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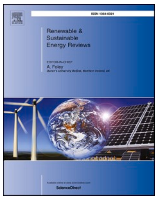

A state-of-the-art analysis and perspectives on the 4th/5th generation district heating and cooling systems

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ABSTRACT

The evolution of district heating systems is characterized by a trend towards lower supply temperatures and higher energy efficiencies. The most recent advancement in this field is the fifth-generation district heating and cooling systems (5GDHCS). Current literature identifies three key features of 5GDHCS: operating at near-ambient temperatures, the use of distributed booster heat pumps at end-users, and the capability to provide both heating and cooling services. However, there is ongoing debate on whether 5GDHCS represents a significant technological leap beyond its predecessor, the fourth-generation district heating system (4GDHS). To resolve fundamental questions surrounding the 5GDHCS concept and to highlight its distinctive features, this paper conducts a detailed comparison between 5GDHCS and 4GDHS, examining their functional, technological, and operational differences. Based on this, limitations in existing definitions of 5GDHCS are identified, and a refined definition better characterizing its unique attributes and advancement is suggested. Additionally, considering the 5GDHCS-related studies are growing fast, with over 30 works published each year since 2021, this paper tries to complement previous reviews with an updated perspective on its latest research progress and practical deployment, through a comprehensive state-of-the-art analysis. Results show that while 5GDHCS is a promising technology to decarbonize domestic heating and to promote sector coupling between electric power and district heating systems, it is still in the early stage of development, marked by substantial research gaps in technical, policy, regulatory, and market aspects. Analysis on an exhaustive collection of real-life cases also indicates a long way ahead to achieve its widespread commercialization.

1. Introduction

The growth of green-house gas (GHG) emissions shows strong relevance to global energy production activities. It is estimated that energy accounts for more than two-thirds of total GHG emissions worldwide [1]. To achieve the climate goal in the Paris Agreement, decarbonizing the energy sector is crucial.

Globally, domestic heating and cooling constitute a significant proportion of overall energy use. Data from the International Energy Agency (IEA) reveals that almost half of the energy consumed within buildings is for space and water heating [2], whilst nearly 9 % of the final electricity consumption goes to space cooling services [3]. Notably, since the year 2000, there has been an annual increase of about 4 % in energy demand for space cooling, potentially leading to a 40 % surge in total electricity demand for space cooling by 2030 compared with the level in 2022 [4].

District heating (DH) is deployed as an efficient and cost-effective way of supplying heat within a local area in many countries. The amount of heat produced for district heating networks witnessed an increase of about 10 % from 2020 to 2022 [5]. It is estimated that DH supplies in the total final heat consumption of the EU-27 will rise from 15 % in 2020 to 31 % in 2050 [6]. Despite the promising development prospect owing to its high energy and economic efficiencies, the decarbonization potential of DH is largely untapped as nearly 90 % of the heat supplied in district networks globally was produced from fossil fuels in 2022, especially in the two largest markets of China (coal-dominated) and Russia (natural gas-dominated) [5]. District heating currently accounts for almost 4 % of global CO_2 emissions, and witnesses

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Abbreviations: GHG, green-house gas; IEA, International Energy Agency; DH, district heating; 1/2/3/4GDHS, first/second/third/fourth-generation district heating system; RES, renewable energy sources; 5GDHCS, fifth-generation district heating and cooling system; COP, coefficient of performance; LCOH, levelized cost of heat; MILP, mixed integer linear programming.

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a growth rate of 1.5 % in 2022 compared with the total emissions in 2021, and around 25 % compared with those in 2010, due to the growing demand and the increased use of fossil fuel-based DH networks [5].

Considering these figures, the problem of how to decarbonize district heating has been receiving increased attention. Over the past decade, innovative DH systems fueled by renewable and waste heat sources, have emerged rapidly, either directly or with the support from heat pumps and storage systems [5]. These advancements play a pivotal role in shaping the evolution of the fourth and fifth generations of district heating systems [7–10]. These innovative systems not only facilitate the integration of recycled heat and renewable generations, maximizing the decarbonization potential of DH, but also foster synergy between district heating and electric power systems by promoting effective sector interactions. Through sustained efforts, the future landscape of district heating is progressively taking form, with decarbonization and better integration into a more efficient, intelligent, and flexible energy system at its core.

1.1. *Generations of district heating*

The use of generations to classify district heating systems with different technological features was widely adopted in Refs. [11–23]. Fundamentally, generations are characterized by a) breakthrough technologies applied in system components (including energy sources, conversion units, distribution networks, and end-user facilities; b) continuously increased energy efficiencies among generations; and c) continuously decreased supply temperatures among generations [11].

An overview of existing five generations of DH is illustrated in Fig. 1. Throughout history, each generation chronologically signifies the dominance of a particular category of technologies over several decades. The first-generation district heating system (1GDHS), dating back to the 1880s, is characterized by its use of steam as the heat carrier. This system delivers heat through condensation in radiators located at the consumer side [7]. The supply temperature of DH flows can range from over 120 °C to up to 200 °C [12–14]. The Second-generation district heating system (2GDHS), emerging in the 1930s, employs pressurized hot water (mostly above 100 °C) to distribute heat [15]. The motivation behind adopting this technology varied across countries, but generally aimed at achieving fuel savings through combined heat and power (CHP) utilization [7]. The third-generation district heating system (3GDHS), also known as the "Scandinavian district heating technology", was introduced in the 1970s in response to oil crises. It involves prefabricated pipes and compact substations, and relies on pressurized water with supply temperatures below 100 °C to enhance its energy efficiency [7,15,16].

The progression to the fourth-generation district heating system (4GDHS) has been propelled by a heightened emphasis on energy efficiency, smart control, and the harnessing of locally available renewable energy sources (RES). Notably, 4GDHS is characterized by maintaining a temperature level closely aligned with the actual demand of connected end-users, reaching a maximum of 60–70 °C [11]. This lower supply temperature reduces network losses and facilitates the economically viable integration of additional renewable and waste heat sources, including solar thermal collectors, geothermal sources, and industry surplus, etc.

Bearing with an expectation to continue the trend for lower supply temperatures, increased energy efficiency, and the integration of breakthrough technologies, the fifth-generation district heating and cooling system (5GDHCS) was developed [9,17]. It has been receiving soaring attention over the past few years, with several dozens of practical systems launched across Europe, primarily started as pilot cases [9, 10]. Similar to 4GDHS, 5GDHCS also recycles waste heat from a wide range of renewable and waste heat sources, as illustrated in Fig. 2. However, it delivers the recycled heat through a water network with supply temperatures close to ambient levels (typically below 30 °C) to minimize heat losses during transmission. This design opens for the possibility to utilize uninsulated pipe networks [18], but potentially results in larger flow rates in the network and increased pumping energy costs due to the smaller temperature difference between the supply and return water [9].

Another key feature of 5GDHCS lies in its capability to provide both

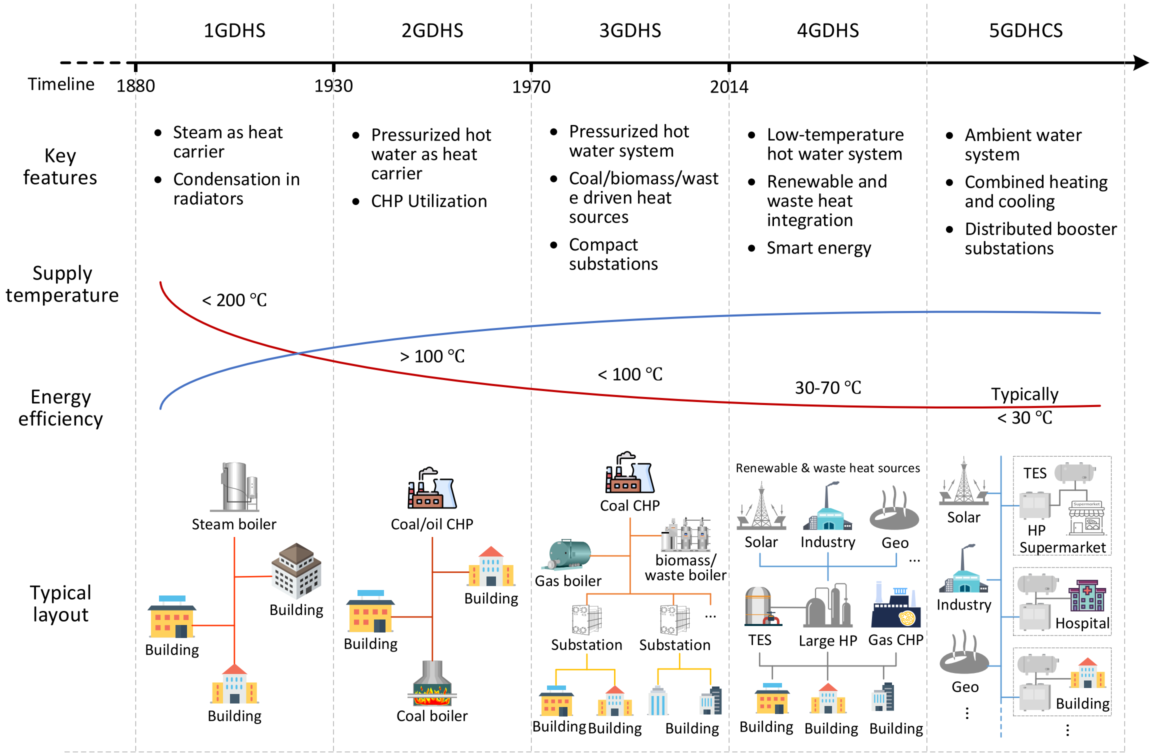

Fig. 1. District heating generations, based on [12].

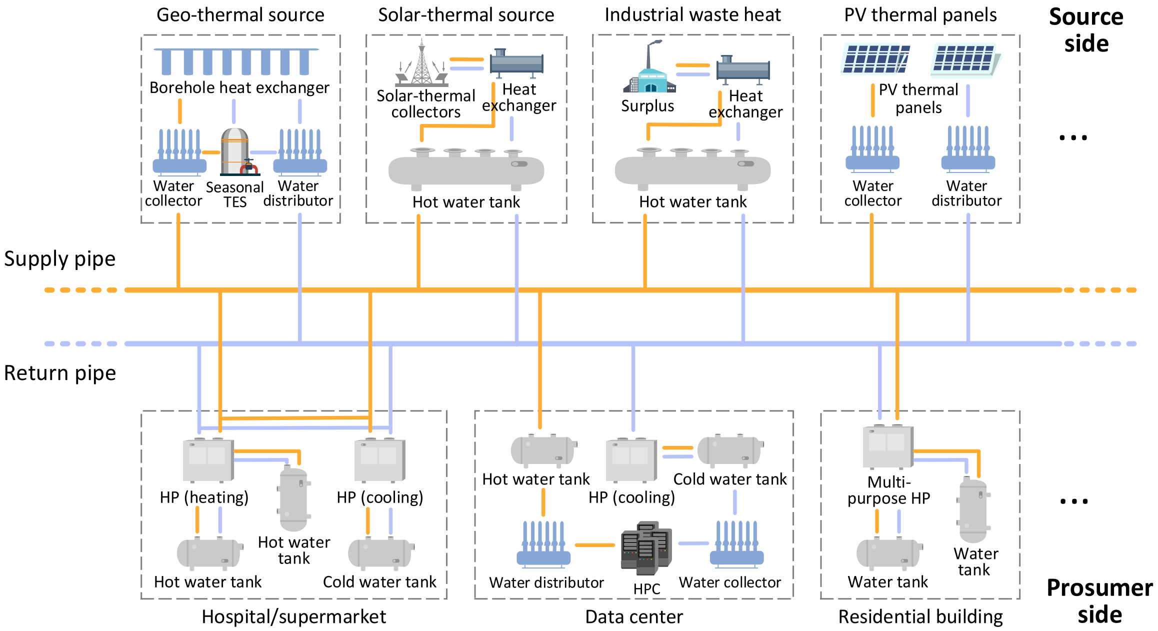

Fig. 2. Sketch diagram of a typical 5GDHCS.

heating and cooling services through a single shared network, facilitated by the widespread deployment of distributed heat pumps that can operate in both heating and cooling modes. With this, excess thermal energy from distributed cooling loads can be recycled for heating purposes – the low-grade heat removed from cooling loads is collected by distributed heat pumps, injected into the supply network, and then recycled by all heat pumps deployed at heating loads collectively [19]. This differs from 4GDHS in that a combined heating and cooling network and distributed heat pumps can save the use of district cooling networks to deliver the excess heat to centralized heat pumps in 4GDHS for temperature elevation (if they are not equipped with heat pumps locally). Given the deployment of district cooling networks is substantially less prevalent than that of district heating networks [24,25], excess heat recycling from a larger scale of cooling loads can be achieved in 5GDHCS than in 4GDHS.

It is worth noting that the selection of distributed heat pumps should align with the end-user’s needs. For end-users with only heating or cooling demands, a booster heat pump operating in either heating or cooling mode is appropriate. Instead, if an end-user requires both heating and cooling, a multi-purpose heat pump capable of generating both is necessary.

From the end-users’ perspective, the deployment of distributed heat pumps also enables most of them to be both consumers and producers of heat/cooling energy. This indicates a significant role shift for end-users to prevalently transition from conventional consumers to active “prosumers”, with the potential of establishing new trading mechanisms such as peer-to-peer energy trading [26,27] for future heating markets. However, additional investments in customer substations and the adoption of finer control strategies will be needed to realize this [9].

It should be noted that some end-users can also act as prosumers in 3/4GDHS (such as supermarkets and buildings with large solar thermal installations), but they only represent a small group of the overall end-users. By contrast, most end-users in 5GDHCS have booster heat pumps installed and can act as prosumers. The prevalence of prosumers in the whole system is an important feature of 5GDHCS compared with other DH generations.

Today district heating is transitioning from the third generation to the fourth and fifth ones in the context of net zero commitments [28]. Although 4GDHS and 5GDHCS originated within the same historical period, they have different technological emphasis and distinct merits and limitations. It is believed that 5GDHCS is not intended to replace other 4GDH technologies in the future [29]. Rather, it can coexist with 4GDHS, offering efficient and sustainable heating and cooling solutions across a broader spectrum of application scenarios.

1.2. *Diverged opinions on the denomination of “fifth-generation”*

In essence, 5GDHCS embodies a fusion of district heating and cooling operations at temperatures close to ambient levels, incorporating distributed heat pumps at customer locations. Systems with similar features were reported to have been existed in Europe since 1991 [30] and were firstly proposed in China as a conceptual system (“Energy Bus”) in 2008 [31,32]. The term “fifth-generation” was firstly used in 2015 in the full name of the Horizon 2020 Project “Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS” [9,33]. Since then, this term has gained widespread acceptance and has been prevalently adopted in most related studies. Aside from this, several alternative terms with similar meanings were also reported and summarized in Refs. [9,34,35]. These include “Bidirectional Low Temperature Networks” [36–39], “Anergy Networks” or “Anergy Grid” [40], “Low-Ex Systems” [30,41], “Cold District Heating” [42,43], “Low Temperature District Heating and Cooling” [19,44], “Ultra-low Temperature District Heating” [45], “Heat Sharing Networks” [46,47], and “Balanced Energy Networks” [47,48].

It was not until 2019 that the full name of “fifth-generation district heating and cooling” was suggested in Ref. [9] to alleviate the confusion and ambiguity in the denomination of such systems. However, diverged opinions were reported in Refs. [11,15,23,49], questioning the justification for introducing a new technological generation beyond the well-established fourth-generation district heating systems.

Insightful perspectives opposing the denomination of “fifth-generation” were expounded in Ref. [11]. While recognizing 5GDHCS as a distinct technological solution involving distributed heat pumps for both heating and cooling services, the authors in Ref. [11] believe that a technology generation should encompass all technologies introduced and operated around the same period and sharing common objectives and capabilities. In this sense, the existing 5GDHCS concept actually represents a new technological solution belonging to the broader 4GDHS family - they arise in the same historical period, have the same overarching aim of decarbonization, share the essential abilities of recycling waste heat from low-temperature sources, and can supply both heat and cooling energy via DH networks with lower heat losses. It is also argued that the 5GDHCS label is misleading as it renders the intuitive perception that a transition towards 5GDHCS is a progression [11]. Therefore, the terminology of "fifth-generation" should be reserved until the 4GDH technologies are firmly established and then later superseded [15].

Despite these opposing viewpoints, it remains an undeniable reality that the term "fifth-generation" has been extensively embraced in the majority of relevant studies. The enthusiasm exhibited by individuals for novel concepts possibly contributed to this widespread adoption, as recognizing the emergence of an entirely new technology has the potential to attract increased research attention and secure additional research grants [11]. However, there seem to be more factors influencing the decisions of the vast majority. One such factor could be attributed to the overly broad definition of "4GDHS".

The current definitions of 4GDHS are outlined in Table 1, wherein it represents a quite broad concept containing all district heating systems that are able to integrate low-temperature heat sources, low-loss networks, as well as smart operation strategies to facilitate the decarbonization and sustainable development of the heating sector. This broadness is good for the generalization of a concept, but may also lead to diverse readings and interpretations. Case in point, the level of DH supply temperature, a key indicator across different DH generations, has been subject to diverse interpretations in existing literatures. The 4GDHS was reported to be characterized by a supply temperature level close to the actual temperature demand of connected end-users, typically capped at a maximum of 60–70 °C [11]. However, there exists an alternate perspective positing that the term "4GDHS" serves as a generic descriptor for all low-temperature systems with supply temperatures ranging from 10 to 70 °C [49]. While in most of existing 5GDHCS related studies, systems with supply temperatures close to ambient levels (typically no higher than 30 °C) were considered as a unique feature of 5GDHCS and those with supply temperatures between 30 and 70 °C were classified as 4GDHS [14,19,22,36,39,50–60].

Another differed understanding of the 4GDHS concept lies in the deployment of distributed heat pumps at consumer substations. While centralized heat pumps installed at waste heat sources were clearly presented as a dominant heating solution in 4GDHS [7], some 4GDHS studies did mention using building-level booster heat pumps to elevate temperature levels to meet the hygienic requirements of domestic hot water [8,61–63]. However, these booster heat pumps were mostly auxiliary heat sources, serving as an alternative to buildings without instantaneous heat exchangers [8]. In contrast, distributed heat pumps become dominant heat sources in 5GDHCS, relegating combined heat and power units, centralized heat pumps, and other waste heat sources to auxiliary roles. This shift is regarded as a pivotal feature of 5GDHCS, not only enabling the provision of both heating and cooling but also renovating the role of end-users from mere heat consumers to active "prosumers" [60,64–70]. Ultimately, the DH sector is expected to transition from its current reliance on fuel-driven solutions to predominantly electricity-driven ones.

Table 1
A summary of existing definitions of 4GDHS.

Reference	Definition of 4GDHS
[7]	*"The 4GDHS is a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems."*
[16]	*"The 4GDHS is a concept whereby smart thermal grids with low temperatures and structured incentives support the integration of low-temperature heat sources and renewable electricity generation."*

The ongoing debate surrounding the denomination of "fifth-generation" underscores the subjective nature of criteria used to define a new technological generation of district heating. A sample definition of technology generation was provided by Ref. [11] as "all of the technologies introduced and operated at about the same time, regarded collectively". It is important to understand that there can be different types of technologies within a generation, but only one would be the "dominant" technology and the rest would be more niche technologies serving specific local conditions. Looking forward, open questions such as what DH technology will dominate the next decades, how large is a technological leap sufficient for defining a new generation of DH, and what are the proper criteria to quantify such a technological leap will continue to spark discussions. The rationality and drawbacks of adopting the term "fifth-generation" reflect the complexities of framing technological progress in this field. The fate of the term - whether it will persist or fade into obscurity, will be determined by the collective choices of stakeholders, unfolding over the course of history.

1.3. Motivations and paper organization

1.3.1. Motivations

This paper focuses on district heating systems falling within the scope of the fifth-generation concept. These include systems either explicitly labelled as the "fifth-generation district heating" or designated as 4GDHS but with substantive features of 5GDHCS. These specifically include supply temperatures near ambient levels and the incorporation of distributed heat pumps as dominant sources for both heating and cooling purposes. For simplicity, all such systems are collectively referred to as 5GDHCS throughout this paper.

As a promising solution to decarbonize future district heating sector, 5GDHCS has been receiving considerable research attention in the past few years. Nevertheless, some fundamental questions concerning its definition, conceptual differences, configuration, operation and control practices, as well as its energy, exergy, and techno-economic competitiveness in comparison with 4GDHS, remain unclear. This paper seeks to track recent advancements in this field, providing a state-of-the-art analysis and offering perspectives on these fundamental questions. In summary, this paper tries to answer the following questions:

Q1: What is the definition of 5GDHCS?
Q2: What are the distinct features of 5GDHCS compared with 4GDHS?
Q3: What is the state-of-the-art progress of 5GDHCS?
Q4: What is the status of practical deployment of 5GDHCS?
Q5: What are the research gaps in existing studies?
Q6: What implications does the development of 5GDHCS bring to the decarbonization of both district heating and electric power sectors?

1.3.2. Paper organization

The remainder of this paper is organized as follows. Section 2 conducts a comprehensive comparison between 5GDHCS and 4GDHS, drawing insights from existing literatures, and engages in a discussion on the definition of 5GDHCS. Section 3 provides an up-to-date review of existing research topics and recent advancements in 5GDHCS. Section 4 identifies research gaps in current studies and delves into potential research questions of interest for future researchers. Section 5 finally concludes this paper by summarizing major findings and key contributions.

2. Comparison between 5GDHCS and 4GDHS

2.1. Drivers and barriers

The popularization of a new technology is never easy - it requires strong drivers from the technological, policy, and social levels, while usually being accompanied by lots of challenges that arise from being forced to leave its current comfort zone. The fourth and fifth generations of district heating technologies are no exceptions. Based on a comprehensive literature survey, possible drivers and barriers of implementing 5GDHCS and 4GDHS are identified and summarized in Table 2, where commonalities and differences between two systems are comparatively displayed.

The promotion of both the fifth and fourth generations of DH is propelled by shared drivers rooted in the commitment to decarbonization, the desire to improve the exploitation of renewable energy and local waste heat, and the motivation to enhance overall energy and exergy efficiencies. However, these objectives are hindered by the absence of regulatory laws, supportive policy frameworks, well-established technical guidelines, and mature market structures. These barriers cast a shadow on the nascent stages of development for both 5GDHCS and 4GDHS, prompting skepticism and uncertainties regarding their social acceptance.

Table 2
A summary of the drivers and barriers for implementing 5GDHCS and 4GDHS.

	Drivers	Barriers
Overlaps in 5GDHCS and 4GDHS	Global commitments to the net zero emissions target [71]. Rising carbon prices [23]. A motivation for integrating more renewable energy in the DH sector [7]. Decoupling of heating and cooling costs from rising prices (including tax) of fossil fuels [72]. A motivation for reducing supply temperatures to reduce heat losses and enhance exergy efficiencies [11,73]. A motivation for saving energy through improved exploitation of local waste heat sources [8,73,74]. Great potential of using local waste heat, e.g., the industrial excess heat was estimated to be able to cover about 17 % of the heating demand of buildings [75]. Sector coupling provides the flexibility from DH systems to electric power systems to enhance grid integration of RES [9,66,71,76]. Geopolitical instabilities encourage energy supply from local energy sources [77].	Nascent stage of development: Lack of guidelines and standards for system design and control [9,31,78], lack of regulatory laws, supportive policies, and markets [66,71,79]. Long payback periods [23]. Barriers to urban waste heat recovery [80,81]: low technical maturity, long payback periods, absence of a legal framework, etc. Uncertainty of user acceptance [66,78,82]: limited knowledge base on the cost effectiveness of the 4/5GDHS [83], complex partnerships and unclear cost-benefit allocation [66,84], the prevalence of cheap natural gas and extensive gas-driven heating solutions in some countries [85]. High investment can be caused by building new or retrofitting existing heating infrastructures [49,90,91], borehole drilling if ground heat is to be utilized [89], etc.
Distinctive points in 5GDHCS	A motivation for electrifying the DH sector at end-users [78]. A growing trend of cooling demand [6,7]. Excess heat from distributed cooling loads in the residential and some small-scale service sectors (e.g., cafés and retailing shops) can be recycled for heating purposes without using a dedicated district cooling network [11,92]. Reduction of urban heat island effect [66,93].	More stress on local electricity distribution networks [94]. High investment can be caused by the installation of distributed heat pumps [78,87]. The costs of heating and cooling depend more on fluctuating electricity prices [72,95,96].
Distinctive points in 4GDHS	A motivation for centrally electrifying the DH sector at sources [7]. Most existing space heating equipment function well with lower supply temperatures (45–60 °C) [97,98].	More stress on higher voltage electricity distribution networks [7]. High investment can be caused by the installation of centralized heat pumps and floor radiant systems [88]. High reliance on versatile renewable and waste heat sources for thermal supply [66].

Electrification serves as a common driver for the development of both 5GDHCS and 4GDHS, but differs in that 5GDHCS focuses primarily on electrifying end-users with the deployment of distributed heat pumps while 4GDHS concentrates more on centralized electrification with centralized heat pumps at sources. Whichever way it may be, electrification aligns with the imperative to reduce GHG emissions in the context of growing heating and cooling demands [6].

On the one hand, a higher level of electrification tightens the coupling between the DH and electric power sectors, fostering greater synergies and interactions. For instance, the thermal storage in the DH sector can offer flexibility services for the power grid, facilitating the integration of more renewable generations through power-to-heat facilities. Additionally, the deployment of distributed heat pumps enables to recycle waste heat from cooling loads for heating purposes, mitigating the urban heat island effect [66].

On the other hand, the massive deployment of electric heat pumps poses challenges such as more stress on the transmission capacity of power lines and increased dependency of heating and cooling costs on fluctuating electricity prices. Specifically, 5GDHCS will put more stress on local distribution electricity networks while 4GDHS will impact primarily on higher voltage distribution electricity networks due to the deployment of large centralized heat pumps. These drawbacks, along with high investment requirements for installing heat pumps, exploiting waste heat sources, and upgrading existing DH infrastructures, present significant barriers to the widespread adoption of both 5GDHCS and 4GDHS.

Noticeably, a distinctive driver of 4GDHS lies in the fact that most existing space heating equipment performs well even with the supply temperatures being under 60 °C, which saves a large amount of investment cost, though the installation cost of floor radiant heating/cooling systems in some outdated buildings and the investment in equipping centralized heat pumps to some low-grade waste heat sources remain necessary. Unlike the highly electrified 5GDHCS, 4GDHS relies more on renewable energy and local waste heat for thermal supply and balancing. The intermittency and uncertainties associated with these sources may pose a threat to the stable operation of DH networks. Overcoming these barriers is crucial for realizing the full potential and promoting the social acceptance of 4GDHS.

2.2. Physical layout and technologies

Despite representing different generations of DH, 5GDHCS and 4GDHS have some commonalities in their physical layouts and adopted technologies. A key similarity lies in their shared capability to integrate a diverse range of renewable and waste heat sources [21,99]. These include geothermal collectors [12,100], solar thermal collectors [101], PV thermal panels [102], industrial surplus heat [30,75], data center waste heat [81,103,104], sewage waste heat [100,105], seawater heat sources [93], supermarket heat recovery [61], low-temperature electrolyzers [106], agrothermal sources [107], and municipal waste incineration [108], etc. Whilst most of these low-grade heat sources can be directly integrated into 5GDHCS, some of them may not meet the required supply temperature level for 4GDHS, necessitating the use of central heat pumps for temperature elevation [7,109,110].

Another significant commonality between 5GDHCS and 4GDHS is the potential to store heat from summer cooling demands and conversely, store cooling energy from winter heating demands. This is facilitated by the deployment of seasonal thermal energy storage at the heat-source side. Key examples of these seasonal TES include aquifer thermal energy storage [11], borehole thermal energy storage [111,112], and frozen soil storages [100].

Nevertheless, throughout different components of the DH system (including the source, network, load, energy storage, and controller), the differences between 5GDHCS and 4GDHS are more pronounced than their similarities [60]. Table 3 provides a detailed comparison of these differences, based on an extensive literature analysis of the physical layouts and technologies utilized by both systems.

Table 3
Differences of the physical layout and technologies in 5GDHCSand 4GDHS.

5GDHCS	4GDHS
Source	
No central heat pumps are needed [9]. Waste heat sources with supply temperatures close to ambient levels can be integrated directly [100,103]. Distributed booster heat pumps are primary heat sources, with renewable and waste heat sources being ancillary contributors [14,99].	May require central heat pumps to elevate the supply temperature of some heat sources to a required level (30–60 °C) [7,109,110]. CHP units and renewable and waste heat sources are primary heat sources [113], with distributed booster heat pumps serving as ancillary contributors [7,8,11].
Network	
The supply temperature is typically lower than 30 °C [37,52]. Weakly insulated or uninsulated pipes can be used [18,77,114]. Smaller temperature difference between the supply and return water causes more pumping costs [9,36,115]. Freely floating temperatures in networks [116]. Usually being community-scale systems with heating radius less than 2 km (possibly due to high pumping costs) [9,10]. Can use one to four pipes to form different network topology [9].	The supply temperature is as close to the actual temperature demand of end-users as possible, at a maximum of 70 °C [11,110,117]. Insulated pipes are still needed [9,11,31]. The temperature difference between the supply and return water can be similar to 3GDHS [8]. Lower heat losses compared with 3GDHS, yet higher losses than 5GDHCS [11]. Usually being regional-scale/community-scale systems with heating radius less than 5 km (due to low supply temperature) [7,8]. Network usually contains two pipes to form radical, looped, or meshed topology [8].
Load	
Has booster substations with distributed water-source heat pumps installed at end-users [9,42,56,118,119]. Can provide both heating and cooling services simultaneously [9,99]. Consumers become prosumers [86]. The extracted heat from distributed cooling demands in the residential and some small-scale service sectors (e.g., cafés and retailing shops) can be recycled for heating purposes without using a dedicated district cooling network [9,19]. Booster heat pumps can elevate the supply temperature to over 60 °C [56,120] to meet the comfort and safety requirements [8] of domestic hot water supply, allowing existing building heat exchangers to be retained. Built-in cooling is enabled with no additional capital costs [121].	Instantaneous heat exchangers, electric heat tracing systems, or micro heat pumps may be needed at loads to meet the requirements of the domestic hot water [8,122]. Usually provides heating services only, but can supply both heating and cooling energy through separate distribution networks [11,123]. Most existing building heat exchangers can be retained, but floor radiant heating systems are needed in some situations [21,88]. The thermal length of heat exchangers is likely to be doubled compared to existing situations [8]. Needs separate plants for cooling and requires additional space and capital costs [121].
Energy storage	
TES is only applicable at the source or load sides due to low sensible storage densities caused by low temperature range in the network [124].	TES can be deployed at source, network or load sides, with higher sensible storage densities than those in 5GDHCS [112].
Controller	
Requires more complex controls for booster substations [53,120], and for the network due to bidirectional mass and energy flows [9,53].	Requires more complex controls for central heat pumps acting as heating or cooling sources for district heating or cooling networks [11].

A notable difference at the source side is the prominent role of distributed booster heat pumps in 5GDHCS, where they serve as the primary heat sources. In contrast, renewable and waste heat sources play a secondary role. This strategic deployment allows for a significant reduction in supply temperature, from the 30° to 60 °C range typical of 4GDHS, to levels closer to the ambient temperature, usually below 30 °C [37,52]. Consequently, the use of weakly insulated or even uninsulated pipes, along with the freely floating temperatures in both warm and cold pipes, emerges as a unique feature of 5GDHCS.

Distributed booster heat pumps can also effectively serve as balancing units during operation. Specifically, when heating and cooling demands increase, these distributed booster heat pumps will increase their power outputs accordingly by converting more electricity into heat or cooling. Conversely, when heating and cooling demands decrease, these heat pumps will adjust in the opposite direction. Since these distributed heat pumps are located much closer to end-users than central ones, they are able to balance demands more quickly.

On the load side, the deployment of distributed heat pumps transforms traditional consumers into active prosumers. This approach also elevates the supply temperature to levels that satisfy the comfort and safety requirements of domestic hot water supply, allowing existing building heat exchangers to be retained. In contrast, some outdated buildings in 4GDHS may require retrofitting with floor radiant heating or cooling systems when the supply temperature drops below 45 °C.

2.3. *Energy, exergy, environmental, and techno-economic performances*

Comparing the energy, exergy, environmental, and techno-economic performances of 5GDHCS and 4GDHS is a challenging task due to the influence of numerous uncertain factors including future demand levels, fluctuations in fuel/electricity/facility prices, and varying tax and subsidies. The results and conclusions can vary significantly from country to country under different policy, economic, and technical backgrounds. Some studies have explored this area, but often reach divergent (or even conflicting) conclusions based on case-specific analysis. Due to the lack of general conclusions regarding their performances, Table 4 summarizes specific findings from each single study, providing a performance comparison between the two systems. It categorizes the results into two groups: those indicating 5GDHCS outweighs 4GDHS, and those suggesting the opposite.

Some studies have quantitively investigated the heat losses of 5GDHCS, where both insulated ([21,67,95]) and uninsulated pipes ([18,92]) are seen to be used. Results in Ref. [67] suggest that the average heat loss per meter in 5GDHCS is 1.19 W/m (much fewer than that in 4GDHS (7.3 W/m)), accounting for around 1.7 % of the total delivered heat. It is concluded in Ref. [115] that the heat losses of 4GDHS account for 3–7% of the total supplied heat, while those of 5GDHCS are negligible due to low operating temperatures and good heat insulation. Results in Ref. [92] show that annually the uninsulated pipes in 5GDHCS have about 11 % heat losses of the total carried heat. The calculation in Ref. [21] indicates that the annual heat losses account for around 2.7 % of the total consumed heat. While these studies focus on analyzing heat losses in some specific cases, there still lacks a clearly-defined acceptable threshold for the heat loss share of 5GDHCS compared to its total energy delivery.

From the perspective of energy efficiency, 5GDHCS performs better in terms of its near-zero heat losses, but this edge is somewhat offset by the higher energy consumption for pumping caused by smaller temperature difference between the supply and return water [9,131,132]. Determining which factor of the two more significantly impacts the system efficiency requires specific analysis for each specific case. There is also ambiguity in the annual or seasonal coefficient of performances of both systems, which are usually determined by the energy performance of individual components. Questions about how the COPs of central and distributed heat pumps are affected by equipment size and operating conditions [133], which type of heat pump has a higher COP [134], and

Table 4
A summary of key conclusions from related studies.

Aspect	5GDHCS outweighs 4GDHS	4GDHS outweighs 5GDHCS
Energy	The proposed 5GDHCS has a larger annual coefficient of performance (COP) than 4GDHS [125]. 5GDHCS reduces about 83 % of the annual heat losses in 4GDHS [67]. The heat losses of 5GDHCS are negligible, while those of 4GDHS accounts for 3–7 % of the total supplied heat [115].	4GDHS has a slightly higher distribution energy efficiency than 5GDHCS [126]. The primary energy saving of 4GDHS is 16 % higher than that of 5GDHCS [127]. The annual pumping energy of 5GDHCS is about 2.5 times more than that of 4GDHS [67]. The pumping energy of 4GDHS is 1 %–2 % of the total supplied heat, while that of 5GDHCSaccounts for 2 %–3 % [115].
Exergy	The proposed 5GDHCS has a larger annual product exergy efficiency than 4GDHS [125].	The exergy efficiency of 4GDHS is about 5 %–10 % higher than that of 5GDHCS [126]. 4GDHS has a higher exergy efficiency than 5GDHCSin the studied case [94].
Environmental	5GDHCS saves more CO_2 emissions than 4GDHS [121].	4GDHS can reduce 11 % more CO_2 emissions than 5GDHCS [127]. 4GDHS can reduce more GHG emissions than 5GDHCS in the studied case [94].
Techno-economic	Compared with 4GDHS, the proposed 5GDHCS can reduce the heating cost by around \$0.6/GJ and shorten the payback period by about 2.4 years [125]. The annual operation cost of 5GDHCS is about 68 % of that of 4GDHS [126]. 5GDHCShas a higher internal rate of return than 4GDHS when heating and cooling demands coexist [121]. The system cost of 5GDCHS becomes lower than that of 4GDHS when the cooling demand ratio rises to 27 % [128].	4GDHS has a lower levelized cost of heat (LCOH) for both the UK and Denmark due to the economy of scale obtained by centralized heat generations [18,50]. The LCOH of 5GDHCS is 34.28 % higher than that of 4GDHS [96]. The 4GDCS has a higher internal rate of return than 5GDHCS when the demand is dominantly heating [121]. The system cost of 4GDHS is lower than that of 5GDHCS considering the cooling demand only accounts for 3 % of the total demand [128]. The LCOH and socio-economic net present value of 4GDHS are more economically preferred than 5GDHCS in most cases [129]. 4GDHS has a lower LCOH than 5GDHCS in the studied case [94].
Others	The peak power demand in 5GDHCS is only one-third of that in 4GDHS because central heat pumps lift the supply temperatures for all heating demands [130].	The electricity demand of 5GDHCS is generally higher than that of 4GDHS in winter due to lower supply temperatures [130]. Water congestion is more likely to occur in 5GDHCS due to larger flow rates [73].

Table 5
A summary of existing definitions of 5GDHCS.

Reference	Definition of 5GDHCS
[9]	*"A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with water source heat pumps. It operates at temperatures so close to the ground that it is not suitable for direct heating purpose."*
[42]	*"A system for distributing cold water in a temperature range between 10°C and 25°C to end-users' substations where it is used to produce, also simultaneously, hot and cold water at different temperatures and for different purposes (space heating, cooling, DHW production) via heat pumps and chillers."*
[112]	*"A 5GDHC system, in terms of technology, provides cold and heat supply at temperatures near the ground via the same transmission pipeline while also controlling the temperature of the receiving water flow on-site to the appropriate level."*
[135]	*"The 5GDHCS is an advanced and sustainable urban energy system working at near-ground temperatures and allow for bi-directional exchange of heat and cold between connected buildings, facilitated by seasonal storage."*
[136]	*"In its most simplified generic form, the 5GDHCS harnesses the shared energy concept which is realized in a network that connects 'prosumers'."*

which DH generation has a higher overall energy efficiency, all point to a need for further experimental studies and quantitative comparison.

The environmental performance of both systems is typically evaluated by CO_2 or GHG emissions. Different case studies yield contradictory results due to varying system configurations [94,121,127]. These discrepancies underscore the need for a standard library of recognized system configurations and simulation scenarios to enable more convincing comparative analysis of 5GDHCS and 4GDHS.

As for the techno-economic performance of both systems, indicators such as levelized cost of heat, annual operation cost, payback period, internal rate of return, and socio-economic net present value, are commonly adopted in existing literatures. Similar problems arise here as in the evaluation of environmental performance – contradictory results from different studies necessitate the establishment of a standard case library. Additionally, these indicators, often used selectively in different studies, provide a limited view of the systems' features. The selection of a suitable heating/cooling technology should require a more comprehensive performance analysis, encompassing both corroborating and conflicting indicators.

Those different findings in Table 4 suggest that there is no consensus on what is the "best" technology, as "best" is dependent on local conditions. Whether it is 4GDHS, 5GDHCS, or other individual solutions, it can achieve the best performances in some specific conditions. Therefore, there needs to be more overall studies to identify what conditions are more favorable for a specific technology and what the dominant next generation of DH technologies would be.

2.4. Discussion

Based on the above literature survey and comparative analysis, it appears that a consensus has emerged regarding the key features of 5GDHCS, which include a) operating at network temperatures close to ambient levels; b) the deployment of distributed heat pumps at the end-user side; and c) the capability to provide both heating and cooling services. Several definitions of 5GDHCS found in existing literatures further support this consensus, as detailed in Table 5.

However, there are some key points worth further exploration. One such aspect is to limit the network temperatures of 5GDHCS to near-ambient levels. It should be noted that there is no consensus on the exact temperature range of "near ambient" in existing literatures. Any network temperature falls within the range of 0–45 °C can be deemed as acceptable for 5GDHCS in some certain literatures [9,20,50,173]. The network temperature being below 30 °C is not a strict constraint. Rather, it is only adopted in this paper as a general quantitative description and some margins of variation can surely occur in different local conditions and operation modes. The network temperature in most studies refer to both supply and return temperatures because heating and cooling are realized through one set of pipelines in 5GDHCS. A few studies ([50,64]) impose a constraint on the supply temperature only, while only one suggesting a range of 8–16 °C for the constraint on the return temperature. Although the lower threshold of network temperatures in most studies ranges from 0 to 20 °C, a potential problem related to near-ambient network temperatures is that in some extremely cold regions, the temperature of return water in pipes may drop below its freezing point. How to tackle the icing issues remains a technical challenge for 5GDHCS. Given that the network temperatures of 5GDHCS will change in summer and winter modes and in the process of transporting available peak waste heat [93,117,174,206], it should not be a mandatory condition to keep network temperatures fixed in 5GDHC systems.

If the supply temperature is really close to the ambient temperature, simply using individual water-source heat pumps with water from the water distribution system might be a better option as constructing new heating pipelines can cost more than simply upgrading existing water distribution systems. Besides, limiting the network temperatures to near-ambient levels would inevitably cause the down gradation of some waste heat sources throwing away heat at higher temperature levels, such as small-scale CHP units and some industrial surplus heat sources. Worse still, this practice will also lead to smaller difference between the supply and return temperatures [9], which will not only increase the mass flow rate in networks, causing higher pumping energy consumption, but also necessitate larger pipe diameters and increased network investment. While it is true that restricting the network temperature down to ambient levels minimizes heat losses, the system's energy and economic efficiencies do not necessarily improve in tandem with lowering supply temperatures. Given above challenges, a more comprehensive analysis is essential to justify the practice of lowering network temperatures to near-ambient levels.

Another aspect is the choice between uninsulated and insulated pipes in 5GDHCS. Since heat losses are inevitable whenever the supply temperature is above the ambient temperature, insulated pipes can save more heat losses than uninsulated ones in any case. Over time, the initial cost of installing insulated pipes could be offset by the continual energy savings they provide. In high-temperature heating networks, enhancing insulation levels might offer marginal benefits due to technical challenges and economic considerations. However, in low-temperature networks, the use of insulated or weakly-insulated pipes could be a more viable and energy-efficient choice considering its long-term energy saving benefits.

Based on the above analysis, the essential differences of 5GDHCS from previous generations of DH systems are highlighted by two significant role transitions at both the source and demand sides that fundamentally renovate the pattern of district heating:

- At the source side, distributed electrified facilities installed at end-users become the **primary** sources to provide both heating and cooling services, relegating traditional centralized or non-electric sources to **secondary** roles.
- At the demand side, distributed active heating/cooling facilities shift from traditional consumers to active prosumers [121], enabling heat/cooling transactions among end-users within a community. This minimizes local energy waste and paves the way for new business models that can improve the allocation efficiency of overall social resources.

The role transition at the source side fundamentally sets 5GDHCS apart from 4GDHS – building-level electrification is predominant in 5GDHCS while 4GDHS focuses primarily on centralized electrification at sources. Both central heat sources (such as CHP units and central heat pumps) and distributed heat pumps can exist in either system, yet the classification of each system depends on which type of sources account for the majority of heating/cooling demands. Based on existing studies, both 5GDHCS and 4GDHS have the potential to achieve superior energy, exergy, environmental, or techno-economic performance, depending on the specific application scenario. 5GDHCS is not necessarily a replacement for 4GDHS; rather, they can coexist and complement each other in a wide range of application cases [11,68].

In light of this, an updated definition for 5GDHCS, emphasizing its key characteristics, is proposed as follows:

> "The 5GDHCS is a category of district heating and cooling systems that a) have distributed electrified facilities (e.g., water-source heat pumps and water-cooled compression chillers [137]) installed at end-user sites acting as **dominant** heating/cooling sources to provide both heating and cooling services; and b) can efficiently recycle and distribute heat and cooling energy from a variety of **auxiliary** renewable and waste heat sources through district heating networks operated at low temperatures levels."

It is important to recognize that the temperature level should not be a rigid constraint for 5GDHCS as the "close-to-the-ambient" level might not always be economically viable or preferred. Notably, systems primarily utilizing individual heat pumps/air-conditioners as heating/cooling sources should not be classified into 5GDHCS as they fall out of the basic scope of "district heating" – they do not require a heating/cooling network to deliver heat/cooling and should belong to the "individual heating" group. Neither should systems with absorption heat pumps or chillers [138] as dominant sources fall within the scope of 5GDHCS as they are not electrically driven. Looking forward, a potential progression of the DH generation might involve hydrogen-driven solutions in the future.

Another topic to consider is the competition between 5GDHCS and individual heat pump solutions. When the supply water temperature is higher than the ambient air temperature, water-source heat pumps in 5GDHCS typically have a higher COP compared with individual air-source heat pumps. However, as the supply water temperatures in 5GDHCS approach ambient levels, the energy efficiency advantage of water-source heat pumps diminishes significantly. Therefore, the choice between 5GDHCS and individual heat pump solutions needs careful reconsideration, especially given that 5GDHCS generally incurs higher upfront costs caused by network construction.

3. State-of-the-art analysis of 5GDHCS

3.1. Landscape of publications

This literature review was conducted within the PSALSAR framework [139], encompassing six basic steps: protocol, search, appraisal, synthesis, analysis, and report. Three databases (Web of Science Core Collections, Scopus, and CNKI) were used to search for the publications related to 5GDHCS. The search initially targeted publications containing the terms "fifth generation heating", "5th generation heating", and "5GDH" within the title, abstract, keywords, and main body. These were first collected and then screened based on the criterion of publication year post-2014. Subsequently, the remaining articles underwent a manual screening process, involving a review of their abstracts to ascertain their relevance to the specified topic. Finally, a snowballing method was applied to analyze the references within these selected publications to uncover other pertinent items. In total, this process yielded 149 publications, comprising 122 journal articles, 19 conference papers, 3 technical reports, 2 dissertations, and 2 book chapters.

The temporal distribution of publications is illustrated in Fig. 3, accompanied by the three-point moving averages [140] of this dataset (depicted by the grey solid curve) to show a smooth changing trend. The

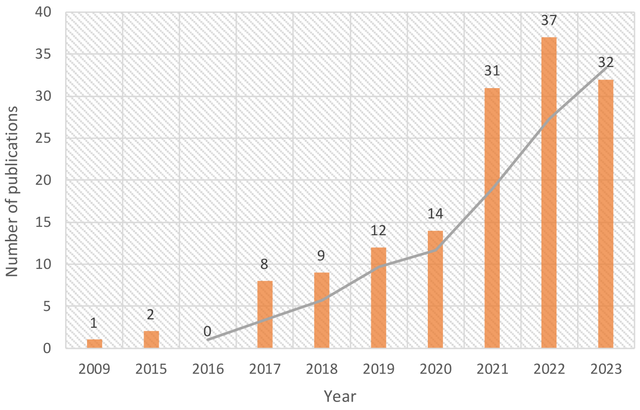

Fig. 3. Number of publications over time.

first publication on this topic was in 2009, found in the snowballing process. Since then, the number of publications maintained at a quite low level until 2016. From 2017, this number rose steadily each year and further witnessed a steep growth in the latest three years - more than 30 items have been published annually since 2021. This publication trend shows in a way that this topic has been receiving increasing research attention since 2017 and has arrived at a new level in the latest three years. Given the rapid development of this field, further review efforts are essential to comprehensively document and understand the latest advancement.

The spatial distribution of publishing affiliations is illustrated in Fig. 4. Affiliations in a total of 26 countries have contributed a share, spreading across North America, Europe, Asia, and Oceania. This indicates a global research landscape is taking shape in this field. The top ten countries leading in publication volume are presented in Fig. 5, where European countries are dominating the list, including Germany, Sweden, the UK, Italy, Denmark, Switzerland, Austria, and Spain. Despite faced with unique challenges in district heating posed by their vast territories, China and the USA have also demonstrated significant engagement in this research area, contributing 14 and 12 publications, respectively.

3.2. Design and planning

Being at its nascent stage of development, the problem of design and planning remains a fundamental barrier for the widespread adoption of 5GDHCS in most areas [9,17]. In existing literatures, designing and planning a 5GDHCS usually focus on two different tasks: a) creating a system from scratch; and b) retrofitting part of an existing DH system, such as heat sources, networks, or booster substations, to upgrade it into a 5GDHCS. Whist existing studies have made noteworthy progress in exploring these tasks, a well-recognized design guideline offering mature solutions for most existing scenarios is still in the process of development [99].

Recent progress in this topic is summarized in Table 6. A critical initial step in the design and planning process is the characterization of heating and cooling demands, for which the Demand Overlap Coefficient is commonly utilized to describe the proportion of heating and cooling demands that can be internally balanced within and among buildings [141,142]. This information is crucial as the economic viability of 5GDHCS has been reported to be closely linked to the Demand Overlap Coefficient [142]. Additionally, there have been significant efforts to develop geospatial representations of heating and cooling demands, as well as potential supply sources [143], commonly referred to as an “energy atlas”, for future DH systems [8,144]. This includes the tasks of quantifying the growing trend in demands, assessing the availability of waste heat resources, and evaluating the potential for renewable energy integration, all of which are vital for supporting the design and planning of future DH infrastructures.

A significant portion of these studies focus on the problems of network configuration and optimization. The number of pipes, topology, and the connection with buildings and waste heat sources are all investigated and optimized to achieve better energy and economic efficiencies, usually facilitated by acknowledged deterministic or heuristic optimization algorithms [145,150]. As the integration of renewable energy continues to grow, the importance of robust network design under multiple uncertainties becomes more pronounced [157]. The rest studies concentrate either on the optimal selection and sizing of equipment, or on the system-scale design and planning using holistic methods. It is noteworthy that a step-by-step technical design framework is developed in Ref. [164], where a straightforward bottom-up approach is employed, starting from matching customers locally before proceeding to determine the network topology and pipe size, and finally setting up pump configurations. However, this framework does not fully address the impact of uncertainties on the design process, and lacks considerations on optimizing the design of each system component.

The process of designing and planning a 5GDHCS engages a diverse group of stakeholders, each with distinct considerations and interests [157]. Developing technical solutions that not only balance these varied interests but also align with social and political acceptance remains a significant challenge and requires continued research efforts in the future [166].

3.3. Operation and control

Beyond the initial stage of design and planning, the operation and control strategies become critical in determining system energy, exergy, environmental and economic performances. Optimal operation and control, aiming to enhance one or several aspects of system performances through optimized management and delicately control of system dispatchable resources (including distributed heat pumps, adjustable heat sources, TESs, network temperatures, mass flow rates, and adjustable loads, etc.), has been an important research topic [9,167,168].

Recent progress in this topic is summarized in Table 7. Generally, operation optimization studies can be classified into two categories according to the timescale of focus: a) the long-term operation that aims to optimize system performances over extended periods such as a week, a month, a year, or even the entire life cycle; b) the short-term operation that focuses on optimizing system performances within a single day, which typically includes the day-ahead optimization [169] and the intra-day real-time optimization [53,120,170].

Both long-term and short-term operation optimizations can strive for

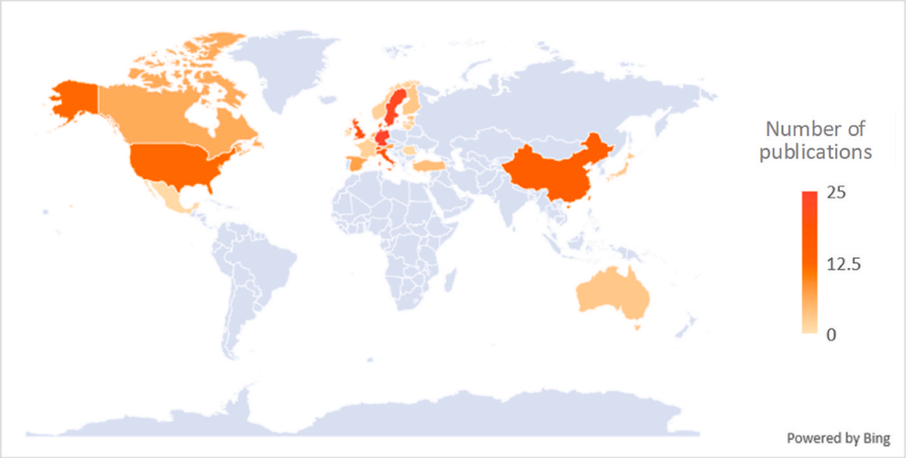

Fig. 4. Geographic distribution of publishing affiliations.

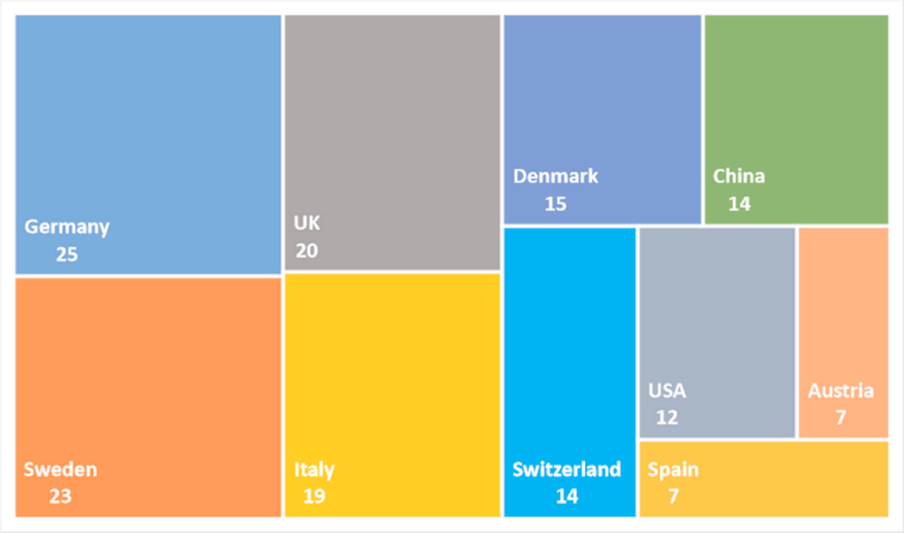

Fig. 5. Number of publications in the top ten countries.

one or multiple objectives of reducing the peak electric power consumption [115], minimizing CO_2 or GHG emissions [39,170,171], and minimizing operation costs [39,53,120,169,170]. In the future, optimizing energy and exergy efficiencies of such systems may also emerge as a focus in certain scenarios. A notable aspect of these studies lies in the strategic utilization of the flexibility of TES and the thermal inertial of DH network to provide additional optimization room for reducing operation costs [169]. The exploitation of flexibility resources from the DH sector offers a cost-effective way to enhance grid integration of renewable generations and increase system overall energy and economic efficiencies [9,66]. With appropriate demand-response programs, distributed heat pumps within 5GDHCS are expected to play a pivotal role in realizing this potential.

A practical barrier hindering system optimization is the lack of reliable information on capital and operational expenditures due to only a limited number of systems in operation [99]. Looking forward, there is a pressing need for the development of robust optimization tools that are capable of handling multiple uncertainties, including variations in cost parameters, electricity prices, outputs from RES, and fluctuating heating/cooling demands.

It is anticipated that bidirectional mass and energy flows in 5GDHCS would require more complex control strategies [9,53], yet few studies have covered this topic. For each component in 5GDHCS, especially for the network and booster substations, key areas including the deployment of physical controllers, the design of control algorithms, and the assessment of their effectiveness in managing these complex systems call for more in-depth theoretical and experimental explorations.

The “bidirectionality” represents an ability of a pipeline to change the direction of energy flows between its connected end-user and the network [9], which is crucial to enable the peer-to-peer energy exchange among different prosumers in 5GDHCS. However, existing studies lack quantitative analysis on this topic. Key questions remain unanswered, such as how to define the relevant parameters, which metrics should be used, and in which units? Is merely counting the number of flips sufficient, or should the analysis be capacity- and/or power-weighted? These questions highlight the need for more detailed quantitative studies. Overall, the topic of peer-to-peer energy sharing in 5GDHCS is still in its nascent stage. More efforts are needed to quantitively explore its potential benefits and to establish a sound market for its development.

Noticeably, peer-to-peer energy exchange is not the only trading way in 5GDHCS. Each prosumer can still purchase heating/cooling from (or sell to) the network operator centrally. If the peer-to-peer energy exchange strategy implies no energy exchange at night, it means the prosumers in this system are either each self-contained or have achieved a balance through trading with the network operator in the central heating market. In the first scenario, there will be some idle pipelines, and the water in these idle pipelines may cool down due to no energy exchange will occur. This is a normal operational condition in 5GDHCS and should not be a significant concern for the following reason:

Heat losses in these idle pipelines will occur anyway even they are actively in use. Considering the network temperatures in 5GDHCS are already very low, this part of heat losses should not count too much, and those cooled water can still be used to generate heat as its temperature remains much higher than the temperature of the liquid refrigerant in the evaporator of heat pumps.

3.4. Simulation and performance analysis

3.4.1. Simulation models and software

Digital simulation is one of the most cost-effective ways to test and analyze modern energy systems, offering an efficient tool for evaluating the system energy, exergy, environmental, and economic performances. Mathematical models, either derived from physical laws or developed through data training, are at the core of simulation. In existing 5GDHCS studies, key component models used for performance analysis typically fall within two categories: self-developed models and software-based models. In the first category, authors establish equations or input-output relationships based on their understanding of the target component, while in the second category pre-developed models in existing software are simply adopted for analysis. A compact summary of key component models in the 5GDHCS-related studies is presented in Table 8, organized according to these two categories.

Models of a wide range of components covering sources, networks, loads, typical conversion units, and storage equipment have been well investigated in existing literatures, where both the self-developed and software-based modeling approaches are extensively adopted. Popular software like TRNSYS and Modelica are mainstream choices, offering comprehensive simulation support for almost every link of 5GDHCS. Other software, such as Polysun, energyPro, IDA ICE, Fluidit Heat, and Netsim, also demonstrate effective performances in simulating specific system components. Notably, the complexity of 5GDHCS sometimes requires a joint use of multiple software [136], each tailored for different components. This co-simulation framework necessitates the use of some connecting tools including the Building Controls Virtual Test Bed [136,187], the Functional Mock-up Unit [136,188] or some Python-based programs [184].

Table 6
A summary of the studies related to design and planning of 5GDHCS.

Sub-topic	Summary
Characterization of heating or cooling demands	The demand overlap coefficient is utilized as a practical metric during the planning phase to identify and cluster complementary demand profiles [142]. The distributions of overlapping heating and cooling demands across Europe are assessed, and potential areas for planning a 5GDHC are identified [141]. A partitioned clustering method is proposed to categorize typical demands and group together specific days with similar demand profiles [145]. A web-based tool, named nPro, is developed to generate customized profiles of heating and cooling loads for the conceptual design of 5GDHCS [146]. The energy atlas with the information of demand levels and waste heat resources for system planning are reviewed and studied [8,144]. A hybrid machine-learning method is proposed to forecast the heating load of clustered buildings [147]. A parameterized residential demands for any city in Europe is estimated [108]. A piecewise stochastic method with linear regression techniques is used to generate artificial demand data for robust design of 5GDHCS [69]. Advice for retrofitting buildings via thermal efficiency investigations is given [148].
Network configuration	Two network structures, i.e., the double-pipe and single-pipe (reservoir network), are compared in terms of the economic efficiency and freedom of expansion [70]. Main factors affecting heat losses are investigated, and a duo-pipe configuration with an optimized U-value is proposed to reduce losses by up to 60 % [149]. The optimal network configuration is obtained with a mixed integer linear programming (MILP) program [145]. A new technique involving alternating the connection of expansion vessels in the network is proposed to reduce the hydraulic pressure and operation costs [91]. Network topology optimization using the minimal spanning tree heuristic [150]. The performance of networks with CO_2 refrigerant as the heat-transport medium is evaluated [151,152]. The optimal connection of buildings to the heating network is studied [153–155]. The optimal design of new DH networks connected to the industrial waste heat is achieved through a routing algorithm based a multi-step method [156]. Optimization methods assisting the robust network design under multiple uncertainties are reviewed and discussed [157]. Six different groups of typical network configurations are identified [15,23,158]. Classifications of networks are provided based on the number of pipes, bidirectional/unidirectional energy and mass flows, and open/closed loop [9].
Optimal selection and sizing of sources and equipment	Design optimization of the solar thermal field for a given 5GDHCS is investigated to improve the system energy efficiency [159]. The integration of low-grade waste heat is optimized [160]. Optimal selection of components in a 5GDHCS is achieved based on the MILP [94]. Configurations of the booster substation are reviewed [42,119]. Optimal selection of heat pumps and long-term/short-term TES is studied [161]. The positioning of heat pumps are optimized [160]. The design of a booster substation and the optimal selection of the refrigerant for heat pumps are presented in detail [56]. Optimal selection and sizing of energy conversion units are realized using a linear programming method [52].
System-scale design and planning	The generation and optimization of system configurations for 5GDHCS are realized using the 'Smart Urban Isle' approach [162]. A holistic co-design methodology involving technical, commercial and stakeholder's considerations is proposed [163]. Different system configurations for decarbonizing China's heating sector are developed and compared [64]. A step-by-step design guide of 5GDHCS is provided [164]. Two multi-period methods for optimal design of the 5GDHC are compared [165]. The optimal system configuration and supply temperature are determined [59]. A system planning framework with a Dantzig-Wolfe approach is proposed [51].

Table 7
A summary of the studies related to operation and control of 5GDHCS.

Sub-topic	Summary
Long-term operation optimization	A yearly operation optimization to reduce the consumed peak electric power [115]. A yearly optimal operation with a nonlinear programming method to minimize CO_2 emissions [171]. A yearly optimization using a MILP method to reduce CO_2 emissions and operation costs [39].
Short-term operation optimization	Multi-objective rolling optimization to determine the real-time supply temperature, with the goal of minimizing operation costs and GHG emissions [170]. Real-time rolling optimization within a day to minimize costs [120]. Day-ahead optimization with a mixed-integer quadratically-constrained program, using the thermal inertial of heating sector to minimize operation costs [169]. An economic MPC optimization model proposed to minimize operation costs [53].
Control strategy	A summary of the control approaches applied to the TES interacting with 5GDHCS, including on/off, PID, rule-based, and MPC controllers [109]. A review on advanced central, distributed and hybrid control in DH networks [168]. A discussion on basic and advanced control strategies of 5GDHCS, including MPC and machine learning algorithms [9,167]. The integration of an optimized temperature control and an on/off control for the operation of distributed heat pumps to reduce the peak electric power [115]. A comparison between a proposed MPC controller based on recurrent artificial neural networks and a rule-based controller in terms of energy savings [172]. A combination of the temperature set-point optimization and agent-based control to allow for the modular integration of multiple sources and consumers [37].

For those self-developed models, most of them are equation-based physical models, but the use of data-driven methods to generate meta-models employing statistical and artificial intelligence algorithms is gaining growing popularity [189]. It should also be noted that some self-developed models are deployed through software like MATLAB [173,183,191], Modelica [92,174,190], TEGSim [182], and Carnot Toolbox [179] to standardize their codes and improve their applicability for a more general scope of use. In the future, there is an increasing need

Table 8
A summary of the adopted simulation models and software in the 5GDHCS studies.

	Self-developed model	Software-based model
Source	Ground-source station [59]. Borehole heat exchanger [173,174]. Air-source heat pump [92]. Cooling tower [92,174]. Surface water heat transfer coil [174].	Borehole heat exchanger in TRNSYS [175]. Solar thermal collector in TRNSYS [175] and Polysun [21]. Ground-/seawater-/air-source central heat pump in energyPRO [14,62], IDA ICE [55], Modelica [176], and TRNSYS [177].
Network	Steady-state model [48,59,92,178–180]. Dynamic model [48,114,157,181,182]. Storage pipe model [183].	Heating network in TRNSYS [175,184], Simulink [22], Modelica [128,153,185,186], and Fluidit Heat [184]. Joint simulation of multiple software: Building Controls Virtual Test Bed [136,187], Functional Mock-up Unit [136,188], and Python [184].
Load	Building heating/cooling system [59,134,174,183,189]. Prosumer substation [60,92]. Building thermal battery model for prosumers and buildings [68].	Building heating/cooling system in TRNSYS [175,177], Modelica [136,153,166,176,185], Polysun [21], Simulink [22], and IDA ICE [55]. Hourly demand profile in BAGEL [186].
Other equipment	Water-source heat pump [59,60,134,173,174,182,190]. Dual-loop booster heat pump [191]. TES: buffer tank storage [59], a general model of TES [60], accumulator tank [92], and borehole TES [182]. Heat exchanger [59,173,182,183,190]. Circulation pump [59,60,182,190]. Electric compression chiller [134,190].	Water-source heat pump in TRNSYS [54,127,175,177,184], Modelica [55,166,176,185,186], Polysun [21], Simulink [22,173], energyPRO [62], and NetSim [117]. TES: Stand-by and buffer TES in TRNSYS [175], aquifer TES in energyPRO [14], and domestic hot-water tank in Polysun [21]. Heat exchanger in TRNSYS [175] and Modelica [176,186]. Circulation pump in Modelica [176], Polysun [36], and TRNSYS [184]. Electric compression chiller in Modelica [185].

for continued research in developing more accurate equation-based and data-driven models capable of simulating different case scenarios [48,86].

3.4.2. Performance analysis through system simulation and monitoring

The majority of the 5GDHCS-related studies focus on performance analysis through system simulation. The typical methodology involves several key steps: a) determining the target system; b) gathering input information such as network parameters and demand profiles; c) establishing component models; d) defining performance indicators; e) conducting simulations and sensitivity analysis; and f) drawing conclusions. Key performance indicators in Step d) often cover a wide range of aspects, from system energy and exergy efficiencies to environmental and economic factors, as well as the capabilities to promote RES integration and shift peak power demands in power systems.

Most conclusions in these studies are derived from specific case studies under particular scenarios and are influenced by various factors. Table 9 presents a summary of these key conclusions and influencing factors. It is worth noting that some of these studies conduct performance analysis based on the real operation data of existing systems [36,38,44,45,47,57,192], but due to the scarcity of such real-life systems, they only represent only a small fraction of the research in this field.

Among all aspects of system performance, there has been a consensus on the improved environmental efficiency and increased share of RES in 5GDHCS compared with other selected DH solutions in these studies. However, when it comes to other performance aspects, studies present diverged conclusions. Some studies indicate that 5GDHCS outperforms other selected DH solutions in terms of energy, exergy, and techno-economic efficiencies, as well as offering better synergy with the power grid by providing more operational reserve and by reducing peak power demands. On the contrary, other studies, based on different case systems and scenarios, arrive at opposite conclusions.

Furthermore, a number of studies suggest that results can vary significantly depending on certain influencing factors. These include technical and economic parameters of some system components, the composition of energy demands, and external factors such as economic policies and subsidies, etc.

Providing a comprehensive and unbiased performance assessment for 5GDHCS is a complex task due to multiple influencing factors. Challenges such as developing comprehensive evaluation frameworks tailored to different stakeholders, acquiring accurate component parameters, dealing with future uncertainties, and establishing a standard library encompassing recognized system configurations and simulation scenarios, all call for continued and dedicated research efforts in this field.

Table 9
Key conclusions and influencing factors in the performance analysis studies.

Aspect	Conclusion	Influencing factor
Energy	Better energy efficiency than some selected DH solutions [21,38,39,54,57,77,92,125,150,175–177,180,183,186,190–192]. Worse energy efficiency than some selected DH solutions [126]. Better or worse energy efficiency depending on the boundary conditions [44,55,185,193].	Network temperature [186,190,191]. Deployment of direct cooling heat exchangers [176,190] and heat recovery systems [194]. Exploitation of renewable heat sources [77,195,196] and building retrofitting [194]. Composition of energy demands [55,185]. Temperature levels required by end-users [47,185].
Exergy	Better exergy efficiency than some selected DH solutions [119]. Worse exergy efficiency than some selected DH solutions [126].	Network temperature [119,126]. Flow rate in the network [119].
Environmental	Better environmental efficiency than some selected DH solutions [14,21,46,54,117,173–175,177,180,192,194,195,197,198].	Ratio of cooling demand to heating [197]. Use of renewable heat sources [195]. Operation mode of heat sources [174]. Capacity of system TES [47].
Techno-economic	Better economic efficiency than some selected DH solutions [14,59,60,77,92,125,173,194,197,199–202]. Worse economic efficiency than some selected DH solutions [18,65,179,203]. Better or worse economic efficiency depending on the boundary conditions [62,83,89,204].	Economic policies [179], demand response programs [205], energy sharing [200], discount rate and electricity price [184,200], and cost of renewable and waste heat sources [65,77,206]. Ratio of cooling demand to heating [83,89], area demand density [83], and area temperate climate [204]. The sizes of TES [200,207] and heat pumps [201]. Nominal network temperature difference [202], indoor set-point temperature [47], and the temperature of heat sources [18].
Others	Increase the share of RES [82,194]. Better interaction with the power grid [58,130,205,208,209]. More stress on power systems [203].	Fossil fuel tax [82]. Subsidies for RES technologies [82]. Demand response programs [205].

3.5. Research projects and real-life systems

Research projects and pilot case systems are essential steps in the lifecycle of new technologies, providing critical insights, testing, and refinement opportunities. In existing literatures, some efforts have been devoted to collecting and analyzing research projects and real-life systems. These endeavors include a website listing 5GDHCS-related publications and research projects [109], a review paper summarizing real-life systems across Europe [9], and an academic article focusing on updating these practical systems in Germany [10]. However, there is a growing body of newly published studies mentioning additional research projects and systems in operation that was not covered by previous studies.

To present a more comprehensive picture of the current status of 5GDHCS-related research and implementation, this section collects information of related research projects and real-life cases from a wider scope of literatures and provides a general analysis on their geographical spread and chronological trends. The method for identifying these projects is to first collect information of 5GDHCS-related real-life systems from a wide scope of sources (including academic publications, reports, websites, etc.), and then manually screen them to assert their relevance.

Throughout existing studies, only research projects that are funded by European countries were reported. Table 10 provides a compact summary of them, among which Germany and EU horizon 2020 funded projects account for the vast majority. The remaining projects received support from the UK, Denmark, Austria, and Italy. Regarding funding trends, the earliest group of projects emerged in 2012. Since then, financial support has been sustained, reflecting a continuous interest and investment in this field.

Table 10
A collection of 5GDHCS-related research projects in existing studies.

Location	Period	Research project
Germany	2019–2024	**IWAES I & II**: Integrative consideration of sustainable heat management of urban districts in the urban development process [105,210].
	2020–2025	**TransUrban.NRW**: Transformation of grid-connected, urban heating and cooling supply with intersectoral Power-2-Heat solutions as a contribution to structural change in the coalfields in NRW [211].
	2020–2025	**SmartQuart** [212].
	2017–2021	**EnEff Stadt WPuQ**: Wind-Solar-Heat Pump Quarter - Renewable Heat Pumps to Minimize Primary Energy Demand [109,213].
	2019–2022	**ErdEis II**: Frozen ground as a heat source [100,214].
The UK	Not available	**GREENSCIES**: Green Smart Community Integrated Energy Systems [161,163,215,216].
	2018–2024	**SCENIC**: Smart Controlled Energy Networks Integrated in Communities [217,218].
Denmark	2021–2023	**COOLGEOHEAT**: Collective renewable energy for all [219].
Austria	2018–2021	**SANBA**: Smart anergy quarter baden [182,220].
Italy	2015–2018	**FLEXYNETS**: Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS [17,197].
Trans-Europe	2012–2017	**D2GRIDS**: Rolling out 5th generation district heating and cooling [221,222].
	2017–2022	**ReUseHeat**: Heat recovery and reuse [79].
	2012–2017	**IEA DHC Annex TS1:** Low temperature district heating for future energy systems [30,223].
	2018–2021	**IEA DHC Annex TS2**: Implementation of low temperature district heating systems [224,225].
	2015–2019	**STORM**: Developed and tested an innovative District Heating & Cooling network controller to increase the use of waste heat and renewable energy sources and boost energy efficiency at district level [226].
	2019–2023	**REWARDHeat**: Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks [227].
	2018–2022	**LIFE4HeatRecovery**: Low Temperature, Urban Waste Heat into District Heating and Cooling Networks as a Clean Source of Thermal Energy [228].
	2016–2020	**HeatNet NEW**: Transition strategies for delivering low carbon district heat [229].

An exhaustive list of the real-life systems reported in existing literatures is presented in Table A1 of Appendix. The number of these systems in different countries are counted and displayed in Fig. 6, along with the average winter temperature of their locations. In general, Germany leads with a total number of 74 systems, followed by Switzerland (16), Italy (9), Sweden (6), and the UK (4). Several countries outside Europe also contribute to a small portion of these practical systems, including China (3), Canada (1), and Australia (1).

By far only a few countries have reported their practical deployment of 5GDHCS, indicating a long way to go for such systems to achieve widespread commercialization and mass deployment. Among these countries, Sweden, Germany, and Switzerland, which experience lower average winter temperatures, appear to be more motivated to promote the deployment of 5GDHCS. Currently, there are 6, 74, and 16 reported real-life systems in these countries, respectively. A geographical correlation is also observed between the number of practical systems and that of funded projects, underscoring the crucial role of financial support and research attention in promoting the implementation of 5GDHCS.

It is important to acknowledge that these conclusions are limited by the scope of available information. There may be additional real-life systems that have not been reported in academic literatures, possibly due to their lack of perceived academic significance. In the future, sustained efforts will be devoted to creating a website to track and disseminate the latest development in practical applications of such systems.

The temporal varying trend of the newly commissioned real-life systems throughout the world is depicted in Fig. 7, where each bar represents the exact number of systems commissioned annually, while the grey solid curve calculates the three-point moving averages of the dataset. Generally, the number shows an increasing trend of newly commissioned systems over the years, and this trend is expected to continue with more research inputs from around the world.

4. Research gaps and prospects of 5GDHCS

4.1. Two fundamental questions

4.1.1. Ambiguity of definition

Since the concept of 5GDHCS was developed, the debate surrounding its definition has never ceased. The focus lies essentially on two questions: what are the substantive differences between 5GDHCS and 4GDHS? and what appropriate criteria should be employed to define a new technological generation of district heating?

Definitions summarized from existing literatures show a general consensus on some key features of 5GDHCS, but they are challenged by some researchers with respect to whether these agreed-upon features represent significant enough technological leaps to define a new technology generation [11,15,23,49]. Additionally, there do exist some potential shortcomings in these definitions, for example, the validity of restricting the supply temperature down to ambient levels and the viability of adopting uninsulated pipes to improve overall economic efficiency, as have been discussed in Section 2.4. There is also a lack of metrics to quantify the 5GDHCS's ability to provide both heating and cooling services. Questions such as the appropriate share between heating and cooling demands that qualifies a 5GDHCS for this ability call for more quantitative analysis.

Together with many studies, this paper provides a perspective on the essential differences between 5GDHCS and preceding DH generations, and further proposes an updated definition for it. Nevertheless, the subjective nature of the criteria for defining a new technological generation in this field will arouse ongoing debate, and to develop a well-recognized definition still requires further efforts.

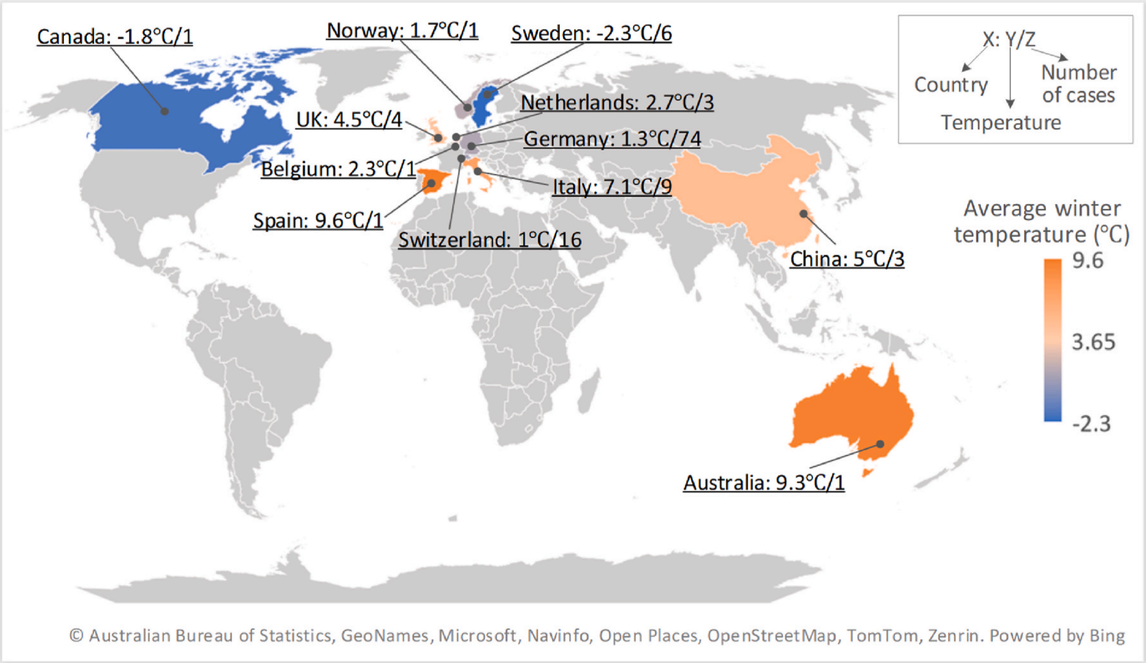

Fig. 6. Number of reported real-life systems and the average winter temperatures in different countries.

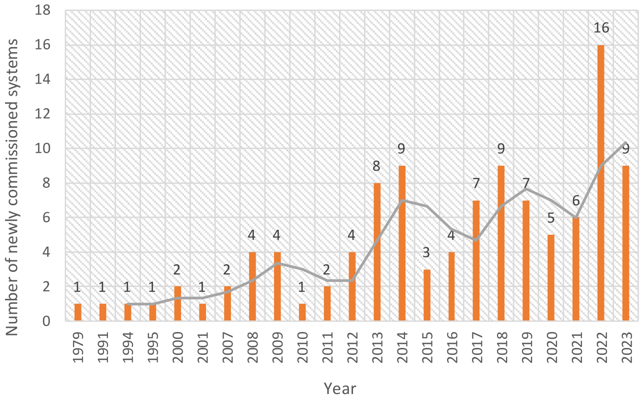

Fig. 7. Varying trend of the number of newly commissioned real-life systems with time.

4.1.2. *Demonstrated significance*

Existing literatures reveal varied and sometimes contradictory findings regarding the superiority of 5GDHCS over other DH alternatives in aspects like energy, exergy, environmental, and techno-economic performances. The motivation of developing and deploying 5GDHCS in real-world are not yet clear. Problems such as does 5GDHCS truly outperform the 4GDHCS, will 5GDHCS dominate future domestic district heating and cooling sectors, and what will the future domestic heating/cooling mix be like and how it will evolve over time, remain unanswered [230,231].

Moreover, performances of 5GDHCS are often influenced by a wide range of technical and non-technical factors, including control and operation strategies, demands levels and compositions, energy prices, taxes and subsidies, etc. Quantifying the boundary conditions for the 5GDHC being energy/energy/environmental/economic efficient poses a significant challenge. This requires not only the establishment of a standard library with recognized case systems and simulation scenarios for robust analysis but also continual inputs of more innovative research efforts [66,141].

4.2. *Technical gaps and prospects*

4.2.1. *Dealing with uncertainty*

Most existing studies on 5GDHCS adopt either predicted or prefixed boundary conditions for their research. These boundary conditions typically include demand levels, outputs from renewable and waste heat sources, energy prices, tax and subsidy policies, and operational parameters of system equipment. Nevertheless, in real-world scenarios, these boundary conditions are subject to change due to various uncertain factors such as weather variations and population growth. Incorporating the influence of these uncertain boundaries will significantly complicate the tasks of system planning, operation, control, and performance analysis, but addressing it is crucial for obtaining reliable research outcomes for real-life systems.

As the integration of renewable energy into 5GDHCS increases, there is an urgent need to develop advanced modeling, simulation, and optimization methods that can handle multiple uncertainties [99,157]. This involves building novel models to better characterize uncertainties, improving the accuracy of forecasting models and methods, converting uncertain models into their deterministic equivalents, and developing robust and probabilistic optimization algorithms, etc.

4.2.2. *Interaction with power grid*

A pivotal feature of 5GDHCS is the prevalent role transition of end-users. The deployment of distributed heat pumps transforms most traditional heating/cooling consumers into active prosumers by enabling them to both consume and produce heat/cooling energy. This role change opens up new space for the heating/cooling system to interact with the electric power system through actively participating in different electricity markets [66,168].

These interactions bring about both negative and positive influence on the operation of power grid. The negative part lies in that local distribution electricity networks will bear huge pressure as they were not originally designed to accommodate the load growth caused by the widespread deployment of distributed heat pumps [84]. Overloading and under-voltage problems can be serious, especially for rural feeders [232]. Quantifying the impacts of the mass deployment of 5GDHCS on existing power grid infrastructures is therefore an important topic.

Developing effective operation and expansion planning strategies to mitigate negative impacts remains a challenge for power engineers.

The positive side is that flexibility resources at the demand side of heating and cooling sectors, including the thermal inertial of buildings and small domestic TES, can be exploited through numerous distributed heat pumps deployed at end-users participating in electricity markets. However, how to unlock and quantify this flexibility and how to aggregate it as a dispatchable resource for power systems require advanced modeling frameworks, smarter operation strategies, and delicately-designed demand-response programs along with prosumer-oriented market mechanisms [15,192]. These aspects remain largely unexplored in existing studies, highlighting a significant area for future research and development.

4.2.3. Technical guidelines and standards

Despite the significant research progress made in 5GDHCS, there remain some technical difficulties in their design, operation, and performance analysis. Table 11 summarizes these technical gaps and outlines potential directions for future research.

The energy atlas, characterizing demand levels and the potential of renewable and waste heat [233] in a region, is essential for the design and planning of 5GDHCS. However, it is not available in many regions, particularly concerning the parts of renewable and waste heat potential and cooling demands. Although a substantial volume of literature addresses the design and planning aspects, most studies focus only on specific elements like network topology optimization or optimal equipment selection and sizing. Holistic guidelines for designing and planning such systems from scratch or retrofit existing DH systems into 5GDHCSs are rarely seen [15,99]. A potential topic of interest would be whether an existing ground- or air-source heat pump can be retrofitted into a water-source heat pump for 5GDHC systems. All of these highlight a need for more comprehensive research.

In terms of system operation and control, current research often overlooks the diverse interests of various prosumers. Similarly, the potential benefits for booster heat pumps to participate in the electricity market and the need to consider uncertainties in robust operation optimization are areas that require further attention. Additionally, the lack of practical deployment of sensors and control strategies for the smart operation of 5GDHCS is another area of concern.

As for the topic of performance analysis through simulation, conflicting results from existing studies necessitate the creation of a standard library system containing recognized systems and scenarios for comparative analysis and cross validation, which is a task yet to be undertaken. Further research should also focus on the security and stability analysis of these systems, as complex hydraulic conditions may increase the risk of component failure and system disruption [235].

Table 11
A summary of technical gaps in existing 5GDHCS-related studies.

Topic	Technical gap
Design & planning	Energy atlas is needed to support the design and planning of 5GDHCS via providing a comprehensive geographical assessment of regional heating and cooling demands, along with the potential of renewable and waste heat sources [233]. Lack of holistic guidelines for designing and planning a 5GDHCS from scratch [99]. Limited experience on how to retrofit existing DH systems into 5GDHCSs [15]. Determining the optimal supply temperature for network design that balances heat losses, pumping costs, and the COP of booster heat pumps to maximize system economic efficiency is still a challenge.
Operation & control	Decentralized optimization among multiple prosumers is needed to meet differed operational objectives while protecting their privacy. Engaging in energy arbitrage and providing flexibility services in the electricity market to reduce operation costs of heat pumps remain largely unexplored. Operation optimization under uncertainties is needed to tackle the increasing random factors at both source and demand sides [99]. There is a scarcity of information on sensor arrangements for implementing complex control logics in practical 5GDHCSs [13,234]. Smarter control strategies are needed to manage bidirectional mass and energy flows in 5GDHCS [9,53,115,136].
Simulation & performance analysis	Establishing a standard library encompassing recognized system configurations and simulation scenarios is needed for comparative analysis and deriving reliable results. Complex hydraulic conditions increase the risk of component failure and system disruption. Analysis on the secure and stable operational region is needed [235]. More experimental work is needed to acquire real data of equipment working within the temperature range of 5GDHCS [206].

4.3. Policy, regulation, and market

The development of 5GDHCS extends beyond a pure technical challenge. Rather, it engages a diverse group of stakeholders with differed interests, and is strongly influenced by local policy, legislative, and social-economic environment [80,157].

Typical stakeholders in 5GDHCS include system operators (potentially with split responsibilities for heat production and distribution [15]), prosumers, regulatory bodies, and external investors [72]. Each stakeholder group has its own considerations to operate such a heating network. These considerations range from ensuring secure and stable energy supply, minimizing running costs, preventing monopolies, to maximizing ownership benefits. Developing technical solutions that not only balance these varied interests but also align with social and political acceptance poses a significant challenge [166].

From the policy perspective, once the feasibility of developing 5GDHCSs is established, a clear roadmap to implement such systems will need to be provided by governments. Currently, low natural gas prices are a major barrier for the deployment of 5GDHCS in some areas. Therefore, policies on increasing the minimum gas prices, along with imposing stronger carbon taxes and offering higher subsidies on renewable technologies and waste heat recovery could be possible ways to overcome it [179].

Apart from policy support, a comprehensive regulatory framework covering the funding mechanisms, technical exploitation of energy resources, network operation, energy trading, and business negotiations for third-party access, plays an important role as well [15,80,166]. Moreover, an attractive legislative environment built by governments and regulators can also serve as a strong incentive for investment [80].

Finally, the sustainable development of 5GDHCS depends on a well-designed business ecosystem supported by long-term financing [72]. This ecosystem should encourage diverse user participation in the operation and pricing of heating networks [68]. Building a dynamic heating market involves designing novel trading mechanisms, developing business models for prosumers, and creating standard contracts [55,66,80], which is a challenging task calling for further research efforts.

5. Conclusion

This paper conducts a state-of-the-art analysis of 5GDHCS and based on this, provides perspectives on its definition, unique features, research gaps, and prospects. The typical application of 5GDHCS is to satisfy domestic heating and cooling demands, including space heating/cooling and domestic hot water use, in a wide range of load types. These loads can be the places in industrial zones and business parks where people work/rest/live, offices, residential areas, multi-floor buildings, or single-family houses, etc.

The aims of this paper are to settle a series of fundamental questions related to the 5GDHCS concept and to complement previous reviews with an updated overview of its latest research and practical development. Following a comprehensive analysis on existing studies, the proposed research questions are answered as follows.

5.1. Q1: What is the definition of 5GDHCS?

Current literatures define the 5GDHCS concept with three key features: a) operation at near-ambient network temperatures; b) deployment of distributed heat pumps at the end-user side; and c) the ability to provide both heating and cooling services. However, these definitions arouse divergent opinions on whether such systems fundamentally differ from the 4GDHS concept. In view of this, a thorough comparison between 5GDHCS and 4GDHS is presented in this paper, examining their functional, technological, and operational differences. Following this, a refined definition of 5GDHCS that better characterizes its unique attributes and advancements is suggested, as detailed in Section 2.4.

5.2. Q2: What are the distinctive features of 5GDHCS compared with 4GDHS?

Compared with 4GDHS, the distinctive features of 5GDHCS lie in two significant role transitions at both the source and demand sides, which fundamentally renovate the pattern of district heating. At the source side, distributed electrified facilities installed at end-users become the **primary** sources to provide both heating and cooling services, relegating traditional centralized or non-electric sources to **secondary** roles. District heating shifts from its current reliance on fuel-driven solutions to predominantly electricity-driven ones. At the demand side, distributed active heating/cooling facilities transition from traditional **consumers** to active **prosumers**, enabling heat/cooling transactions among end-users within a community and profoundly changing the structure and mechanism of heating market.

5.3. Q3: What is the state-of-the-art of existing 5GDHCS-related literatures?

Studies related to the topic of 5GDHCS are growing fast, with over 30 publications each year since 2021. Generally, existing studies focus on four major aspects: design and planning, operation and control, modelling and simulation, and performance analysis through simulation or data monitoring. Each area receives significant attention, with detailed state-of-the-art progress discussed in in Section 3.

5.4. Q4: What is the status of practical deployment of 5GDHCS?

An exhaustive list of real-life 5GDHCS implementations reported in existing literatures is presented in Appendix Table A1. Germany is taking the lead in practical applications, followed by several Western European countries, China, Canada, and Australia. However, the deployment remains limited and is only seen in a few countries. Despite the upgoing trend for newly commissioned systems over recent years, there is still a long way to go to achieve widespread commercialization and mass deployment of such systems.

5.5. Q5: What are the research gaps in existing studies?

Research gaps in existing 5GDHCS-ralated studies are summarized into three categories. The first category contains two fundamental questions concerning the establishment of a well-recognized definition and the demonstrated superiorities of 5GDHCS over other DH solutions. The second category consists of three technical gaps including methods to handle uncertainty, integrated operation of 5GDHCS and power systems to unlock flexibility, and the creation of comprehensive guidelines and standards to support system design, planning, operation, and control. The last category identifies the lack of supportive policies, regulations, and market ecosystems for the development of 5GDHCS. Detailed discussions on these gaps are presented in Section 4.

5.6. Q6: What implications does the development of 5GDHCS bring on the decarbonization of both the district heating and electric power sectors?

5GDHCS has a potential in reducing GHG emissions in the district heating sector due to its high level of electrification and extensive exploitation of renewable and waste heat energy. Flexibility resources from the DH sector, including TESs and the thermal inertial of heating networks and buildings, can be utilized to enhance grid integration of RES within power systems. Therefore, the development of 5GDHCS also plays a positive role in the decarbonization of the electric power sector. However, this benefit is somehow mitigated by the potential overloading and under-voltage problems caused by mass deployment of distributed heat pumps in 5GDHCS. It is essential to overcome such negative impacts before it can realize its full positive potential.

It is worth noting that the analysis of research projects and real-life systems is constrained by the scope of available data. There may be undocumented real-life systems not featured in academic literatures. Future efforts will focus on developing a website to track and share developments in the practical application of these systems.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the first author used ChatGPT 4 in order to polish the language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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

Data will be made available on request.

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Appendix

Table A.1
A summary of the real-life 5GDHCS reported in existing studies.

Country	Year of commission	Name or description	Network temperature (°C)	Network length (km)
Australia (1)	/	The new campus of the University of Melbourne [207]	10–20	/
Belgium (1)	2017	A system in Leuven [9]	0–20	/
Canada (1)	2009	The Whistler Athletes Village [79]	<54	/
China (3)	2007	Shanghai Jiading Dongfang Haoyuan (low rise residential community) [31]	/	/
	2019	Shanghai Changxing Island Yudao Wealth Mansion	/	/
	2008	Shanghai Pujiang Zhigu Business Park	/	/
Germany (74)	2022	A system in Arealnetz Lott [10]	0–30	0.15
	2021	A system in Bad Nauheim Süd [10,100]	-2–20	6
	2023	A system in Lagarde-Campus [10]	0–10	5.5
	2022	A system in Ressourcenschutzsiedlung Kaster (Resource Protection Settlement Kaster) [10]	10–20	1.88
	2026	A system in Urban Tech Rep./Schumacher-Q [10].	20	12.5
	2017	A system in Bodenmais [10]	20–40	0.95
	2022	A system in Westlich der Bahn (West of the Railway) [10]	0–20	1.5
	2014	A system in Dollnstein [10]	20–40	1.8
	2018	A system in Projekt Noorblick (Project Noorblick) [10]	0–10	4.2
	2020	A system in Solarsiedlung am Ohrberg (Solar Settlement at Ohrberg) [10]	0–20	1
	2013	A system in Sonnematte [10]	-5–20	1.8
	2020	A system in Seniorenwohnpark Eden (Senior Living Park Eden) [10]	10–20	1.2
	2019	A system in Afrastraße [10]	0–10	0.65
	2023	A system in Wohnen am Stadtteilpark Hassel (Living at the Hassel District Park) [10]	0–20	1.5
	2018	A system in Geltinger Bucht (Geltinger Bay) [10]	0–10	6.6
	2022	A system in Westlich der Alzeyer Straβe (West of Alzeyer Street) [10]	10–20	/
	2018	A system in Alte Ziegelei (Old Brickworks) [10]	-5–20	2.8
	2016	A system in Osterfeld II/III [10]	20–50	4.6
	2023	A system in Shamrockpark [10]	10–20	2
	2022	A system in Erkingshof [10]	0–10	1
	2019	A system in Bregning-West [10]	0–10	1.63
	2016	A system in Steinhäldenweg II [10]	10–20	1.2
	2023	A system in Brainergy Park [10]	0–20	3.7
	2022	A system in Forschungszentrum (Research Center) [10]	20–40	0.6
	2021	A system in Vinger Weg [10]	10–20	1.2
	2022	A system in Bgm-Bitterolf-Straße (Mayor Bitterolf Street) [10]	0–20	1.6
	2023	A system in Kirchfeld (Church Field) [10]	10–20	1.3
	2022	A system in Eulbusch III [10]	0–10	0.65
	2023	A system in Alte Brauerei (Old Brewery) [10]	0–20	0.5
	2018	A system in Meitingen [10]	20–30	0.9
	2021	A system in Auf Leim (On Glue) [10]	0–20	1
	2020	A system in Hüttengelände (Hut Area) [10]	/	0.92
	2017	A system in Geltinger Birk [10]	0–10	4.9
	2022	A system in Grünes Leben am Schafhaus (Green Living at Schafhaus) [10]	0–10	1
	2018	A system in Eisspeicher-Quartier (Ice Storage Quarter) [10]	0–10	0.5
	2019	A system in Heidegarten (Heath Garden) [10]	0–10	3.15
	2022	A system in Öchsner II [10]	0–10	1
	2023	A system in Am Bahnhof (At the Train Station) [10]	0–20	1.15
	2021	A system in Weiermatten [10]	0–30	2.2
	2016	A system in Max-Ernst-Straße [10]	0–20	0.53
	2022	A system in Am Bergle [10]	-3–20	0.66
	2023	A system in Kellerbergbreite [10]	10–20	2.5
	2015	A system in Berender Redder [10]	0–10	13.9
	2021	A system in Wichelkoppeln [10]	0–10	2.9
	2022	A system in Soester Norden (Northern Soest) [10]	-2–20	7.3
	2019	A system in Bergheim [10]	0–20	0.45
	2019	A system in Eschmar West [10]	0–20	0.5
	2021	A system in In de Brinke [10]	0–20	5.5
	2022	A system in Lehmkuhle (Clay Pit) [10]	0–10	/
	2022	A system in Am Parkfeld (At the Park Field) [10]	10–20	2
	2023	A system in Am Luhedich [10]	0–20	0.85
	2011	A system in Vordere Viehweide (Front Cattle Meadow) [10]	0–20	0.5
	2012	A system in Wüstenrot [9,12]	0–20	/
	2009	A system in the “Neumatten” area in March-Hugstetten [9]	10–20	2.5
	2010	A system in Aurich [9]	10–30	2
	2017	A system in the “Sohnius-Weide” district in Nümbrecht [9]	0–30	0.45
	2016	A system in the “Hochvogelstraβe" area in Biberach [9]	0–20	/
	1994	A system in the “Stiegelpotte” area in Spenge [9]	20	/
	2000	A system in the “Sattlerweg” area in Herford [9]	20–30	0.7
	2000	A system in the “Obstanger” area in Herford [9]	10–20	/
	2013	A system in the “Karl-May-Weg"district in Fischerbach [9]	0–20	1
	2017	A system in the “Max-Ernst-Straße" area in Schifferstadt [9]	10–20	/
	2011	A system in the “Küferweg" district in Mainz [9]	0–10	/

(continued on next page)

Table A.1 (*continued*)

Country	Year of commission	Name or description	Network temperature (°C)	Network length (km)
	2001	A system in Ohrberg [9]	10–20	/
	2014	A system in Troisdorf [9]	10	5
	1979	A system in Dorsten-Wulfen [9]	10	1.2
	2014	A system in the “Berender Redder” area in Schleswig [9]	10–20	7.5
	/	A system in Bad Nauheim [12,114]	0–20	12
	2020	The district Shamrock Park in Herne	10–30	/
	2022	A system in Schleswig [100]	/	/
	/	LowEx network in the city quarter of Ludwigsburg [30]	40	/
	/	A new housing area in Kassel Feldlager [30]	40	/
	/	A system in Jenfelder Au, Hamburg [42]	10	/
	2020	A system in Neustadt am Rübenberge [12]	10–20	/
Italy (9)	2007	A system in the “Complesso della Torre” district in Savona [9]	10–30	/
	2013	A system in the “Arsenale nord” district in Venice [9]	10–30	/
	2014	A system in the “Porto piccolo Sistiana” in Trieste [9]	0–30	2
	2018	A system in Ospitaletto [9]	10–30	2.3
	2014	A system in Sale Marasino [9]	10–20	0.1
	/	A residential district in the Pantelleria island [54].	10–30	5
	2013	A system in Berlingo [42]	10–20	/
	/	A system in Sale Morosino [42]	/	/
	/	A system near near Bologna [42]	/	/
Netherlands (3)	2009	A system in Duindorp, the Hague [9]	10–20	/
	2008	A system in Herleen [9]	20–30	/
	2013	Mijnwater 2.0 [72]	10–30	/
Norway (1)	1995	University of Bergen [9]	0–20	/
Spain (1)	/	A Mediterranean rural municipality in Andalusia [126,236]	0–30	/
Sweden (6)	2022	Embassy of Sharing [166]	0–20	/
	2018	E.ON ectogrid™ [166,195]	0–40	/
	2017	Hästskon [166]	0–20	/
	2014	NUS [166]	0–20	/
	2018	A system in South Sweden [92]	10–30	/
	/	Hyllie in Malmö [117]	30	/
Switzerland (16)	2013	ETH Campus Hönggerberg in Zürich (Known as the Anergy Grid) [9,171]	0–30	1.5
	2012	A system in Jardins de la Pâla, Bulle [9]	0–20	0.85
	2014	A system in the Familienheimgenossen-schaft district in Zürich (FGZ) [9,224]	0–30	1.5
	2012	A system in the Suurstoffi district in Risch Rotkreuz [9] [38,39,44]	0–30	/
	2015	A system in La Tour-de-Peilz [9]	0–20	4.1
	2013	A system in the “Krommen Kelchbach” district in Naters [9]	0–20	/
	2009	A system in Brig-Glis [9]	0–20	/
	1991	A system in Oberwald/Obergoms [9,42]	10–20	2.2
	2008	A system in the “Visp-West” district in Visp [9]	0–20	4.2
	2008	A system in Genève-Lac-Nations [9]	0–20	6
	2014	A system in REKA village, Blatten-Belalp [9]	0–40	/
	2017	A system in the “Sedrun” district in Tujetsch [9]	0–10	/
	2015	A system in Saas Fee [9]	0–20	/
	2013	A system in the “Rheinfels/Kleinbruggen” district in Chur [9]	0–20	0.48
	2014	A system in Richti Wallisellen [9]	0–30	/
	/	A system in the Krommen Kelchbach district [79]	0–20	/
The UK (4)	2012	A system in Brooke Street in Derby [9]	0–10	/
	2019	A system in Plymouth [223].	0–20	/
	2018	The balanced energy network (BEN) at London South Bank University [46,47,192]	10–30	/
	/	A system in the London Borough of Islington [161,163]	0–20	/

References

[1] Cozzi L. World energy outlook 2023. Paris: International Energy Agency; 2023. https://www.iea.org/reports/world-energy-outlook-2023.

[2] Briens F, Martinez-Gordon R. Heating. IEA; 2023. https://www.iea.org/energy-system/buildings/heating.

[3] IEA. Space cooling. Paris: IEA; 2023. https://www.iea.org/reports/space-cooling-2.

[4] Delmastro C, Martinez-Gordon R. Cooling. IEA; 2023. https://www.iea.org/energy-system/buildings/space-cooling.

[5] Delmastro C, Briens F. District heating. IEA; 2023. https://www.iea.org/energy-system/buildings/district-heating.

[6] Fallahnejad M, Kranzl L, Haas R, Hummel M, Müller A, García LS, Persson U. District heating potential in the EU-27: evaluating the impacts of heat demand reduction and market share growth. Appl Energy 2024;353:122154. https://doi.org/10.1016/j.apenergy.2023.122154.

[7] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Mathiesen BV. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[8] Lund H, Østergaard PA, Chang M, Werner S, Svendsen S, Sorknæs P, Thorsen JE, Hvelplund F, Mortensen BOG, Mathiesen BV, Bojesen C, Duic N, Zhang X, Möller B. The status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[9] Buffa S, Cozzini M, D’Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renewable Sustainable Energy Rev 2019;104:504–22. https://doi.org/10.1016/j.rser.2018.12.059.

[10] Wirtz M, Schreiber T, Müller D. Survey of 53 fifth-generation district heating and cooling (5GDHC) networks in Germany. Energy Technol 2022;10:2200749. https://doi.org/10.1002/ente.202200749.

[11] Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O, Arabkoohsar A, Mathiesen BV. Perspectives on fourth and fifth generation district heating. Energy 2021;227:120520. https://doi.org/10.1016/j.energy.2021.120520.

[12] Zeh R, Ohlsen B, Philipp D, Bertermann D, Kotz T, Jocic N, Stockinger V. Large-scale geothermal collector systems for 5th generation district heating and cooling networks. Sustainability 2021;13. https://doi.org/10.3390/su13116035.

[13] Gong Y, Ma G, Jiang Y, Wang L. Research progress on the fifth-generation district heating system based on heat pump technology. J Build Eng 2023;71:106533. https://doi.org/10.1016/j.jobe.2023.106533.

[14] Revesz A, Jones P, Dunham C, Davies G, Marques C, Matabuena R, Scott J, Maidment G. Developing novel 5th generation district energy networks. Energy 2020;201:117389. https://doi.org/10.1016/j.energy.2020.117389.

[15] Taylor M, Qadrdan M, Woodman B, Wu J, Co-Director U. The future of district heating and cooling networks. UK Energy Research Centre; 2023. https://ukerc.ac.uk/publications/the-future-of-district-heating-and-cooling-networks/.
[16] Ostergaard D, Smith K, Tunzi M, Svendsen S. Low-temperature operation of heating systems to enable 4th generation district heating: a review. Energy 2022;248. https://doi.org/10.1016/j.energy.2022.123529.
[17] Home - flexynets, (n.d.). http://www.flexynets.eu/en/.
[18] Gudmundsson O, Schmidt R-R, Dyrelund A, Thorsen JE. Economic comparison of 4GDH and 5GDH systems – using a case study. Energy 2022;238:121613. https://doi.org/10.1016/j.energy.2021.121613.
[19] Ruesch F, Haller M. Potential and limitations of using low-temperature district heating and cooling networks for direct cooling of buildings. Energy Proc 2017;122:1099–104. https://doi.org/10.1016/j.egypro.2017.07.443.
[20] Kilkis B, Caglar M, Sengul M. Energy benefits of heat pipe technology for achieving 100% renewable heating and cooling for fifth-generation, low-temperature district heating systems. Energies 2021;14. https://doi.org/10.3390/en14175398.
[21] Sarbu I, Mirza M, Muntean D. Integration of renewable energy sources into low-temperature district heating systems: a review. Energies 2022;15. https://doi.org/10.3390/en15186523.
[22] Bilardo M, Sandrone F, Zanzottera G, Fabrizio E. Modelling a fifth-generation bidirectional low temperature district heating and cooling (5GDHC) network for nearly Zero Energy District (nZED). Energy Rep 2021;7:8390–405. https://doi.org/10.1016/j.egyr.2021.04.054.
[23] Averfalk H, Benakopoulos T, Best I, Dammel F. Low-temperature district heating implementation guidebook. IEA DHC Report. IEA DHC; 2021. https://www.iea-dhc.org/fileadmin/documents/Annex_TS2/IEA_DHC_Annex_TS2_Transition_to_low_temperature_DH.pdf.
[24] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. https://doi.org/10.1016/j.energy.2017.04.045.
[25] Østergaard PA, Werner S, Dyrelund A, Lund H, Arabkoohsar A, Sorknæs P, Gudmundsson O, Thorsen JE, Mathiesen BV. The four generations of district cooling - a categorization of the development in district cooling from origin to future prospect. Energy 2022;253:124098. https://doi.org/10.1016/j.energy.2022.124098.
[26] Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019;100:143–74. https://doi.org/10.1016/j.rser.2018.10.014.
[27] Zhou Y, Wu J, Long C. Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework. Appl Energy 2018;222:993–1022. https://doi.org/10.1016/j.apenergy.2018.02.089.
[28] U. Nations, Net Zero Coalition, United Nations (n.d.). https://www.un.org/en/climatechange/net-zero-coalition.
[29] Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems. Energy Rep 2022;8:10037–47. https://doi.org/10.1016/j.egyr.2022.07.162.
[30] Schmidt D, Kallert A, Blesl M, Svendsen S, Li H, Nord N, Sipila K. Low temperature district heating for future energy systems. In: Ulseth R, editor. Fraunhofer Gesellschaft; 2017. p. 26–38. https://doi.org/10.1016/j.egypro.2017.05.052.
[31] After Covid-19 epidemic: development of energy bus and 5th generation district heating and cooling system, [n.d.)].
[32] Long W, Bai W, Liang H, Fan R. Energy system in low carbon city. 79-84+127 Heat Vent Air Cond 2009;39.
[33] Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS | FLEXYNETS Project | Fact Sheet | H2020, CORDIS | European Commission (n.d.). https://cordis.europa.eu/project/id/649820.
[34] García-Céspedes J, Herms I, Arnó G, de Felipe JJ. Fifth-generation district heating and cooling networks based on shallow geothermal energy: a review and possible solutions for mediterranean Europe. Energies 2023;16:147. https://doi.org/10.3390/en16010147.
[35] Liu X, Yan Z, Xie D, Zhang P, Wang H, Long W. Research and prospect of strong coupling pathway for electricity-heat integrated energy network. AEPS 2022;46:204–15. https://doi.org/10.7500/AEPS20210429008.
[36] Pumping power prediction in low temperature district heating networks. In: RUESCH F, ROMMEL M, SCHERER J, editors. Proceedings of international conference CISBAT 2015 future buildings and districts sustainability from nano to urban scale; 2015. https://doi.org/10.5075/epfl-cisbat2015-753-758.
[37] Bünning F, Wetter M, Fuchs M, Müller D. Bidirectional low temperature district energy systems with agent-based control: performance comparison and operation optimization. Appl Energy 2018;209:502–15. https://doi.org/10.1016/j.apenergy.2017.10.072.
[38] Dynamic analysis of the low-temperature district network “Suurstoffi” through monitoring. In: VETTERLI N, SULZER M, editors. Proceedings of international conference CISBAT 2015 future buildings and districts sustainability from nano to urban scale; 2015. https://doi.org/10.5075/epfl-cisbat2015-517-522.
[39] Prasanna A, Dorer V, Vetterli N. Optimisation of a district energy system with a low temperature network. Energy 2017;137:632–48. https://doi.org/10.1016/j.energy.2017.03.137.
[40] Ruesch F, Scherer J, Kolb M. Erdreich als Speicher – grosse Anergienetze. In: Erdreich als Speicher – grosse Anergienetze. ZHAW School of Engineering, Winterthur; 2016. p. 43–8. https://www.zhaw.ch/storage/engineering/institute-zentren/icp/veranstaltungen/siges-2016/konferenzbuch-siges2016.pdf. [Accessed 14 December 2023].
[41] Heera A. LowExTra: Niedrig-Exergie-Trassen zum Speichern und Verteilen von Wärme, nexus (accessed December 14, 2023), https://nexusinstitut.de/lowextra-niedrig-exergie-trassen-zum-speichern-und-verteilen-von-waerme/; 2017.
[42] Pellegrini M, Bianchini A. The innovative concept of cold district heating networks: a literature review. Energies 2018;11:236. https://doi.org/10.3390/en11010236.
[43] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017;79:1275–84. https://doi.org/10.1016/j.rser.2017.05.135.
[44] Vetterli N, Sulzer M, Menti U-P. Energy monitoring of a low temperature heating and cooling district network. Energy Proc 2017;122:62–7. https://doi.org/10.1016/j.egypro.2017.07.289.
[45] Østergaard D, Svendsen S. Space heating with ultra-low-temperature district heating – a case study of four single-family houses from the 1980s. Energy Proc 2017;116:226–35. https://doi.org/10.1016/j.egypro.2017.05.070.
[46] Song WH, Wang Y, Gillich A, Ford A, Hewitt M. Modelling development and analysis on the balanced energy networks (BEN) in London. Appl Energy 2019;233–234:114–25. https://doi.org/10.1016/j.apenergy.2018.10.054.
[47] Wang Y, Gillich A, Lu D, Saber EM, Yebiyo M, Kang R, Ford A, Hewitt M. Performance prediction and evaluation on the first balanced energy networks (BEN) part I: BEN and building internal factors. Energy 2021;221:119797. https://doi.org/10.1016/j.energy.2021.119797.
[48] Novitsky NN, Shalaginova ZI, Alekseev AA, Tokarev VV, Grebneva OA, Lutsenko AV, Vanteeva OV, Mikhailovsky EA, Pop R, Vorobev P, Chertkov M. Smarter smart district heating. Proc IEEE 2020;108:1596–611. https://doi.org/10.1109/JPROC.2020.2990490.
[49] Averfalk H, Werner S. Economic benefits of fourth generation district heating. Energy 2020;193:116727. https://doi.org/10.1016/j.energy.2019.116727.
[50] Gudmundsson O, Dyrelund A, Thorsen J. In: Kurnitski J, Thalfeldt M, editors. Comparison of 4th and 5th generation district heating systems; 2021. https://doi.org/10.1051/e3sconf/202124609004.
[51] Wirtz M, Heleno M, Moreira A, Schreiber T, Müller D. 5th generation district heating and cooling network planning: a Dantzig–Wolfe decomposition approach. Energy Convers Manag 2023;276:116593. https://doi.org/10.1016/j.enconman.2022.116593.
[52] Wirtz M, Kivilip L, Remmen P, Muller D. 5th Generation District Heating: a novel design approach based on mathematical optimization. APPLIED ENERGY 2020;260. https://doi.org/10.1016/j.apenergy.2019.114158.
[53] Taylor M, Long S, Marjanovic O, Parisio A. Model predictive control of smart districts with fifth generation heating and cooling networks. IEEE Trans Energy Convers 2021;36:2659–69. https://doi.org/10.1109/TEC.2021.3082405.
[54] Calise F, Liberato Cappiello F, Cimmino L, Dentice d'Accadia M, Vicidomini M. Optimal design of a 5th generation district heating and cooling network based on seawater heat pumps. Energy Convers Manag 2022;267:115912. https://doi.org/10.1016/j.enconman.2022.115912.
[55] Zarin Pass R, Wetter M, Piette MA. A thermodynamic analysis of a novel bidirectional district heating and cooling network. Energy 2018;144:20–30. https://doi.org/10.1016/J.ENERGY.2017.11.122.
[56] Martinazzoli G, Pasinelli D, Lezzi A, Pilotelli M. Design of a 5th generation district heating substation prototype for a real case study. Sustainability 2023;15. https://doi.org/10.3390/su15042972.
[57] Reiners T, Gross M, Altieri L, Wagner H-J, Bertsch V. Heat pump efficiency in fifth generation ultra-low temperature district heating networks using a wastewater heat source. Energy 2021;236:121318. https://doi.org/10.1016/j.energy.2021.121318.
[58] Edtmayer H, Nageler P, Heimrath R, Mach T, Hochenauer C. Investigation on sector coupling potentials of a 5th generation district heating and cooling network. Energy 2021;230:120836. https://doi.org/10.1016/j.energy.2021.120836.
[59] Taylor M, Gao W, Masum S, Qadrdan M. Techno-economic assessment of Bi-directional low temperature networks. Appl Energy 2023;347:121202. https://doi.org/10.1016/j.apenergy.2023.121202.
[60] Liu X, Zhang P, Yan Z. Analysis on multi-energy flow of prosumer-based integrated energy system driven by the fifth generation district heating and cooling network. Dianli Xitong Zidonghua/Automation of Electric Power Systems 2023;47:78–90. https://doi.org/10.7500/AEPS20220818004.
[61] Zühlsdorf B, Christiansen AR, Holm FM, Funder-Kristensen T, Elmegaard B. Analysis of possibilities to utilize excess heat of supermarkets as heat source for district heating. Energy Proc 2018;149:276–85. https://doi.org/10.1016/j.egypro.2018.08.192.
[62] Østergaard PA, Andersen AN. Economic feasibility of booster heat pumps in heat pump-based district heating systems. Energy 2018;155:921–9. https://doi.org/10.1016/j.energy.2018.05.076.
[63] Ommen T, Thorsen JE, Markussen WB, Elmegaard B. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 2017;137:544–55. https://doi.org/10.1016/j.energy.2017.05.165.
[64] Kilkis B. An exergy-based minimum carbon footprint model for optimum equipment oversizing and temperature peaking in low-temperature district heating systems. Energy 2021;236:121339. https://doi.org/10.1016/j.energy.2021.121339.
[65] Jebamalai JM, Marlein K, Laverge J. Design and cost comparison of district heating and cooling (DHC) network configurations using ring topology – a case study. Energy 2022;258:124777. https://doi.org/10.1016/j.energy.2022.124777.
[66] Angelidis O, Ioannou A, Friedrich D, Thomson A, Falcone G. District heating and cooling networks with decentralised energy substations: opportunities and

barriers for holistic energy system decarbonisation. Energy 2023;269:126740. https://doi.org/10.1016/j.energy.2023.126740.

[67] Gross M, Karbasi B, Reiners T, Altieri L, Wagner H-J, Bertsch V. Implementing prosumers into heating networks. Energy 2021;230:120844. https://doi.org/10.1016/j.energy.2021.120844.

[68] Guo Y, Wang S, Wang J, Zhang T, Ma Z, Jiang S. Key district heating technologies for building energy flexibility: a review. Renew Sustain Energy Rev 2024;189:114017. https://doi.org/10.1016/j.rser.2023.114017.

[69] Hachez J, Chicherin S, Chaudhry AM, Bram S. Regression versus probabilistic approach for operational data – heat demand of buildings to be connected to a district heating system. Energy Build 2023;294:113209. https://doi.org/10.1016/j.enbuild.2023.113209.

[70] Sommer T, Sulzer M, Wetter M, Sotnikov A, Mennel S, Stettler C. The reservoir network: a new network topology for district heating and cooling. Energy 2020;199:117418. https://doi.org/10.1016/j.energy.2020.117418.

[71] Marques C, Dunham C, Jones P, Turnell H, Revesz A, Maidment G. Opportunities and challenges for implementing smart local energy systems in cities and towns, demonstrated through case studies. VOL 128, PT 1, Amer Soc Heating, Refrigerating and Air-Conditioning Engs, Atlanta. In: Ashrae transactions 2021; 2022. p. 420–8. https://www.webofscience.com/wos/woscc/full-record/WOS:001057523300048 (accessed November 9, 2023).

[72] HeatNetNWE_Heerlen-Transition-Roadmap_District-Heating.pdf, (n.d.). https://guidetodistrictheating.eu/wp-content/uploads/2019/12/HeatNetNWE_Heerlen-Transition-Roadmap_District-Heating.pdf (accessed December 19, 2023).

[73] Guelpa E, Capone M, Sciacovelli A, Vasset N, Baviere R, Verda V. Reduction of supply temperature in existing district heating: a review of strategies and implementations. Energy 2023;262:125363. https://doi.org/10.1016/j.energy.2022.125363.

[74] Luo A, Fang H, Xia J, Lin B, jiang Y. Mapping potentials of low-grade industrial waste heat in Northern China, Resources. Conserv Recycl 2017;125:335–48. https://doi.org/10.1016/j.resconrec.2017.06.018.

[75] Manz P, Kermeli K, Persson U, Neuwirth M, Fleiter T, Crijns-Graus W. Decarbonizing district heating in EU-27 + UK: how much excess heat is available from industrial sites? Sustainability 2021;13:1439. https://doi.org/10.3390/su13031439.

[76] Schweiger G, Rantzer J, Ericsson K, Lauenburg P. The potential of power-to-heat in Swedish district heating systems. Energy 2017;137:661–9. https://doi.org/10.1016/j.energy.2017.02.075.

[77] Belliardi M, Caputo P, Ferla G, Cereghetti N, Antonioli Mantegazzini B. An innovative application of 5GDHC: a techno-economic assessment of shallow geothermal systems potential in different European climates. Energy 2023;280:128104. https://doi.org/10.1016/j.energy.2023.128104.

[78] Meibodi SS, Loveridge F. The future role of energy geostructures in fifth generation district heating and cooling networks. Energy 2022;240:122481. https://doi.org/10.1016/j.energy.2021.122481.

[79] Lindhe J, Javed S, Johansson D, Bagge H. A review of the current status and development of 5GDHC and characterization of a novel shared energy system. Science and Technology for the Built Environment 2022;28:595–609. https://doi.org/10.1080/23744731.2022.2057111.

[80] Lygnerud K, Wheatcroft E, Wynn H. Contracts, business models and barriers to investing in low temperature district heating projects. Appl Sci 2019;9:3142. https://doi.org/10.3390/app9153142.

[81] Wahlroos M, Pärssinen M, Rinne S, Syri S, Manner J. Future views on waste heat utilization – case of data centers in Northern Europe. Renew Sustain Energy Rev 2018;82:1749–64. https://doi.org/10.1016/j.rser.2017.10.058.

[82] Pakere I, Gravelsins A, Lauka D, Bazbauers G, Blumberga D. Linking energy efficiency policies toward 4th generation district heating system. Energy 2021;234:121245. https://doi.org/10.1016/j.energy.2021.121245.

[83] Zhang Y, Johansson P, Kalagasidis AS. Roadmaps for heating and cooling system transitions seen through uncertainty and sensitivity analysis. Energy Convers Manag 2023;292:117422. https://doi.org/10.1016/j.enconman.2023.117422.

[84] Doubleday K, Hafiz F, Parker A, Elgindy T, Florita A, Henze G, Salvalai G, Pless S, Hodge B-M. Integrated distribution system and urban district planning with high renewable penetrations. WIREs Energy and Environment 2019;8:e339. https://doi.org/10.1002/wene.339.

[85] Krasatsenka A. Following the path «from 3rd to 4th generation DHC networks» in Belgium. Euroheat and Power (English Edition) 2017;14:10–1.

[86] Pakere I, Kacare M, Murauskaite L, Huang P, Volkova A. Comparison of suitable business models for the 5 generation district heating system implementation through game theory approach. Environmental and Climate Technologies 2023;27:1–15. https://doi.org/10.2478/rtuect-2023-0001.

[87] Ochs F, Magni M, Dermentzis G. Integration of heat pumps in buildings and district heating systems—evaluation on a building and energy system level. Energies 2022;15:3889. https://doi.org/10.3390/en15113889.

[88] Yang X, Pan L, Guan W, Tian Z, Wang J, Zhang C. Optimization of the configuration and flexible operation of the pipe-embedded floor heating with low-temperature district heating. Energy Build 2022;269:112245. https://doi.org/10.1016/j.enbuild.2022.112245.

[89] Li X, Yilmaz S, Patel MK, Chambers J. Techno-economic analysis of fifth-generation district heating and cooling combined with seasonal borehole thermal energy storage. Energy 2023;285. https://doi.org/10.1016/j.energy.2023.129382.

[90] Volkova A, Krupenski I, Pieper H, Ledvanov A, Latosov E, Siirde A. Small low-temperature district heating network development prospects. Energy 2019;178:714–22. https://doi.org/10.1016/j.energy.2019.04.083.

[91] Sommer T, Mennel S, Sulzer M. Lowering the pressure in district heating and cooling networks by alternating the connection of the expansion vessel. Energy 2019;172:991–6. https://doi.org/10.1016/j.energy.2019.02.010.

[92] Abugabbara M, Javed S, Johansson D. A simulation model for the design and analysis of district systems with simultaneous heating and cooling demands. Energy 2022;261:125245. https://doi.org/10.1016/j.energy.2022.125245.

[93] Schibuola L, Tambani C, Buggin A. Seawater opportunities to increase heating, ventilation, and air conditioning system efficiency in buildings and urban resilience. Front Energy Res 2022;10. https://www.frontiersin.org/articles/10.3389/fenrg.2022.913411. [Accessed 8 November 2023].

[94] Nérot B, Lamaison N, Mabrouk MT, Bavière R, Lacarrière B. Optimization framework for evaluating urban thermal systems potential. Energy 2023;270:126851. https://doi.org/10.1016/j.energy.2023.126851.

[95] Kilkis B. A comprehensive exergy-based outlook of renewable technology integration for the fifth generation district energy systems. In: Uyar TS, Javani N, editors. Renewable energy based solutions. Cham: Springer International Publishing; 2022. p. 559–95. https://doi.org/10.1007/978-3-031-05125-8_24.

[96] Arnaudo M, Dalgren J, Topel M, Laumert B. Waste heat recovery in low temperature networks versus domestic heat pumps - a techno-economic and environmental analysis. Energy 2021;219:119675. https://doi.org/10.1016/j.energy.2020.119675.

[97] Østergaard DS, Svendsen S. Experience from a practical test of low-temperature district heating for space heating in five Danish single-family houses from the 1930s. Energy 2018;159:569–78. https://doi.org/10.1016/j.energy.2018.06.142.

[98] Østergaard DS, Svendsen S. Are typical radiators over-dimensioned? An analysis of radiator dimensions in 1645 Danish houses. Energy Build 2018;178:206–15. https://doi.org/10.1016/j.enbuild.2018.08.035.

[99] Gjoka K, Rismanchi B, Crawford RH. Fifth-generation district heating and cooling systems: a review of recent advancements and implementation barriers. Renew Sustain Energy Rev 2023;171:112997. https://doi.org/10.1016/j.rser.2022.112997.

[100] Zeh R, Schmid M, Ohlsen B, Venczel S, Stockinger V. 5th generation district heating and cooling networks as a heat source for geothermal heat pumps. In: Borge-Diez D, Rosales-Asensio E, editors. Geothermal heat pump systems. Cham: Springer International Publishing; 2023. p. 259–91. https://doi.org/10.1007/978-3-031-24524-4_9.

[101] Kilkis B. Exergy-rational utilization of solar energy with advanced PVT systems and heat pipe technology in 100% renewable cities. 202231DUMMY. https://doi.org/10.1088/1755-1315/1085/1/012029.

[102] Pakere I, Blumberga D. Solar energy in low temperature district heating. Environmental and Climate Technologies 2019;23:147–58. https://doi.org/10.2478/rtuect-2019-0085.

[103] Khosravi A, Laukkanen T, Vuorinen V, Syri S. Waste heat recovery from a data centre and 5G smart poles for low-temperature district heating network. Energy 2021;218:119468. https://doi.org/10.1016/j.energy.2020.119468.

[104] Feike F, Oltmanns J, Dammel F, Stephan P. Evaluation of the waste heat utilization from a hot-water-cooled high performance computer via a heat pump. Energy Rep 2021;7:70–8. https://doi.org/10.1016/j.egyr.2021.09.038.

[105] Kugler T, Schittenhelm C, Volkmer S, Ryba M, Moormann C, Kurth D, Koenigsdorff R. Sustainable heating and cooling management of urban quarters. Sustainability 2022;14:4353. https://doi.org/10.3390/su14074353.

[106] Swarts T, Morren J, van den Akker W, Slootweg JG, van Voorden A. Techno-economic analysis of low-temperature electrolysis' waste-heat utilization. In: 2023 IEEE Belgrade PowerTech; 2023. p. 1–6. https://doi.org/10.1109/PowerTech55446.2023.10202802.

[107] Brennenstuhl M, Zeh R, Otto R, Pesch R, Stockinger V, Pietruschka D. Report on a plus-energy district with low-temperature DHC network, novel agrothermal heat source, and applied demand response. Appl Sci 2019;9:5059. https://doi.org/10.3390/app9235059.

[108] Suciu R-A. Fifth generation district energy systems for low carbon cities. EPFL; 2019. https://doi.org/10.5075/epfl-thesis-7332.

[109] 5GDHC networks: Scientific publications and literature, (n.d.). http://www.mwirtz.com/5gdhc_literature.

[110] Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 2017;140:1228–38. https://doi.org/10.1016/j.energy.2017.08.078.

[111] Hemmatabady H, Formhals J, Welsch B, Schulte DO, Sass I. Optimized layouts of borehole thermal energy storage systems in 4th generation grids. Energies 2020;13:4405. https://doi.org/10.3390/en13174405.

[112] Behzadi A, Holmberg S, Duwig C, Haghighat F, Ooka R, Sadrizadeh S. Smart design and control of thermal energy storage in low-temperature heating and high-temperature cooling systems: a comprehensive review. Renew Sustain Energy Rev 2022;166:112625. https://doi.org/10.1016/j.rser.2022.112625.

[113] Lund H, Ostergaard P, Chang M, Werner S, Svendsen S, Sorknaes P, Thorsen J, Hvelplund F, Mortensen B, Mathiesen B, Bojesen C, Duic N, Zhang X, Moller B. R13 the status of 4th generation district heating: research and results. Energy 2018;164:147–59. https://doi.org/10.1016/j.energy.2018.08.206.

[114] Hirsch H, Nicolai A. An efficient numerical solution method for detailed modelling of large 5th generation district heating and cooling networks. Energy 2022;255:124485. https://doi.org/10.1016/j.energy.2022.124485.

[115] Toffanin R, Caputo P, Belliardi M, Curti V. Low and ultra-low temperature district heating equipped by heat pumps—an analysis of the best operative conditions for a Swiss case study. Energies 2022;15:3344. https://doi.org/10.3390/en15093344.

[116] Wirtz M, Neumaier L, Remmen P, Müller D. Temperature control in 5th generation district heating and cooling networks: an MILP-based operation optimization. Appl Energy 2021;288:116608. https://doi.org/10.1016/j.apenergy.2021.116608.

[117] Brange L, Englund J, Lauenburg P. Prosumers in district heating networks – a Swedish case study. Appl Energy 2016;164:492–500. https://doi.org/10.1016/j.apenergy.2015.12.020.

[118] Interactive A. Water source heat pump (WSHP) system, Sefaira support. https://support.sefaira.com/hc/en-us/articles/210226593-Water-Source-Heat-Pump-WSHP-System; 2020.

[119] Gao YJ, Wang SG, Jiang S, Wu XZ, Wang JH, Zhang TF, Ma ZJ. Configurations and exergy analysis of district heating substations based mainly on renewable energy. E3S Web Conf. 2022;356:01005. https://doi.org/10.1051/e3sconf/202235601005.

[120] Hermansen R, Smith K, Thorsen JE, Wang J, Zong Y. Model predictive control for a heat booster substation in ultra low temperature district heating systems. Energy 2022;238:121631. https://doi.org/10.1016/j.energy.2021.121631.

[121] P. Jones, C. Dunham, C. Davidson, A roadmap to achieve 5th generation heat networks in the UK, (n.d.).

[122] Yang X, Li H, Svendsen S. Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating. Build Serv Eng Res Tecnol 2016;37:468–78. https://doi.org/10.1177/0143624415613945.

[123] Østergaard PA, Werner S, Dyrelund A, Lund H, Arabkoohsar A, Sorknæs P, Gudmundsson O, Thorsen JE, Mathiesen BV. The four generations of district cooling - a categorization of the development in district cooling from origin to future prospect. Energy 2022;253:124098. https://doi.org/10.1016/j.energy.2022.124098.

[124] Zhang Y, Johansson P, Sasic Kalagasidis A. Assessment of district heating and cooling systems transition with respect to future changes in demand profiles and renewable energy supplies. Energy Convers Manag 2022;268:116038. https://doi.org/10.1016/j.enconman.2022.116038.

[125] Sun F, Xie Y, Svendsen S, Fu L. New low-temperature central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps for higher energy efficiency. Energies 2020;13. https://doi.org/10.3390/en13246582.

[126] Yang X, Svendsen S. Ultra-low temperature district heating system with central heat pump and local boosters for low-heat-density area: analyses on a real case in Denmark. Energy 2018;159:243–51. https://doi.org/10.1016/j.energy.2018.06.068.

[127] Calise F, Cappiello FL, Cimmino L, Dentice d'Accadia M, Vicidomini M. A comparative thermoeconomic analysis of fourth generation and fifth generation district heating and cooling networks. Energy 2023;284:128561. https://doi.org/10.1016/j.energy.2023.128561.

[128] Mans M, Blacha T, Schreiber T, Müller D. Development and application of an open-source framework for automated thermal network generation and simulations in Modelica. Energies 2022;15:4372. https://doi.org/10.3390/en15124372.

[129] Meesenburg W, Ommen T, Thorsen JE, Elmegaard B. Economic feasibility of ultra-low temperature district heating systems in newly built areas supplied by renewable energy. Energy 2020;191:116496. https://doi.org/10.1016/j.energy.2019.116496.

[130] Kauko H, Rohde D, Hafner A. Local heating networks with waste heat utilization: low or medium temperature supply? Energies 2020;13. https://doi.org/10.3390/en13040954.

[131] Kauko H, Kvalsvik KH, Rohde D, Hafner A, Nord N. Dynamic modelling of local low-temperature heating grids: a case study for Norway. Energy 2017;139:289–97. https://doi.org/10.1016/j.energy.2017.07.086.

[132] Park B-S, Imran M, Hoon I-Y, Usman M. Thermo-economic optimization of secondary distribution network of low temperature district heating network under local conditions of South Korea. Appl Therm Eng 2017;126:117–33. https://doi.org/10.1016/j.applthermaleng.2017.07.080.

[133] Barco-Burgos J, Bruno JC, Eicker U, Saldaña-Robles AL, Alcántar-Camarena V. Review on the integration of high-temperature heat pumps in district heating and cooling networks. Energy 2022;239:122378. https://doi.org/10.1016/j.energy.2021.122378.

[134] Buonomano A, Calise F, Palombo A. Buildings dynamic simulation: water loop heat pump systems analysis for European climates. Appl Energy 2012;91:222–34. https://doi.org/10.1016/j.apenergy.2011.09.031.

[135] Boesten S, Ivens W, Dekker SC, Eijdems H. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. In: Advances in geosciences. Copernicus GmbH; 2019. p. 129–36. https://doi.org/10.5194/adgeo-49-129-2019.

[136] Abugabbara M, Javed S, Bagge H, Johansson D. Bibliographic analysis of the recent advancements in modeling and co-simulating the fifth-generation district heating and cooling systems. Energy Build 2020;224:110260. https://doi.org/10.1016/j.enbuild.2020.110260.

[137] Udomsri S, Bales C, Martin AR, Martin V. Decentralized cooling in district heating network: system simulation and parametric study. Appl Energy 2012;92:175–84. https://doi.org/10.1016/j.apenergy.2011.10.009.

[138] Bruno JC, Usman A. Efficient integration of advanced absorption heat pumps and chillers in district heating and cooling networks. In: 36th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems (ECOS 2023), ECOS 2023. Spain: Las Palmas De Gran Canaria; 2023. p. 875–83. https://doi.org/10.52202/069564-0079.

[139] Mengist W, Soromessa T, Legese G. Method for conducting systematic literature review and meta-analysis for environmental science research. MethodsX 2020;7:100777. https://doi.org/10.1016/j.mex.2019.100777.

[140] Mark. How to calculate the 3-point moving averages from a list of numbers and describe the trend. Owlcation; 2023. https://owlcation.com/stem/How-to-calculate-the-3-point-moving-averages-from-a-list-of-numbers-and-describe-the-trend.

[141] Zhang Y, Johansson P, Kalagasidis AS. Quantification of overlapping heating and cooling demand for the feasibility assessment of bi-directional systems over Europe. Energy Build 2023;294:113244. https://doi.org/10.1016/j.enbuild.2023.113244.

[142] Wirtz M, Kivilip L, Remmen P, Müller D. Quantifying demand balancing in bidirectional low temperature networks. Energy Build 2020;224:110245. https://doi.org/10.1016/j.enbuild.2020.110245.

[143] Davies G, Lagoeiro H, Turnell H, Wegner M, Foster A, Evans J, Revesz A, Leiper A, Smyth K, Hamilton J, Cooke H, Maidment G. Evaluation of low temperature waste heat as a low carbon heat resource in the UK. Appl Therm Eng 2023;235:121283. https://doi.org/10.1016/j.applthermaleng.2023.121283.

[144] Möller B, Wiechers E, Persson U, Grundahl L, Connolly D. Heat Roadmap Europe: identifying local heat demand and supply areas with a European thermal atlas. Energy 2018;158:281–92. https://doi.org/10.1016/j.energy.2018.06.025.

[145] Geraedts M, Alpízar-Castillo J, Ramírez-Elizondo L, Bauer P. Optimal sizing of a community level thermal energy storage system. In: 2022 IEEE 21st Mediterranean electrotechnical conference (MELECON); 2022. p. 52–7. https://doi.org/10.1109/MELECON53508.2022.9842945.

[146] Wirtz M. nPro: a web-based planning tool for designing district energy systems and thermal networks. Energy 2023;268:126575. https://doi.org/10.1016/j.energy.2022.126575.

[147] Habib M, Timoudas TO, Ding Y, Nord N, Chen S, Wang Q. A hybrid machine learning approach for the load prediction in the sustainable transition of district heating networks. Sustain Cities Soc 2023;99:104892. https://doi.org/10.1016/j.scs.2023.104892.

[148] Millar M-A, Elrick B, Jones G, Yu Z, Burnside NM. Roadblocks to low temperature district heating. Energies 2020;13:5893. https://doi.org/10.3390/en13225893.

[149] Schmitt S, Zeh R, Stockinger V. Quantification of heat losses and gains of 5th generation district heating and cooling networks compared to conventional heating networks. Bauphysik 2022;44:337–43. https://doi.org/10.1002/bapi.202200036.

[150] Allen A, Henze G, Baker K, Pavlak G. Evaluation of low-exergy heating and cooling systems and topology optimization for deep energy savings at the urban district level. Energy Convers Manag 2020;222:113106. https://doi.org/10.1016/j.enconman.2020.113106.

[151] Nagano T, Kajita J, Yoshida A, Amano Y. Estimation of the utility value of unused heat sources for a CO2 network system in Tokyo. Energy 2021;226:120302. https://doi.org/10.1016/j.energy.2021.120302.

[152] Kajita J, Yoshida A, Amano Y. Evaluation of a CO2 network system for district heating and cooling using energy storage tanks. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85138234126&partnerID=40&md5=35903de4b1e8f524cd38fa9c282e6200; 2021.

[153] von Rhein J, Henze GP, Long N, Fu Y. Development of a topology analysis tool for fifth-generation district heating and cooling networks. Energy Convers Manag 2019;196:705–16. https://doi.org/10.1016/j.enconman.2019.05.066.

[154] Allen A, Henze G, Baker K, Pavlak G, Murphy M. An optimization framework for the network design of advanced district thermal energy systems. Energy Convers Manag 2022;266:115839. https://doi.org/10.1016/j.enconman.2022.115839.

[155] Abugabbara M, Lindhe J. A novel method for designing fifth-generation district heating and cooling systems. E3S Web Conf. 2021;246:09001. https://doi.org/10.1051/e3sconf/202124609001.

[156] Lumbreras M, Diarce G, Martin-Escudero K, Campos-Celador A, Larrinaga P. Design of district heating networks in built environments using GIS: a case study in Vitoria-Gasteiz, Spain. J Clean Prod 2022;349:131491. https://doi.org/10.1016/j.jclepro.2022.131491.

[157] Egberts P, Tümer C, Loh K, Octaviano R. Challenges in heat network design optimization. Energy 2020;203:117688. https://doi.org/10.1016/j.energy.2020.117688.

[158] Werner S. Network configurations for implemented low-temperature district heating. Energy 2022;254. https://doi.org/10.1016/j.energy.2022.124091.

[159] Buonomano A, Forzano C, Palombo A, Russo G. Solar-assisted district heating networks: development and experimental validation of a novel simulation tool for the energy optimization. Energy Convers Manag 2023;288:117133. https://doi.org/10.1016/j.enconman.2023.117133.

[160] Hering D, Xhonneux A, Müller D. Design optimization of a heating network with multiple heat pumps using mixed integer quadratically constrained programming. Energy 2021;226:120384. https://doi.org/10.1016/j.energy.2021.120384.

[161] Revesz A, Jones P, Dunham C, Riddle A, Gatensby N, Maidment G. Ambient loop district heating and cooling networks with integrated mobility, power and interseasonal storage. Build Serv Eng Res Tecnol 2022;43:333–45. https://doi.org/10.1177/01436244221085921.

[162] Jansen S, Mohammadi S, Bokel R. Developing a locally balanced energy system for an existing neighbourhood, using the 'Smart Urban Isle' approach. Sustain Cities Soc 2021;64:102496. https://doi.org/10.1016/j.scs.2020.102496.

[163] Revesz A, Dunham C, Jones P, Bond C, Fenner R, Mody S, Nijjhar R, Marques C, Maidment G. A holistic design approach for 5th generation smart local energy systems: project GreenSCIES. Energy 2022;242:122885. https://doi.org/10.1016/j.energy.2021.122885.

[164] B. (Bart) Roossien, Technical design framework for cold heating and cooling networks, (n.d.).

[165] Wirtz M, Heleno M, Romberg H, Schreiber T, Müller D. Multi-period design optimization for a 5th generation district heating and cooling network. Energy Build 2023;284:112858. https://doi.org/10.1016/j.enbuild.2023.112858.

[166] Abugabbara M, Gehlin S, Lindhe J, Axell M, Holm D, Johansson H, Larsson M, Mattsson A, Näslund U, Puttige AR, Berglöf K, Claesson J, Hofmeister M, Janson U, Jensen AWB, Termén J, Javed S. How to develop fifth-generation district heating and cooling in Sweden? Application review and best practices proposed by middle agents. Energy Rep 2023;9:4971–83. https://doi.org/10.1016/j.egyr.2023.04.048.

[167] Buffa S, Fouladfar MH, Franchini G, Lozano Gabarre I, Andrés Chicote M. Advanced control and fault detection strategies for district heating and cooling systems—a review. Appl Sci 2021;11:455. https://doi.org/10.3390/app11010455.

[168] Vandermeulen A, van der Heijde B, Helsen L. Controlling district heating and cooling networks to unlock flexibility: a review. Energy 2018;151:103–15. https://doi.org/10.1016/j.energy.2018.03.034.

[169] Hering D, Cansev ME, Tamassia E, Xhonneux A, Müller D. Temperature control of a low-temperature district heating network with model predictive control and mixed-integer quadratically constrained programming. Energy 2021;224:120140. https://doi.org/10.1016/j.energy.2021.120140.

[170] Qin Q, Gosselin L. Multiobjective optimization and analysis of low-temperature district heating systems coupled with distributed heat pumps. Appl Therm Eng 2023;230:120818. https://doi.org/10.1016/j.applthermaleng.2023.120818.

[171] Gabrielli P, Acquilino A, Siri S, Bracco S, Sansavini G, Mazzotti M. Optimization of low-carbon multi-energy systems with seasonal geothermal energy storage: the Anergy Grid of ETH Zurich. Energy Convers Manag X 2020;8:100052. https://doi.org/10.1016/j.ecmx.2020.100052.

[172] Buffa S, Soppelsa A, Pipiciello M, Henze G, Fedrizzi R. Fifth-generation district heating and cooling substations: demand response with artificial neural network-based model predictive control. Energies 2020;13:4339. https://doi.org/10.3390/en13174339.

[173] Quirosa G, Torres M, Becerra JA, Jiménez-Espadafor FJ, Chacartegui R. Energy analysis of an ultra-low temperature district heating and cooling system with coaxial borehole heat exchangers. Energy 2023;278:127885. https://doi.org/10.1016/j.energy.2023.127885.

[174] Bu T, Fan R, Zheng B, Sun K, Zhou Y. Design and operation investigation for the fifth-generation heating and cooling system based on load forecasting in business districts. Energy Build 2023;294:113243. https://doi.org/10.1016/j.enbuild.2023.113243.

[175] K.M. Heissler, 5th generation district heating networks - potentials for reducing CO2-emissions and increasing the share of renewable energies in residential districts, (n.d.).

[176] Modelling and simulation of the fifth-generation district heating and cooling, (n.d.). https://lucris.lub.lu.se/ws/portalfiles/portal/98018067/MA_LicDiss.pdf (accessed October 16, 2023).

[177] Calise F, Cappiello FL, Dentice d'Accadia M, Petrakopoulou F, Vicidomini M. A solar-driven 5th generation district heating and cooling network with ground-source heat pumps: a thermo-economic analysis. Sustain Cities Soc 2022;76:103438. https://doi.org/10.1016/j.scs.2021.103438.

[178] Barone G, Buonomano A, Forzano C, Palombo A. A novel dynamic simulation model for the thermo-economic analysis and optimisation of district heating systems. Energy Convers Manag 2020;220:113052. https://doi.org/10.1016/j.enconman.2020.113052.

[179] Duran P, Torio H, Schoofeldt P, Klement P, Hanke B, von Maydell K, Agert C. Technology pathways and economic analysis for transforming high temperature to low temperature district heating systems. Energies 2021;14. https://doi.org/10.3390/en14113218.

[180] Rogers R, Lakhian V, Lightstone M, Cotton JS. Modeling of low temperature thermal networks using historical building data from district. Energy Systems 2019:543–50. https://doi.org/10.3384/ecp19157543.

[181] Betancourt Schwarz M, Mabrouk MT, Santo Silva C, Haurant P, Lacarrière B. Modified finite volumes method for the simulation of dynamic district heating networks. Energy 2019;182:954–64. https://doi.org/10.1016/j.energy.2019.06.038.

[182] Huber D, Illyés V, Turewicz V, Götzl G, Hammer A, Ponweiser K. Novel district heating systems: methods and simulation results. Energies 2021;14:4450. https://doi.org/10.3390/en14154450.

[183] Im Y-H, Liu J. Feasibility study on the low temperature district heating and cooling system with bi-lateral heat trades model. Energy 2018;153:988–99. https://doi.org/10.1016/j.energy.2018.04.094.

[184] Saini P, Huang P, fiedler F, Volkova A, Zhang X. Techno-economic analysis of a 5th generation district heating system using thermo-hydraulic model: a multi-objective analysis for a case study in heating dominated climate. Energy Build 2023;296:113347. https://doi.org/10.1016/j.enbuild.2023.113347.

[185] Blacha T, Mans M, Remmen P, Mueller D. Dynamic simulation of bidirectional low-temperature networks - a case study to facilitate the integration of renewable. Energies 2019. https://doi.org/10.26868/25222708.2019.210670.

[186] Maccarini A, Sotnikov A, Sommer T, Wetter M, Sulzer M, Afshari A. Influence of building heat distribution temperatures on the energy performance and sizing of 5th generation district heating and cooling networks. Energy 2023;275:127457. https://doi.org/10.1016/j.energy.2023.127457.

[187] Wetter M. Co-Simulation of building energy and control systems with the building controls virtual test bed. Journal of Building Performance Simulation 2011;4:185–203. https://doi.org/10.1080/19401493.2010.518631.

[188] Functional Mock-up Interface, (n.d.). https://fmi-standard.org/.

[189] Long N, Almajed F, von Rhein J, Henze G. Development of a metamodelling framework for building energy models with application to fifth-generation district heating and cooling networks. Journal of Building Performance Simulation 2021;14:203–25. https://doi.org/10.1080/19401493.2021.1884291.

[190] Abugabbara M, Lindhe J, Javed S, Bagge H, Johansson D. Modelica-based simulations of decentralised substations to support decarbonisation of district heating and cooling. Energy Rep 2021;7:465–72. https://doi.org/10.1016/j.egyr.2021.08.081.

[191] Jiang Y, Ma G, Gong Y, Wang L. Simulation research of a dual-loop booster heat pump system on district heating under ultra-low temperature. Appl Therm Eng 2023;228:120475. https://doi.org/10.1016/j.applthermaleng.2023.120475.

[192] Gillich A, Godefroy J, Ford A, Hewitt M, L'Hostis J. Performance analysis for the UK's first 5th generation heat network – the BEN case study at LSBU. Energy 2022;243:122843. https://doi.org/10.1016/j.energy.2021.122843.

[193] Zhu T, Ommen T, Meesenburg W, Thorsen J, Elmegaard B. Steady state behavior of a booster heat pump for hot water supply in ultra-low temperature district heating network. Energy 2021;237. https://doi.org/10.1016/j.energy.2021.121528.

[194] Bornand B, Girardin L, Belfiore F, Robineau J-L, Bottallo S, Maréchal F. Investment planning methodology for complex urban energy systems applied to a hospital site. Front Energy Res 2020;8. https://www.frontiersin.org/articles/10.3389/fenrg.2020.537973 (accessed November 8, 2023).

[195] E.O. Energiinfrastruktur, E.ON ectogridTM | A revolutionary heating and cooling solution, (n.d.). https://www.eon.se/en_US/foeretag/ectogrid (accessed December 23, 2023).

[196] Gao W, Masum S, Qadrdan M, Rhys Thomas H. A numerical study on performance efficiency of a low-temperature horizontal ground-source heat pump system. Energy Build 2023;291:113137. https://doi.org/10.1016/j.enbuild.2023.113137.

[197] District Heating and Cooling Networks Based on Decentralized Heat Pumps: Energy Efficiency and Reversibility at Affordable Costs, HPT - Heat Pumping Technologies (n.d.). https://heatpumpingtechnologies.org/publications/district-heating-and-cooling-networks-based-on-decentralized-heat-pumps-energy-efficiency-and-reversibility-at-affordable-costs/.

[198] Franzén I, Nedar L, Andersson M. Environmental comparison of energy solutions for heating and cooling. Sustainability 2019;11:7051. https://doi.org/10.3390/su11247051.

[199] Youn Y-J, Im Y-H. Technical feasibility assessment for a novel fifth-generation district heating model of interconnected operation with a large-scale building. Sustainability 2022;14:12857. https://doi.org/10.3390/su141912857.

[200] Millar M-A, Yu Z, Burnside N, Jones G, Elrick B. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. Appl Energy 2021;291:116672. https://doi.org/10.1016/j.apenergy.2021.116672.

[201] Quirosa G, Torres M, Soltero VM, Chacartegui R. Energetic and economic analysis of decoupled strategy for heating and cooling production with CO2 booster heat pumps for ultra-low temperature district network. J Build Eng 2022;45:103538. https://doi.org/10.1016/j.jobe.2021.103538.

[202] Vivian J, Emmi G, Zarrella A, Jobard X, Pietruschka D, De Carli M. Evaluating the cost of heat for end users in ultra low temperature district heating networks with booster heat pumps. Energy 2018;153:788–800. https://doi.org/10.1016/j.energy.2018.04.081.

[203] Kauko H, Pinel D, Graabak I, Wolfgang O. Assessing the potential of seasonal thermal storage for local energy systems: case study for a neighborhood in Norway. Smart Energy 2022;6:100075. https://doi.org/10.1016/j.segy.2022.100075.

[204] Brumana G, Franchini G, Ghirardi E, Ravelli S. Optimization of solar district heating & cooling systems. J. Phys.: Conf. Ser. 2022;2385:012113. https://doi.org/10.1088/1742-6596/2385/1/012113.

[205] Potential study on demand side management in district heating and cooling networks with decentralized heat pumps - -, (n.d.). https://bia.unibz.it/esploro/outputs/conferenceProceeding/Potential-study-on-demand-side-management/991005772682101241 (accessed October 16, 2023).

[206] Qin Q, Gosselin L. Economic assessment of bidirectional low-temperature district energy systems with seasonal energy storage and photovoltaic thermal hybrid solar system. In: Wang LL, Ge H, Zhai ZJ, Qi D, Ouf M, Sun C, Wang D, editors. Proceedings of the 5th international conference on building energy and environment. Singapore: Springer Nature; 2023. p. 1029–37. https://doi.org/10.1007/978-981-19-9822-5_109.

[207] Vecchi A, Rismanchi B, Mancarella P, Sciacovelli A. Daily and seasonal thermal energy storage for enhanced flexible operation of low-temperature heating and cooling network. In: Ecos 2021; 2021. http://hdl.handle.net/11343/281896 (accessed December 23, 2023).

[208] Cai H, Thingvad A, You S, Marinelli M. Experimental evaluation of an integrated demand response program using electric heat boosters to provide multi-system services. Energy 2020;193:116729. https://doi.org/10.1016/j.energy.2019.116729.

[209] Quirosa G, Torres M, Chacartegui R. Analysis of the integration of photovoltaic excess into a 5th generation district heating and cooling system for network energy storage. Energy 2022;239:122202. https://doi.org/10.1016/j.energy.2021.122202.

[210] IWAES – Integrative consideration of sustainable heat management of urban districts in the urban development process, (n.d.). https://www.iwaes.de/.

[211] TransUrban.NRW – Shaping the future of energy together, (n.d.). https://www.reallabor-transurban-nrw.de/.

[212] SmartQuart, SmartQuart (n.d.). https://smartquart.energy/english-abstract/.

[213] EnArgus, (n.d.). https://www.enargus.de/pub/bscw.cgi/?op=enargus.eps2&q=%2201173971/1%22&v=10&id=374538.

[214] ErdEis II - Energie PLUS Concept GmbH, (n.d.). https://energie-plus-concept.de/forschungsprojekte/erdeis-2.

[215] Turnell H, Marques C, Jones P, Dunham C, Revesz A, Maidment G. Driving success towards zero carbon energy targets for UK's Local Authorities. International Journal of Sustainable Energy Planning and Management 2023;38: 83–96. https://doi.org/10.54337/ijsepm.7548.

[216] GreenSCIES, GreenSCIES (n.d.). https://greenscies.com.

[217] Jones SR, Gillott M, Boukhanouf R, Walker G, Tunzi M, Tetlow D, Rodrigues L, Sumner M. A system design for distributed energy generation in low-temperature district heating (LTDH) networks. Future Cities and Environment 2019;5:2. https://doi.org/10.5334/fce.44.

[218] World's first prosumer residential community heat and electricity network wins national award - the University of Nottingham, (n.d.). https://www.nottingham.ac.uk/news/pressreleases/2018/october/world's-first-prosumer-residential-community-heat-and-electricity-network-wins-national-award.aspx.

[219] Coolgeoheat, (n.d.). https://www.coolgeoheat.eu/(accessed January 3, 2024).

[220] SANBA-smart anergy quarter Baden, (n.d.). https://www.nefi.at/en/project/sanba-smart-anergy-quarter-baden.

[221] 5GDHC |, (n.d.). https://5gdhc.eu/.

[222] D2Grids - Increasing the share of renewable energy by accelerating the roll-out of demand-driven smart grids delivering low temperature heating and cooling to NWE cities, (n.d.). https://vb.nweurope.eu/projects/project-search/d2grids-increasing-the-share-of-renewable-energy-by-accelerating-the-roll-out-of-demand-driven-smart-grids-delivering-low-temperature-heating-and-cooling-to-nwe-cities/.

[223] IEA DHC Annex TS1, (n.d.). https://www.iea-dhc.org/the-research/annexes/2012-2017-annex-ts1.

[224] Schmidt D, Lygnerud K, Werner S, Geyer R, Schrammel H, Østergaard DS, Gudmundsson O. Successful implementation of low temperature district heating case studies. Energy Rep 2021;7:483–90. https://doi.org/10.1016/j.egyr.2021.08.079.

[225] IEA DHC Annex TS2, (n.d.). https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts2.

[226] The STORM project | The STORM project, (n.d.). https://storm-dhc.eu/en (accessed October 17, 2023).

[227] Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks | REWARDHeat Project | Fact Sheet | H2020, CORDIS | European Commission (n.d.). https://cordis.europa.eu/project/id/857811.

[228] Home, (n.d.). https://www.life4heatrecovery.eu/.

[229] HeatNet. Transition strategies for delivering low carbon district heat. https://vb.nweurope.eu/projects/project-search/heatnet-transition-strategies-for-delivering-low-carbon-district-heat/; 2020.

[230] Mallows R. Technical annex - hydrogen heating. NIC; 2023. https://nic.org.uk/studies-reports/national-infrastructure-assessment/second-nia/hydrogen-for-heat-annex/.

[231] Lindhe J, Larsson M, Willis M, Tiljander P, Johansson D. Challenges and potentials of using a local heat pump in a 5 GDHC solution: results from field and laboratory evaluations. Energy 2024;289:129807. https://doi.org/10.1016/j.energy.2023.129807.

[232] Protopapadaki C, Saelens D. Heat pump and PV impact on residential low-voltage distribution grids as a function of building and district properties. Appl Energy 2017;192:268–81. https://doi.org/10.1016/j.apenergy.2016.11.103.

[233] Pakere I, Gravelsins A, Lauka D, Blumberga D. Will there be the waste heat and boiler house competition in Latvia? Assessment of industrial waste heat. Smart Energy 2021;3:100023. https://doi.org/10.1016/j.segy.2021.100023.

[234] De Lorenzi A, Gambarotta A, Morini M, Rossi M, Saletti C. Setup and testing of smart controllers for small-scale district heating networks: an integrated framework. Energy 2020;205:118054. https://doi.org/10.1016/j.energy.2020.118054.

[235] Sommer T, Sotnikov A, Sulzer M, Scholz V, Mischler S, Rismanchi B, Gjoka K, Mennel S. Hydrothermal challenges in low-temperature networks with distributed heat pumps. Energy 2022;257:124527. https://doi.org/10.1016/j.energy.2022.124527.

[236] Lizana J, Ortiz C, Soltero VM, Chacartegui R. District heating systems based on low-carbon energy technologies in Mediterranean areas. Energy 2017;120: 397–416. https://doi.org/10.1016/j.energy.2016.11.096.