vast majority of which are small grids (<10 GWh/y) fuelled largely by biomass plants. DC: Small but growing market for DH. Mainly used in hospitals and commercial buildings.	26% of all apartments are heated with district heating. 15% of total heating demand from District Heating	Austria's DH systems are usually operated by one company, which owns at least one heat production unit (co-generation or heat-only boiler) and the corresponding network. In many cases, these companies are fully or partly owned by local authorities such as the municipality. Many DH suppliers use service companies to handle metering and billing Price regulation delegated to local authorities at the provincial level.	Research projects – Data Driven Load Management focuses on increasing flexibility through load prediction algorithms and over and under heating suitable buildings in small DH grids in eastern Austria. Flexibility topic is addressed in DH context in Thermalflex project.	As the DH systems are operated as monopolies, customers that are unhappy with prices cannot switch suppliers. To improve the situation for DH customers, more transparency in how prices are set and adjusted should be provided.
Belgium/ Flanders 2019 status	DH: 624 GWh in 2019 834 GWh 2020	DH: over 76 utilities of various size	Equiv to 42 743 households	See VREG report 2021	Per project	Customers distrust towards DHC utilities
Danmark 2019 status	DH: 25.2 GW (heat) 7.2 GW (el) Production plants: 68% from CHP units 32% from DH units Fuel mix: 64% for RES 2% EL from HP 60.000 km of pipes 20% of distribution losses	DH: over 400 utilities of various size The backbone of DH systems is the 3rd generation networks with individual extensions operating on lower temperatures. DC: expected to be established as part of DH utilities. Already existing or soon to be executed local DC districts are expected to cool the multi-storey residential and commercial buildings in all Danish big cities (e.g. Copenhagen, Aarhus, Aalborg)	DH delivers 51% of heat consumption in building 65% of residential buildings are connected to DH	Until end of 2019 obligatory connection for buildings in DHC areas Regulatory framework allowing direct customer-utility contract. No national legal framework for DR rather voluntary initiatives undertaken by specific DHC utility	Preliminary tests in major cities, such like Nordhavn project [101]; Respond project [102] Varme + initiative is the preliminary step towards direct DR control by the DH utility. DH customers rent a DH substation	High trust in DHC utilities
Germany 2019 status	energy input: 2019: DH: 130–145,7 TWh	570 DH utilities steam and water DH networks mostly 3rd generation	Ref [2]: 2019: district heating in 6,6 % of residential	Regulatory framework allowing direct customer-utility	Preliminary tests in Gutleutmatten, Freiburg	Generally high trust of DHC utilities high grade of trust in rural

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Table A2 (*continued*)

	Capacity MW/MWh	DH and DC status	Share of building stock connected	Legal framework for DHC and DR in DHC	Experiments of DR initiatives in existing DHC systems	Customers approach to DHC utilities
	(two different references 2020: DH: 113 TWh heat demand 2019: DH: 111,9 TWh (thereof 52,8 TWh households) DH & DC: 118,5 TWh (thereof 49,8 TWh households)	systems A few 4th generation systems in rural areas and sporadic 5th generation networks	buildings District heating as a source of energy in new residential dwellings: 2000: 7,0 % 2019: 26,8 % District heating as a source of energy in existing residential dwellings: 2000: 12,3 % 2019: 14,0%	contract. Compulsory connection is rarely existing, in case of new settlements and sale of land by the municipalities No regulatory framework for DR besides privacy regulations.	Shamrockpark, Herne Sonnensiedlung, Moosburg	areas, more distrust in urban areas The smaller the networks, the greater the trust.
Italy 2019 status	Heat delivery in DH: 9227 GWh in 2020 (9133 GWh in 2019 and 3854 GWh in 2000) and about 10 GW installed. Overall pipe length: 4666 km Energy share: Renewable source (e.g. geothermal, RE heat pumps, waste heat) 26.3%, Cogeneration from fossil 50.3%, Boiler from fossil 26% DC: 130 GWh, 200 MW installed. Overall pipe length 35.4 km	DH: 266 utilities of various size (about 50% 2nd generation and 50% 3rd generation) DC: 33 utilities	DH: Total #substations 88 610, Total building heated volume 375.2 Mm^3: 63% residential (about 2% of Italian buildings), 34% services, 3% industrial end-users DC: Total building cooled volume 8.8 Mm^3:	Legal framework is focused on a) the energy efficiency of buildings b) requirements for pipeline at high pressures c) requirements for high efficiency DH There's no obligation to be connected to DHC when available. No national legal framework for DR rather voluntary initiatives undertaken by specific DHC utility	Experiments are being set-up in the Turin network only on public buildings.	–
Netherlands 2020 status	DH: 6900 GWh	DH: 23 DH operators are active. The backbone of DH networks is 3rd generation networks. Last 2 decades 4GDH (70/40) was introduced for new districts, DC: Very few specific DC grids for commercial districts. Cooling from Aquifer Thermal Energy Storage (ATES) is well developed with around 3000 installations for commercial buildings and neighbourhoods. An unknown number of ATES systems (Apr. 30) delivers heating and cooling to newly built districts (5GDHC)	Total #connections are 435.000. There are 13 large-scale DH grids (>5000 connections) and 365 medium size grids (<5000 connections) DC: Number of dwellings connected to 5GDHC grids is unknown (estimate 25 000)	legal framework protects end-users (customers) against malpractices. Operators apply fixed tariffs and have limited possibilities to apply temporal variations to stimulate DR. New law on district heating is being developed.	The WarmingUP-programme includes a project on DR ("Vraa gsturing"in Dutch). Experiments are being set-up. Following a questionnaire among stakeholders and experts, the consumer support, participation and large initial investment are the key challenges to accelerate the adoption of district heating/cooling solutions.	Customers distrust towards utilities. Operators are perceived as monopolists.
Spain 2021 status	Installed capacity DH (2021): 757.5 MW Installed capacity DHC (2021): 880 MW Installed capacity DC (2021): 1.9 MW Note 75% of installed capacity is used for heating. Main fuel (installed capacity): – 39% biomass – 59% natural gas – 1% other fuels – 1% other renewables 752 km of pipes	Total: 494 facilities DH: 451 facilities DHC: 40 facilities DC: 3 facilities Steady growth in number of facilities and installed capacity.	5.800 building connected. In terms of costumers 70% belong to services sector, 23% to households, and 7% to industrial. In terms of installed power 46% belong to service sector, 32% to households, and 22% to industrial.	No specialized framework for DHC. According to the construction and operations licenses of each municipality and/or company's contract. Yet, DHC is implicitly being promoted within the plan of recuperation, transformation and resilience (PRTR) through different plans and regulation of building and neighbourhood renovation and efficient thermal generation	None known.	An opposition of change and new technologies in heating and cooling sector by citizens.

(*continued on next page*)

Table A2 (*continued*)

	Capacity MW/MWh	DH and DC status	Share of building stock connected	Legal framework for DHC and DR in DHC	Experiments of DR initiatives in existing DHC systems	Customers approach to DHC utilities
UK 2019 status	Around 14 TWh [1]	• 13 995 heat networks in the UK • 2087 district heating networks • 1109 networks provided space heating, hot water and cooling • Just 1664 networks provided cooling (of which 141 provided only cooling) [2]	14 000 networks in the UK with 480 000 customers, which now accounts for less than 3% of heat demand. Heat networks could meet the heat demand of 17% of UK homes and 24% of commercial and public sector buildings by 2050.	UK is considering regulatory frameworks for heat networks.	Project Based	2017 Heat Networks Consumer Survey is the first significant survey of consumers on heat networks in the UK, covering around 5000 consumers, of which around 3000 consumers are on a heat network and 2000 consumers are on another heating system. Costumers are satisfied in general.

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