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Review article

Fifth generation district heating and cooling: A comprehensive survey

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ABSTRACT

District heating (DH) networks are a key component of low-carbon urban heating in the future, as greenhouse gas emissions and sustainability concerns drive the heating sector to transform itself. DH is not a new technology, but it has been constantly evolving. The latest generation of DH facilitates the distribution of low-temperature renewable heat sources. In recent years, most studies have focused on managing peak demand, improving low-carbon technologies, and improving load prediction. However, there is a risk of misinterpretation, as recent generations of DH, which operate at significantly lower temperatures than conventional DH, are being developed simultaneously. This review aims to analyze the different definitions of the fifth-generation district heating and cooling (5GDHC) and introduce a straightforward concept of this new technology. It also describes the potential strengths, weaknesses, and challenges of integrating 5GDHC into existing systems, as well as practical recommendations. Finally, it analyzes the crucial components and notable characteristics of 5GDHC to provide a clear picture of its evolution and uniqueness.

1. Introduction

Climate change is a defining issue for our generation, prompting the development and implementation of serious measures to mitigate its impact on human life. Energy is one of the most critical factors in today's world (Hammar and Levihn, 2020), and the energy sector is experiencing radical transformations, including shifts in perspectives regarding energy usage and conservation. District heating (DH), a crucial component of the energy sector, plays a pivotal role in addressing climate change by enabling the widespread adoption of renewable energy sources (Sorknæs et al., 2020), integrating environmentally friendly technologies (Lake et al., 2017), and exploiting synergies through sector integration (Pozzi et al., 2021). As a result, DH remains at the forefront of energy research and receives significant attention from the research community.

All modern DH systems operate on a demand-driven basis, meaning that suppliers generate sufficient heat, cooling, and pressure to meet the needs of their customers. DH networks are common in various regions across North America, Europe, and Asia (Lund et al., 2018). These networks have undergone continuous improvements to reduce energy losses during distribution and achieve the highest possible efficiency rates (Buffa et al., 2019). Over time, DH systems have evolved through five generations, each with distinct features outlined in Table 1, adapted from Lund et al. (2018). Each generation typically corresponds to the prevailing technology of its time. Additionally, advances in component design, manufacturing processes, and construction techniques have contributed to a steady improvement in energy efficiency and a reduction in operating temperatures between older and newer generations of DH systems.

DH networks traditionally rely on a centralized control station to boil water and transfer hot water or steam through pipe networks to distribute heat to customers (Mazhar et al., 2018). However, early generations of DH systems often suffer from significant heat loss and high installation costs (Chicherin et al., 2020). For example, during the summer, when DH networks only need to meet hot water demand, thermal losses can amount to as much as 25% of the generated energy due to prolonged water retention in the pipe networks (for Storing Summer Heat To Use in Winter, 2022). To address these drawbacks, recent studies have focused on proposing innovative technologies for the fourth generation of DH (4GDH) networks. These technologies include excess heat utilization (Nielsen et al., 2020), novel thermal storage solutions (Yang et al., 2021), decentralized components, and the integration of renewable energy sources (Sorknæs et al., 2020). By incorporating these technologies, 4GDH networks significantly reduce

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Table 1
Classification of previous generations of DH.

Generation	Heat source	Temperature	Pipeline material	Advantages	Disadvantages
First (1880s)	Coal and waste	Steam (greater than 150 °C)	Concrete/steel	For industrial setups	High heat losses, inefficient, reliability and safety issue
Second (1930s)	Coal, waste, and oil	Pressurized hot water (greater than 100 °C)	Steel	Reliable operation, high flexibility, and energy savings	Cannot integrate low-grade renewable sources
Third (1970s)	Coal, biomass, waste, geothermal, and solar	Pressurized hot water (less than 100 °C)	Pre-insulated steel	Energy efficiency	Costly, cannot integrate renewable sources
Fourth (Current)	Mainly renewable energy	Hot water (less than 80 °C)	Pre-insulated twin flexible plastic	Lower heat losses, cost-effective, integration of low grade renewable heat sources, and efficient	Heat loss still remains, require extensive insulation
Fifth (Current)	Low temperature water	Near ambient ground (less than 45 °C)	Uninsulated plastic	Heat losses and insulation are greatly reduced, modular expansion	Requires significantly larger pipe diameters

operating temperatures, effectively utilize various energy sources, and minimize heat loss (Østergaard et al., 2022).

Furthermore, 4GDH systems effectively utilize sustainable heat sources, such as geothermal energy and waste incineration. However, these systems have some limitations. For example, it is currently not possible to use a single pipe to provide both heating and cooling services to buildings simultaneously (Buffa et al., 2019). To address this issue, the concept of 5th generation district heating and cooling (5GDHC) has been introduced. 5GDHC networks are still in their early stages of development, but numerous pilot projects have been conducted in Europe (Buffa et al., 2019), primarily using operating models that differ from traditional district heating and cooling (DHC) systems. The development of 5GDHC marks a significant leap from previous DH generations, introducing a range of improvements, including enhanced energy efficiency, substantial reduction in loss within DH grids, and seamless integration of DH networks into smart energy systems. Currently, there are no established technical procedures or standards for 5GDHC, and knowledge of its operational and management aspects is limited. While preparing this study, the authors identified multiple attempts to define 5GDHC, resulting in misinterpretation and reader confusion. Therefore, this study aims to elucidate the essential aspects of 5GDHC, categorize the gathered information, and provide a clear understanding to contribute to the development of this field.

1.1. Review methodology

The primary challenge during the preparation of this study was to identify and select relevant literature on DH. Relevant papers were those that directly discussed the topic of 5GDHC and its key components. The authors conducted a thorough search for relevant literature from 2015 to January 2023, primarily from online platforms such as technical journals, conference proceedings, and websites of prominent companies specializing in the design and installation of DH systems.

Initially, the authors identified the most recent DH review studies using key keywords such as *district heating*, *smart district heating*, *low-temperature district heating*, *low carbon heating*, and *distributed heat sources*. Next, we carefully reviewed the reference sections of these reviews to identify additional technical papers to be included in this review based on their relevance, quality, and significance to the 5GDHC topic. The authors found no quantitative research on statistical analysis applied to previous 5GDHC systems.

1.2. Relevant surveys

Table 2 presents the primary contributions of the most recent comprehensive reviews covering various aspects of DH. Overall, the number of DH-related reviews has increased significantly in recent years, demonstrating a growing interest in the topic.

In 2022, Østergaard et al. (2022) analyzed the role of low-temperature operation in heating systems, including temperature and energy requirements, typical malfunctions, and emerging enhancement techniques. Jodeiri et al. (2022) investigated the challenges of integrating sustainable heat sources into 4GDH systems and offered insights into future DH deployment directions. In 2021, Mbiydzenyuy et al. (2021) reviewed successful machine learning (ML) models for addressing DH issues, identified gaps between the DH and ML communities, and proposed a roadmap for leveraging ML advancements in the DH industry. Ntakolia et al. (2021) reviewed ML research in the DHC sector over the past few decades, analyzing the impact of factors such as weather and socioeconomic conditions on heat load prediction. Zhang et al. (2021) provided a comprehensive overview of the flexibility of DH systems in Northern China, exploring potential approaches for enhancing system flexibility and analyzing the significance of seasonal heat energy storage for DH applications.

In 2020, Abugabbara et al. (2020) investigated computational tools for evaluating DHC systems and described necessary control procedures for the successful implementation of 5GDHC systems. In 2019, Sarbu et al. (2019) conducted a comprehensive review of heat distribution network modeling and optimization, discussing major components, modeling techniques, and categorizing the latest research on DH optimization. Buffa et al. (2019) presented a comprehensive analysis of 5GDHC, providing a novel definition, analyzing benefits and drawbacks, and conducting a statistical analysis of key features observed in multiple 5GDHC systems. In 2018, Mazhar et al. (2018) provided an overview of the latest developments and distinctive features of a typical DH grid, summarized the economic and social impacts of DHs, and focused on analyzing the fourth generation DHs, representing the latest advancements in DH technology. In 2017, Werner (2017b) discussed various DH and cooling aspects, including technical, market, supply, institutional, and environmental factors, and presented a case study of current European DHC systems, highlighting their practical applications and outcomes.

Despite the abundance of DH-related reviews published in recent years, a comprehensive review of the fundamental aspects of 5GDHC is still lacking. This highlights the need for a comprehensive survey of these latest technologies.

1.3. Contributions

As discussed in Section 1.2, existing surveys on DH have primarily focused on specific aspects or domains, lacking a holistic understanding of the entire system. Additionally, the emergence of 5GDHC has introduced new hypotheses, procedures, and applications. Therefore, a comprehensive survey of recent DH research is imperative to benefit stakeholders, engineers, and researchers involved in building new DH

Table 2
Summary of existing DH surveys, which describes publication years and primary contributions.

ID	Ref	Year	Contributions
1	Jodeiri et al. (2022)	2022	• Explores the primary challenges associated with the integration of sustainable heat sources into 4GDH systems. • Identifies the current obstacles and provides insights into future directions for the deployment of DH.
2	Østergaard et al. (2022)	2022	• Analyzes the temperature and energy requirements of common heating systems. • Conducts a comprehensive review of typical heating malfunctions in buildings connected to DH. • Explores key prospects and emerging techniques for enhancing low-temperature heating systems.
3	Mbiydzenyuy et al. (2021)	2021	• Explores recent successful applications of ML models in addressing DH issues. • Presents and discusses the current gaps between the DH and ML communities. • Proposes a roadmap for leveraging ML advancements in the DH industry.
4	Zhang et al. (2021)	2021	• Provides a comprehensive overview of the flexibility of district heating systems in Northern China. • Explores potential approaches for enhancing the flexibility of DH systems. • Analyzes the significance of seasonal heat energy storage for DH applications.
5	Ntakolia et al. (2021)	2021	• Reviews the research on ML in the DHC sector over the past few decades. • Analyzes the impact of crucial factors, such as weather and socio-economic conditions, on heat load prediction.
6	Abugabbara et al. (2020)	2020	• Investigates recent studies that utilize computational tools for evaluating DHC systems. • Describes the necessary control procedures for the successful implementation of 5GDHC systems.
7	Sarbu et al. (2019)	2019	• Conducts a comprehensive review of heat distribution network modeling and optimization. • Discusses and reviews the major components and modeling techniques of a DH system. • Categorizes the latest research on DH optimization. • Provides various potential future directions for the topic of heat distribution networks.
8	Buffa et al. (2019)	2019	• Presents a novel and unambiguous definition of 5GDHC, incorporating the latest features of this technology. • Provides a comprehensive analysis of the benefits and drawbacks associated with 5GDHC. • Conducts a statistical analysis of key features observed in multiple 5GDHC systems.
9	Mazhar et al. (2018)	2018	• Provides an overview of the latest developments and distinctive features of a typical DH grid. • Offers a comprehensive summary of the economic and social impacts of DHs. • Focuses on analyzing the fourth generation DHs, which represents the latest advancements in DH technology.
10	Werner (2017b)	2017	• Provides a comprehensive analysis of various aspects of DHC, including technical, market, supply, institutional, and environmental factors. • Presents a case study of current European DHC systems, highlighting their practical applications and outcomes.

systems, integrating new technologies into existing ones, or conducting novel DH investigations. This review aims to bridge these gaps by summarizing and analyzing current DH studies, including generation, transmission, storage, and distribution. Additionally, it provides a comprehensive overview of 5GDHC, emphasizing critical areas of investigation, including:

- Conducts a comprehensive review of various aspects involving 5GDHC.
- Categorizes and analyzes each component comprising a standard 5GDHC network.
- Explores the major challenges associated with 5GDHC technologies.
- Describes and compares the implementation and operational costs of piloted systems.

The rest of this review is organized into six sections, each focusing on a specific aspect of a DH system. Section 2 provides an overview of the background and fundamental components of a DH system. Subsequent sections discuss each component in detail, including the heat source for 5GDHC (Section 3), thermal storage (Section 4), transmission networks (Section 5), and distribution networks (Section 6). Section 7 presents various future scenarios for 5GDHC, and Section 8 offers a comprehensive summary of the review, highlighting its strengths and weaknesses.

2. Background

To provide a common understanding of 5GDHC, this section explores existing definitions and highlights its importance through a strengths, weaknesses, opportunities, and threats (SWOT) analysis. Lund et al. emphasize that future generations of DH will harness renewable energy sources and facilitate significant reductions in heat consumption, in line with the global trend of reducing carbon emissions (Lund et al., 2018). Several defining characteristics of 5GDHC position it within a sustainable energy network:

- Low-temperature heat inside the pipe.
- Multi-energy system (MES), including cooling.
- Big share in the future energy market.
- Renewable energy sources.
- Minimum heat losses.
- Heat recycling and renewable energy integration.

2.1. 4GDH versus 5GDHC

5GDHC is currently under development alongside 4GDH, and these two technologies share many properties and characteristics (Schmidt et al., 2017; Nord et al., 2018). Both technologies aim primarily to decarbonize the energy sector. Additionally, 4GDH aligns with certain key principles of 5GDHC that will receive increased focus in the coming decades (Ommen et al., 2017). For example, the International Energy Agency (IEA) DHC Annex considers 5GDHC a subcategory of 4GDH networks. For example, Annex XIII Project 05, titled "Optimized transition towards low-temperature and low-carbon DH systems" (Annex, 2023), aims to facilitate the transition to low-temperature DH by providing adequate support for long-term decision-making to 4GDH companies.

The concept of 5GDHC can be misinterpreted as a linear evolution from previous DH generations. However, the transition to 5GDHC includes a broader range of technological innovations than the transition to 4GDH, which primarily focused on improving energy efficiency. Therefore, 5GDHC does not represent a sequential development following 4GDH; instead, both technologies are evolving concurrently. As a result, 5GDHC and 4GDH complement each other in their respective advancements and cannot be fully substituted for one another (Lund et al., 2021). 5GDHC is a rapidly emerging technology that is currently under development. Consequently, numerous studies have attempted to define 5GDHC definitively (Volkova et al., 2022). However, this multitude of definitions has created confusion and highlighted the need for a standardized and universally accepted definition of 5GDHC. The following are examples of some confusing definitions of 5GDHC:

- Low-temperature DHC (Im and Liu, 2018; Schmidt et al., 2017)
- Ultra-low temperature DH (ULTDH) (Ommen et al., 2017)
- Bidirectional low temperature district energy (Bünning et al., 2018; Bilardo et al., 2021)
- Cold DH (Pellegrini and Bianchini, 2018)

The aforementioned terms associated with 5GDHC are often unclear and difficult for general readers to understand. For example, some definitions emphasize temperature levels in the distribution medium, making them difficult to distinguish from other generations of DH. Additionally, some definitions contain contradictory terms, such as the pairing of the adjective "cold" with the noun "heating", which can be confusing. The existence of multiple definitions for the same concept can lead to misinterpretations and hinder the widespread adoption of 5GDHC. Consequently, finding a single comprehensive definition that encompasses all these aspects presents a significant challenge.

2.2. 5GDHC definition

To mitigate misinterpretation and confusion with 4GDH, it is strongly recommended, both by this study and previous research, to adopt the unambiguous term "Fifth-Generation District Heating and Cooling" (5GDHC) as the exclusive definition (Buffa et al., 2019; Wirtz et al., 2020). Furthermore, this terminology aligns with the classification of previous DH generations, which is based on the progressive reduction in the temperature of the distribution medium, as established by Lund et al. (2018). 5GDHC exhibits a range of distinct properties, such as robustness, bi-directional energy flows, decentralized integration with the electrical grid, and access to new sources of low-grade heat, all of which contribute to its significant growth potential (Bilardo et al., 2021). Furthermore, the adoption of a unified 5GDHC concept enhances its competitiveness and applicability in meeting heating and cooling demands on a comparable scale.

While previous reviews have covered the general principles and technologies of 5GDHC, our paper delves deeper into the key characteristics of 5GDHC networks and their practical applications in order to provide a comprehensive definition for 5GDHC as follows:

"5GDHC is a highly innovative and integrated energy system designed to provide efficient and sustainable heating and cooling solutions for urban areas in a more efficient and sustainable way than traditional district heating and cooling systems. It combines a set of advanced technologies, including centralized and decentralized heat pumps, large-scale thermal storage, smart grid systems, and thermal networks, to enable flexible energy generation, distribution, and utilization. Unlike previous generations of district heating and cooling, 5GDHC focuses on optimizing energy efficiency, reducing carbon emissions, and enhancing resilience to climate variations through the integration of various heat and cooling sources and advanced control strategies".

2.3. What is 5GDHC

The term 5GDHC was initially introduced in the H2020 project (Smart et al., 2020), representing a new generation of energy supply grids characterized by a significant number of local substations. Unlike previous generations, 5GDHC uses brine or water as the carrier medium, allowing it to deliver heat at temperatures close to the ambient ground temperature (31.84 °C in summer and 17.74 °C in winter) (Buffa et al., 2019). The low-temperature nature of 5GDHC offers several advantages, including minimal heat loss, reduced insulation costs, and the ability to utilize urban and industrial waste heat as well as various renewable heat sources.

In contrast to previous generations that directly transfer generated heat from power stations to local energy centers, each node in the 5GDHC system incorporates a heat pump (HP) to extract heat or cooling as needed (Zeh et al., 2023). This decentralized approach enables each node to utilize an appropriately sized HP based on its specific requirements. Additionally, 5GDHC promotes the integration of electrical, gas, and thermal grids in a decentralized smart energy network through the use of hybrid substations, fostering increased efficiency and flexibility.

5GDHC systems facilitate the exchange of thermal energy between buildings with varying supply and demand profiles. By participating in the network as both heat consumers and producers, end consumers become "prosumers" (Zinsmeister et al., 2021). These prosumers are interconnected with the low-temperature main grid, and the incorporation of HPs in each substation allows them to independently meet their heating/cooling requirements, regardless of the loop temperature. The low-temperature grid can be accessed through distributed building substations and adjusted to match the temperature needs on the demand side (Hermansen et al., 2022).

Simultaneously, excess heat from buildings can be transferred to the network and utilized as a heat source for neighboring buildings (Huang et al., 2020). The system incorporates storage capacity for heat and cold to balance the discrepancy between demand and supply, thus optimizing energy utilization and recycling within the network and reducing the need for external energy input to a minimum. Additionally, these systems are designed to be adaptable to low-grade renewable energy sources and waste energy sources (Meibodi and Loveridge, 2022).

Fig. 1 shows a schematic diagram of a district-level 5GDHC network, highlighting its self-contained nature. The system consists of two thermal loops: one for heating (warm water) and one for cooling (cold water) (Boesten et al., 2019). By incorporating HPs and energy storage at each end, the thermal loop efficiently recycles thermal energy. 5GDHC leverages various energy sources, including geothermal, water, wind, and solar, by supplying cooling water to power plants and integrating heat sources into the network (Boesten et al., 2019). This cyclic process enhances energy efficiency by redirecting cold water from residential usage to power plants for cooling, while simultaneously channeling waste heat from power plants to end-users. Different stakeholders, such as residential dwellings, industrial buildings, and offices, exhibit distinct energy load profiles that encompass year-round balance, seasonal variations, or dominance in either heat or cold consumption (Dang et al., 2022).

5GDHC grids facilitate the exchange of residual heat/cold among interconnected nodes, rather than linearly transporting heat from a supplier to a customer (Wirtz et al., 2020). For instance, glazed supermarkets and office buildings often need to reject heat year-round, especially during the day. On the other hand, residential buildings typically require heat in the winter and evenings during the shoulder seasons (spring and fall). Additionally, there is a significant potential for heat exchange when neighboring buildings experience simultaneous heat and cold demands (Boesten et al., 2019). The advantages of such exchange become more apparent as the system scales up, as the diversity of load profiles increases the likelihood of simultaneous supply and demand, effectively offsetting each other.

Storage facilities, including seasonal and short-term energy storage, play a crucial role in 5GDHC systems (Quirosa et al., 2022). They buffer the temporal gaps between renewable energy availability and heat pump operation, as well as between heat/cold production and demand during peak seasons. Thermal storage systems also significantly reduce the required power output of HPs, lowering investment costs. Winter is the peak heat season, while summer is the peak cold season. Through seasonal storage, excess heat generated during the hot season

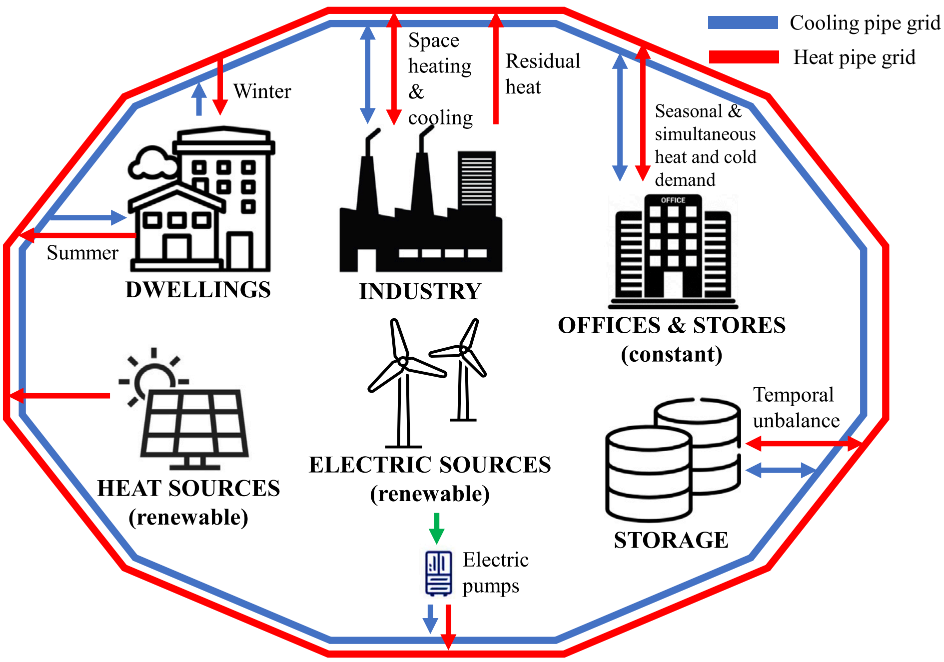

Fig. 1. Self-contained 5GDHC prototype. Note: It is self-balanced throughout the year because cold return flows from the heating supply and warm return flows from the cooling supply can meet a large portion of the demand. The residual heat/cold demand can be provided based on renewable energy.

can be stored and used during the cold season to meet part of the heat demand (Egging-Bratseth et al., 2021).

The incorporation of diverse renewable electricity sources into the 5GDHC grid is another significant transformation, allowing the utilization of heat pumps and transport pumps during periods of renewable energy abundance (Calise et al., 2022). Shallow geothermal energy, for example, is a reliable and secure renewable source with a vast thermal reach, enabling efficient distribution of available heat and cold throughout the city. In cases where renewable electricity is not accessible, alternative energy sources such as thermal mass and local buffers can be employed to ensure a continuous energy supply (Boesten et al., 2019).

The energy transferred through 5GDHC pipelines is characterized as free-floating, as the ambient ground temperature is not directly suitable for heat transfer (Boesten et al., 2019). This free-floating temperature also enhances the overall performance of the thermal grid. For instance, it allows for an increase in the number of warm pipes when this facilitates the utilization of higher temperature heat sources. Consequently, the thermal grids can also function as storage facilities for prosumers (Hennessy et al., 2019).

Fig. 2 shows the diverse temperature levels supported in the 5GDHC system, as well as the presence of HPs and the corresponding temperature levels at each node. Several crucial factors need to be considered, such as source temperature, pipeline temperature, supply and return temperature of local HPs, storage capacity, storage temperatures, and operational duration (Wirtz et al., 2021). Each temperature range has a specific configuration of HPs and buffers, with the possibility of using a dedicated HP for domestic hot water (DHW) if the standard HP fails to deliver the required temperatures adequately. With the integration of various renewable electricity sources, 5GDHC can be considered a multi-energy system (MES).

2.4. The 5 principles of 5GDHC

Five main principles of 5GDHC to ensure a robust and efficient energy grid that meets current and future demands are:

- Real closed energy loop: The heated or cooled buildings constantly lose energy due to various factors. This can be addressed by either (a) exchanging energy between buildings to meet heating/cooling demands, or (b) utilizing external energy sources (Lindhe et al., 2022). The fundamental principle of 5GDHC is to establish a closed energy grid that optimally utilizes return flows at different time and spatial scales, incorporating energy storage to address temporal imbalances and minimize energy wastage (Lindhe et al., 2022). For instance, conventional air conditioners release hot air into the environment while blowing cold air into a room. In contrast, the first principle of 5GDHC enables the capture and reuse of this hot air as a heating source within the network.
- Increasing usage of low-grade energy sources: 5GDHC aims to significantly reduce the use of high-grade energy sources to minimize its carbon footprint and meet local energy needs (Boesten et al., 2019). This transition involves embracing low-grade energy sources, such as waste heat from cooling processes, industrial waste heat, and shallow geothermal energy, which can eliminate fossil fuels from the network's energy production process. Additionally, high-temperature demand within the system can be met entirely with high-grade renewable energy sources such as deep geothermal or biomass energy (Romanov and Leiss, 2022).
- Demand-driven energy supply: The third principle of 5GDHC is to generate and distribute energy only when and where it is needed. When a demand for heating or cooling arises, the system responds quickly and at the required temperature level (Wirtz et al., 2021). This principle requires the systems to effectively deliver heating/cooling at various temperature levels to meet the diverse needs of consumers.
- Decentralization and local sources: Earlier generations of district heating predominantly relied on centralized systems, which circulated excess energy that was often wasted (Lindhe et al., 2022). Consequently, the fourth principle of 5GDHC emphasizes decentralization, gradually expanding local clusters to facilitate direct energy flow between and within buildings. This approach reduces transmission losses and promotes effective planning, cost optimization, and incentive structures. In the context of 5GDHC, heating/cooling can be simultaneously provided to diverse customers at various temperature levels, accurately aligning with their specific needs.

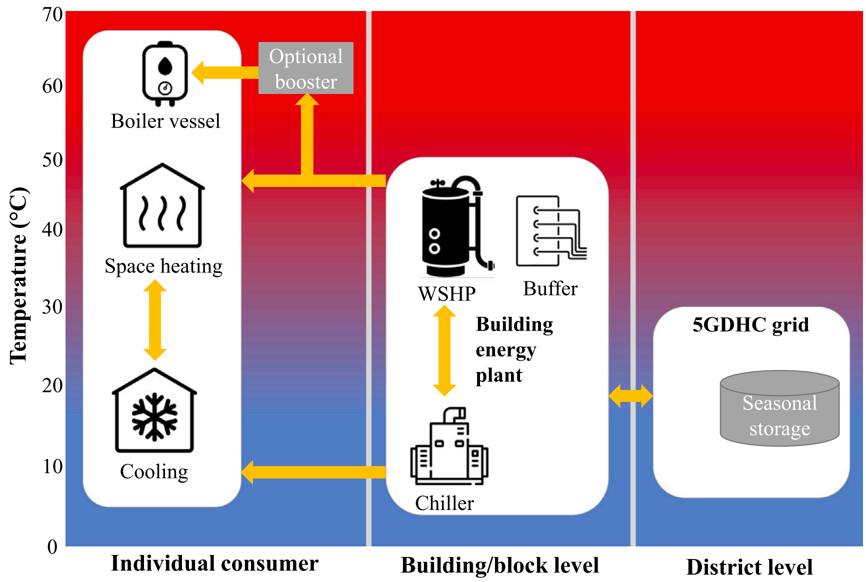

Fig. 2. Illustration of various components in different levels of the 5GDHC. The temperature of the heat/coolant changes from low to high as it moves from the generation side to the demand side.

- An integrated approach to energy flows: This principle embodies a holistic approach that includes various energy vectors, such as power grids, solar plants, and hydrogen conversion, aiming to mitigate energy waste across sectors and minimize peak loads (Sarbu et al., 2022). To achieve this, the integrated system leverages smart control mechanisms to accurately forecast and manage the supply and demand of diverse energy vectors from various sources to cater to distinct consumers (Dang et al., 2022). The approach not only further reduces waste but also prioritizes local balancing before interacting with the external grid, alleviating strain on the electricity grid and promoting a more stable and balanced system.

2.5. Why is 5GDHC important?

Fig. 3 presents a SWOT analysis of 5GDHC technology, highlighting its importance for the future smart energy grid. The analysis compares 5GDHC with previous generations of DH and conventional heating systems such as air conditioners and boilers, providing a comprehensive evaluation of its strengths, weaknesses, opportunities, and threats.

Low-temperature heating supply mechanisms in 5GDHC offer several advantages. First, they enable the efficient recovery of excess heat through a comprehensive circular design, harnessing energy synergies between district-level heat sources and heat sinks (Pozzi et al., 2021). Additionally, low-temperature urban excess heat (UEH) can be readily retrieved without the need for HPs or extensive transmission pipelines, as it is in close proximity to the heat demand side. This is in contrast to conventional high-temperature heating systems (Sandvall et al., 2021), which require high-grade heat sources and can experience significant heat losses during transmission.

Second, 5GDHC's bi-directional capability allows each substation to both retrieve and supply heat to the network simultaneously, ensuring the delivery of heating/cooling regardless of the network's overall temperature (Taylor et al., 2023). This flexibility is essential for accommodating the diverse heating and cooling needs of buildings and other consumers in a district.

Third, 5GDHC is highly flexible, comparable to individual heating systems, due to the freedom provided by its substations. Each substation typically incorporates a local HP, which can deliver thermal energy at both low and high temperatures to meet the specific needs of a building's heat emission system. Additionally, 5GDHC is scalable, allowing for easy expansion and rapid urban development through the interconnection of individual microgrids. For example, high-temperature HPs can be integrated into existing gas boiler circuits to match the high-temperature output of the boiler system (79 °C), achieving a high coefficient of performance (COP) and reducing gas consumption by 40% (Gillich et al., 2022). Moreover, 5GDHC systems are highly stable against changes in boundary conditions, such as varying consumer demands and building efficiency, as HPs can reliably supply thermal energy at both low and high temperature ranges to meet the heat emission network requirements of buildings.

Fourth, 5GDHC's focus on low temperatures has several advantages, including reduced thermomechanical stress and thermal loss in the heat transfer pipelines. This enables the use of high-density polyethylene (PE) pipes and components, which are commonly found in the water supply sector (Calixto et al., 2021). Compared to traditional DH systems, PE pipes can be deployed and adjusted to meet various requirements more easily and quickly, minimizing installation time and costs. In 5GDHC, pipe joints can be easily fitted without the need for complex processes such as tungsten inert gas (TIG) welding, high-precision inspections (X-ray, ultrasonic), and joint insulation, which were previously required in older DH generations (Kim and Kim, 2018). Furthermore, the low-temperature nature of 5GDHC enhances the energy efficiency of heat rejection units, solar thermal collectors, and combined heat and power (CHP) plants. Notably, the integration of seasonal thermal energy storage (TES) within 5GDHC networks is a crucial feature to consider (Yang et al., 2021). Multiple sources, such as seasonal TES and low-temperature heat storage in the ground or aquifers, can be utilized for heat/cold storage to maximize performance.

While 5GDHC offers numerous advantages over traditional DH systems, deploying a new system or integrating it into existing systems can be costly and complex due to the various components required in a local substation, such as a DHW tank and a local water-source heat pump (WSHP) (Østergaard and Andersen, 2018). For example, in the Duindorp district of the Netherlands, the additional cost per residence for installing a 5GDHC system was approximately €5500 compared to traditional heating systems (Foster et al., 2016). However, a centralized HP system powered by renewable energy can still be a competitive alternative. In addition to the cost and complexity of deployment, 5GDHC systems also require a higher volume velocity to deliver the same amount of heat as traditional DH networks due to the marginal difference in temperature between the warm and cold pipes,

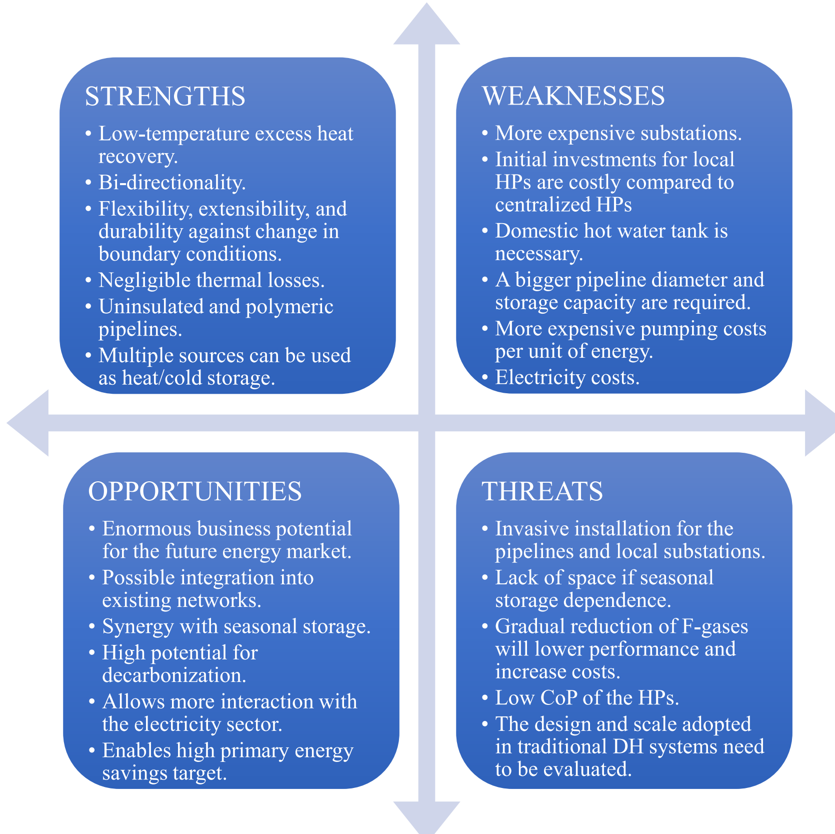

Fig. 3. SWOT analysis of the 5GDHC.

where brine is used as the carrier medium. However, the use of larger diameter pipes inherently reduces pressure loss (Kim and Kim, 2018).

Despite the challenges, the interconnection between the electrical grid and 5GDHC systems through the exploitation of excess heat sources and HPs presents an opportunity for heat providers and multi-utility companies to introduce new business models and prototypes (Zhang et al., 2022). The adoption of 5GDHC technologies also plays a significant role in accelerating the decarbonization of the heat sector, resulting in a substantial reduction in direct CO2 emissions and pollutants. Wirtz et al. implemented a practical use case of a 5GDHC prototype in Europe (Wirtz et al., 2020), utilizing an optimized mathematical model, demonstrating that the 5GDHC-based system produced over 50% fewer CO2 emissions and achieved 34% higher exergy efficiency compared to the previous system. Consequently, the development of 5GDHC is crucial for establishing sustainable green districts and retrofitting existing building stocks. However, the transition from previous generations of DH systems to 5GDHC systems is theoretically achievable but requires a thorough assessment of pipeline capacities and the challenging revision of traditional DH design blueprints to accommodate added components such as heat pumps and seasonal thermal energy storage (Volkova et al., 2022). Detailed setup configurations for 5GDHC have not been extensively described in the existing literature, and only a few entities have acquired knowledge of this technology through pilot projects (Wirtz et al., 2022).

A significant threat identified in the SWOT analysis presented in Fig. 3 is the heat sector's compliance with the F-gas regulation, which mandates the phase-down of fluorinated greenhouse gases (HFCs) (Purohit and Höglund-Isaksson, 2017). This regulation is expected to impact the performance and increase the cost of new equipment in the coming years. The European Union (EU) has taken a leading role in this process, having introduced its own "F-Gas" regulation in 2006 (Union, 2006), followed by an updated version in 2015 (Mota-Babiloni et al., 2015). In April 2022, the Commission proposed a legislative revision to further amend the F-gas Regulation. However, the European Heat Pump Market and Statistics Report (Pezzutto et al., 2017) shows that the HP market has doubled in size every 10–12 years. Additionally, the production costs of HPs are projected to decline by approximately 22% by 2024 and 39% by 2030, further enhancing the competitiveness of 5GDHC compared to conventional DH technologies and individual fossil-based heating systems.

2.6. How does an DH system operate?

DH networks can range in size from small housing schemes to entire areas or metropolises, and can include any type of building. A conventional DH grid typically starts with a generation module that produces heat using water as the primary heat transfer medium. The generated heat is then transferred through a network of pipes to customers, or stored for future use (Mazhar et al., 2018). Key components of a standard DH system include:

- Generation: A key advantage of DH is its ability to integrate multiple heat sources. By implementing a comprehensive management plan, diverse centralized and decentralized heating systems can be incorporated to ensure reliable operation and flexibility within the DH grid (Pieper et al., 2019). Moreover, under suitable conditions, a 5GDHC grid can also serve as a district cooling (DC) system during the summer season, utilizing the same heat sources.
- Transmission and distribution: The primary function of the transmission and distribution network is to transport energy to consumers and facilitate the return of cooled water to the source through an underground pipe network (Fallahnejad et al., 2018). The piping infrastructure is a costly component of the DH system, typically consisting of a combination of pre-insulated and field-insulated pipes used in concrete underpass and direct burial applications, respectively.

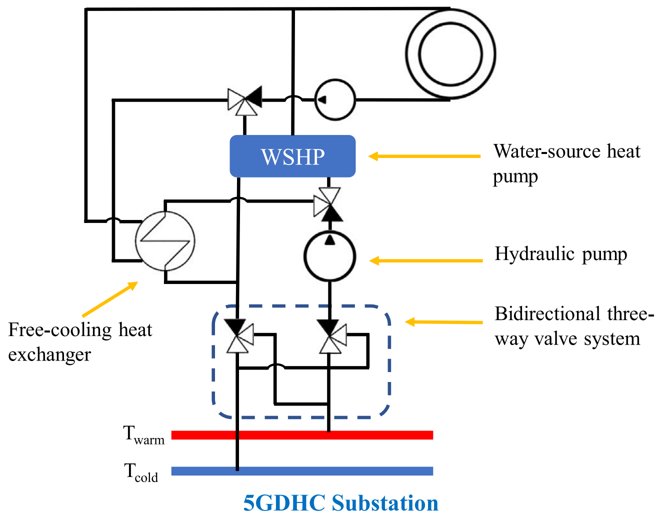

Fig. 4. Detailed description of a bi-directional 5GDHC substation, motivated by Buffa et al. (2019).

- Storage: Thermal storage plays a dual role in the 5GDHC system, functioning as a heat sink during periods of low heat demand and as a heat source when the network is under high load (Yang et al., 2021). Energy storage is a crucial element of 5GDHC because it mitigates potential issues arising from the increasing utilization of variable renewable energy sources and ensures system stability and reliability.

Heat and cold transportation to customers in a 5GDHC system is facilitated through a substation that contains one or more HPs responsible for generating the required temperatures to meet demand, as shown in Fig. 4. The substation also includes a boiler and a booster HP, which work together to generate DHW. This design eliminates the need for the 5GDHC network to transport thermal energy at specific temperatures, as each node in the network receives precisely what it requires. The bidirectional nature of these HPs allows them to supply both heating and cooling energy as needed. Furthermore, these HPs operate with a high coefficient of performance (COP), optimizing electric energy consumption to the point where they can be powered by renewable sources (Wirtz et al., 2021). Additionally, the HPs enhance system robustness by providing additional heat if the returned cold water remains above freezing temperatures.

3. Generation (Heat and cooling sources)

A key feature of 5GDHC is its remarkable flexibility in incorporating renewable heat sources. By using advanced control strategies, a wide range of centralized and decentralized heat sources can be seamlessly integrated into the DH grid, ensuring reliable operation and enhanced flexibility (Neuberger and Adamovskỳ, 2019). Additionally, with specific geographical features and additional requirements, the DH grid can effectively function as a district cooling system using the same heat source. The cooling heat source for 5GDHC systems is typically ambient ground temperature, meaning that the system uses the relatively constant temperature of the ground to provide cooling for buildings.

3.1. Heat sources

The heat source for a 5GDHC system can be a variety of renewable and non-renewable energy sources. Common heat sources incorporated in 5GDHC systems include:

- CHP power plants: These plants offer an efficient, clean, and decentralized approach to generating heat and electricity. These plants use various types of fuel to drive a prime mover, resulting in different ratios of heat and electricity production.
- Waste heat: This type of heat is generated as a byproduct in manufacturing, agricultural, or waste incineration processes, making it a valuable source of renewable energy.
- Geothermal: Geothermal energy, derived from the heat stored beneath the earth's surface, is a renewable energy source that can be harnessed for heating purposes.
- Solar thermal: By harnessing solar radiation and converting it into heat, solar thermal technology provides a renewable energy source for heating buildings.
- Conventional boilers: These boilers are useful for fulfilling peak load demands when other heat sources cannot fully satisfy the requirements. They can use various fuel sources, including renewable biomass.
- Heat pump: HPs are electrically-driven devices that transfer heat from a low-temperature source to a higher-temperature location. They are particularly effective when excess electricity is available.

Wei et al. (2010) conducted a comprehensive evaluation of heat sources using a fuzzy ranking technique to assess them based on important factors such as economic considerations, environmental impacts, and energy efficiency. Their proposed algorithm incorporated both numerical and non-numerical data to account for subjective, quantitative, qualitative, and objective aspects. The ranking of the selected heat sources, based on the mentioned criteria, was as follows: (1) CHP, (2) gas boilers, (3) water-source heat pumps, (4) coal boilers, (5) ground-source heat pumps, (6) solar energy-based heat pumps, and (7) oil boilers.

3.1.1. CHP heat sources

CHP, also known as cogeneration, is a widely adopted method in DH systems that efficiently generates both thermal energy and electricity using a variety of technologies and fuels (Wang et al., 2015). CHP has been the predominant source of thermal energy for DH networks globally and is expected to play a vital role in future high-density urban grids (Murugan and Horák, 2016). The inclusion of CHP plants in the DH system eliminates the need for independent heat production for domestic consumers. Without CHP, low-temperature heat sources are inefficiently generated by using high-temperature combustion exhaust gas. In contrast, CHP plants efficiently produce low-grade heat sources for domestic consumers as a byproduct of combustion, making CHP a preferable option due to its superior exergy and energy efficiency (Mahian et al., 2020). Furthermore, the heat network facilitates the distribution of the generated heat from large-scale CHP plants.

CHP is a mature technology, and recent research has focused on hybrid combinations, efficiency improvements, the use of better fuel sources, and comprehensive analysis (Wang et al., 2015; Olympios et al., 2020). For example, Wang et al. (2015) proposed various modeling techniques to optimize the management and operation of heat in combined CHP DH systems. These studies aim to achieve thermo-economic optimization of demand and supply within an integrated network. While fuel-cell CHPs stand out as a distinct variant, other types of CHP have been extensively developed, with their applications influenced by socioeconomic factors. Table 3 provides an overview of some notable trends in CHP.

3.1.2. Renewable heat sources

Renewable energy sources are highly preferred for 5GDHC systems due to their environmental friendliness and compatibility with low-temperature heat grids. Table 4 provides an overview of major renewable technologies that can be integrated into DH systems, ordered by their technology readiness level (TRL) as defined by the European Commission, ranging from 1 to 9. Waste heat, which was previously

Table 3
Overview of notable CHP variants for DH, highlighting their potential benefits and challenges.

Variant	Overview	Prospects	Challenges	Ref
Biomass	Biofuels, such as wood or energy crops, are used to provide heat.	• Significant growth is anticipated as there is a trend toward reducing carbon emissions. • Micro-combined CHP (mCHP) would be a crucial element of decentralized heat sources. • Optimization methods for economic, environmental and energy factors of Biomass CHP-based DH are proposed.	• Policies and infrastructure are insufficient. • Competition from other sectors.	Soltero et al. (2018) and Rezaei et al. (2021)
Gas	Gas is a major source of energy in CHP systems.	• Reliable and environmentally friendly technology. • Recent research has concentrated on applying alternative gas sources, such as syngas and biogas, to existing CHP systems.	• Requires considerable investments for alternative gas sources. • Competition from other sectors, especially transportation.	Jensen et al. (2020)
Coal	One of the most important fossil fuels burnt to provide heat.	• Old and relatively mature technology. • Existing large-scale plants (300–600 MW). • Most research tries to address operational problems to improve efficiency.	• High carbon emissions • Low efficiency compared with recent technologies. • Probably will become obsolete	Mirkowski and Jelonek (2019)
Combined Cycle Gas Turbine	A gas turbine is used to operate an electrical generator, and waste heat from the turbine is recovered to generate steam.	• Mature, developed technology capable of having variable fuel sources. • Previous studies have optimized performance and enhanced energy ratios produced with different thermodynamic cycles. • Management processes in complicated simulation systems have been studied to improve operation.	• Regulatory frameworks are required to foster this technology. • Control procedures, particularly in conjunction with DH, are quite complicated.	Yuan-Hu et al. (2019) and Zhang et al. (2019a)
Organic Rankine Cycle (ORC)	Low to medium temperature heat sources, such as solar thermal energy, biofuels, geothermal, and waste heat to produce power.	• Small-scale applications (a few kWs). • Huge potential for decentralized low-temperature 4th and 5th generation of DH. • Different fuels have been used to visualize potential performance in recent studies.	The choice of possible fluid sources becomes narrow with the recent banning of chlorofluorocarbons (CFCs).	Jang and Lee (2018) and Kavathia and Prajapati (2021)
Fuel-cell	Relies on the electrochemical process to transform the chemical inside a fuel into electricity.	• Mature, commercially available technology. • a clean energy source deemed a partial element in future DHP. • Recent studies have analyzed the operation of domestic operating conditions with both heat and energy generation.	• Poor infrastructure for providing hydrogen. • Fuels are more competitive than hydrogen production.	Fan et al. (2020) and Olabi et al. (2020)

overlooked due to its low temperature, has gained attention as a promising renewable source (Ziemele et al., 2018; Wang et al., 2019). While geothermal and solar thermal sources are ranked at TRL-9, their potential for utilization is less favorable compared to other sources such as bioenergy, industrial heat, and waste incineration.

3.2. Cooling source

The cooling heat source for 5GDHC systems is typically ambient ground temperature. This means that the system uses the relatively constant temperature of the ground to provide cooling for buildings. There are a number of ways to utilize ambient ground temperature for cooling in 5GDHC systems. One common approach is to use a ground-coupled heat exchanger (GCHE) (Ghoreishi-Madiseh et al., 2019). A GCHE is a system of pipes that are buried in the ground. The pipes are filled with a heat transfer fluid, such as water or brine. As the heat transfer fluid circulates through the pipes, it absorbs heat from the ground. The cooled heat transfer fluid is then pumped to buildings and used to cool them.

Another approach to using ambient ground temperature for cooling in 5GDHC systems is to use an aquifer thermal energy storage (ATES) system (Sheldon et al., 2021). An ATES system uses the groundwater in an aquifer to store and release heat. In the summer, the groundwater is cooled by pumping it through a heat exchanger and then back into the aquifer. In the winter, the groundwater is heated by pumping it through a heat exchanger and then back into the aquifer. The cooled or heated groundwater can then be pumped to buildings and used to cool or heat them. In addition to using ambient ground temperature, 5GDHC systems can also use a variety of other cooling sources, such as:

- Surface water: Surface water, such as rivers and lakes, can be used to cool buildings in 5GDHC systems. Surface water is typically cooler than ambient air temperature, making it an ideal source of cooling in hot climates.
- Wastewater: Wastewater from sewage treatment plants can also be used to cool buildings in 5GDHC systems. Wastewater is typically cooler than ambient air temperature and contains a significant amount of thermal energy.
- Seawater: Seawater can be used to cool buildings in 5GDHC systems in coastal areas. Seawater is typically cooler than ambient air temperature and contains a significant amount of thermal energy.

Table 4
Overview of trending renewable energy sources for 5GDHC, highlighting their potential benefits and challenges.

Technology	Overview	Prospects	Challenges	Ref
Waste heat (TRL-9)	The thermal energy that is not used in a process and is released into the environment.	• Delivers a huge amount of heat to nearby buildings. • Reduces some common DH fuel costs.	• Poor infrastructure for connecting industrial waste heat and DH systems. • Big differences in waste heat quality due to variants of industrial waste sources.	Huang et al. (2020) and He et al. (2018)
Solar thermal (TRL-9)	Sunlight and solar collectors are utilized to deliver water for HC purposes.	• High potential for usage in small-scale decentralized settings • Can provide cooling during warmer seasons using absorption chillers.	• Geographic assessments and careful planning are essential • Variations can significantly influence performance in peak demand	Tian et al. (2019) and Huang et al. (2019)
Bioenergy (TRL-9)	Matured renewable sources, including biofuels and biogas.	• Can be applied to small-scale rural grids and industrial thermal plants. • Can also be utilized in large-scale DH systems.	• Costly and the poor infrastructure. • Big competition from other sectors, such as transportation and agriculture. • Performance optimization has been overlooked.	Mäki et al. (2021) and Akgül and Seçkiner (2019)
Geothermal ground source (TRL-9)	Usually built above geothermal sources, such as hot springs, geysers or aquifers.	• Oldest and most mature DH sources • Produces year-round low-cost heating and cooling.	• Geologically limited. • Heavy investment costs.	Sáez Blázquez et al. (2018) and Zeh et al. (2021)
Waste incineration (TRL-9)	Urban waste is burnt to deliver heating to nearby buildings.	• Plays an important role in future CHP plants. • The energy output relies heavily on external circumstances.	• Lack of proper waste infrastructure • Potential health effects when the emissions are improperly managed	Penttinen et al. (2021)
Industrial waste heat (TRL-9)	The waste heat generated from industrial processes.	• Commonly harnessed in industrial setups. • High temperature heat sources are mostly available in solid carriers	• Poor infrastructure for connecting industrial waste heat and DH grids. • Harnessed waste heat quality can be affected by different industrial segments. • Requires thermal storage, mainly high-density latent heat storage.	Ziemele et al. (2018) and Wang et al. (2019)
Seawater (TRL-6)	Seawater is utilized to provide heating and space cooling.	• Able to transfer heat over longer distances. • Works on large-scale DH systems.	• Only functional near coastal cities. • Early state of development and costly.	Su et al. (2020)
Air-source absorption HP (TRL-3)	The air-source evaporator exploits low-grade heat from the ambient air to produce hot water.	• Novel technology that is still in the research stages. • The prospect of operation using spare electricity in small-scale decentralized setups is enormous.	• Unreliable due to its reliance on the outdoor atmosphere. • Can only be applied to small-scale decentralized grids.	Wu et al. (2020, 2021)

Despite the simultaneous provision of heating and cooling and the recovery of wasted energy, 5GDHC systems are still facing challenges in meeting the growing demand for cooling, which is projected to rise significantly in the future (Gjoka et al., 2023). Additionally, cooling demands typically peak during the summer, causing seasonal imbalances. As a result, separate provisions for cooling may be necessary, either through individual chillers or a dedicated supply and return pipe network with its own centralized plant (Werner, 2017a). Lastly, advanced storage technologies can be used to mitigate the challenges posed by seasonal imbalances; this topic will be discussed in the subsequent section.

4. Storage technologies for DH

4.1. Thermal storage

Heat storage is essential for 5GDHC and future generations of DH systems, primarily due to the growing reliance on renewable energy sources, which can be intermittent and unpredictable. Heat storage serves as a vital tool to address the community's increasing demand for efficient and environmentally friendly energy utilization, resulting in reduced energy consumption (Dahash et al., 2019; Romanchenko et al., 2021). The implementation of heat storage offers two significant environmental advantages. First, it enables significant reductions in fossil fuel usage through fuel substitution, leading to a transition to more sustainable energy sources. Second, it contributes to a substantial decrease in the emission of key pollutants, including carbon dioxide (CO2), nitrogen oxides (NOx), sulfur dioxide (SO2), and chlorofluorocarbons (CFCs).

Compared to electrical storage, heat storage is generally recognized as the more cost-effective option, as it allows for direct delivery of heat to domestic users without the need for advanced infrastructure or expensive material conversions. Sensible heat storage systems represent the earliest prototypes in heat storage, while latent heat storage is a rapidly emerging technology (Ghazaie et al., 2022). Thermal storage plays a critical role in the future integration of electric and heat networks. It can serve as a heat sink during periods of low heat demand and as a heat source during peak-demand seasons (Dahash et al., 2019). Additionally, thermal storage can be implemented in both large-scale centralized systems, such as underground pits or caverns, and decentralized small-scale systems, such as household drums. Decentralized heat storage offers greater flexibility, while centralized heat storage is easier to manage (Moallemi et al., 2019). A comprehensive analysis of heat storage, combined with district heating, is provided in Table 5.

4.2. Cooling storage

Cooling storage technologies for 5GDHC systems are used to store surplus cooling energy during the day and release it at night, when cooling demand is higher. This can help to reduce the need for mechanical compression chillers, which can be expensive and energy-intensive to operate (Kılıç, 2022). There are a number of different cooling storage

Table 5
Overview of key thermal storage technologies for 5GDHC, highlighting their potential benefits and challenges.

Approach	Summary	Prospects	Challenges	Ref
Pit storage/Geothermal storage	Water is pumped into an underground cavern or man-made reservoir.	• Large scale storage mechanism. • A mature and commercially available technology.	• Huge heat losses and cost of infrastructure development. • Require extended access time with limited control. • Supports only long-term and peak shaving options.	Formhals et al. (2021)
Aquifer thermal energy storage	Extraction and injection of groundwater (heat/cold) from aquifers.	Cost-effective technology to reduce the energy consumption and emission of a building.	Strongly dependent on the temporal variation of temperature in the aquifer.	Schmidt et al. (2018) and Todorov et al. (2020)
Building materials	Relatively new passive storage approach using thermal inertia, such as filled concrete block, stone or masonry.	• High heat capacity and density • Relatively inexpensive and durable. • Ongoing research.	• Can be expensive to install. • Can only be used as a buffer for short-term storage. • Limited control once the building is finished.	Dominković et al. (2018) and Kuczyński and Staszczuk (2020)
Tanks	Hot water is kept in a simple insulated drum	• Supports both small-scale and large-scale applications. • Low higher density fluids are being proposed.	• Small energy storage density. • High losses and low efficiency. • Extended charging and discharging duration with limited control.	Dahash et al. (2019) and Romanchenko et al. (2021)
Latent energy storage	Stores heat in a storage medium (potential energy between the particles of the substance)	• High storage density with low thermal conductivities. • Ongoing research is progressing at a rapid pace.	• Corrosion/decay issues over long-term usage. • Not suitable for all tanks and metallic encapsulates.	Jouhara et al. (2020)

technologies available, but the most common types used in 5GDHC systems are:

- Sensible heat storage: Sensible heat storage systems store thermal energy by raising the temperature of a storage medium, such as water or concrete (Frate et al., 2020). The stored energy is then released by lowering the temperature of the storage medium. They are the most common type of cooling storage system used in 5GDHC systems (Guelpa and Verda, 2019). They are relatively simple and inexpensive to install, and they can be used to store large amounts of thermal energy. Sensible heat storage systems typically use a tank of water as the storage medium. The water is cooled during the day using a chiller or other cooling device. The chilled water is then stored in the tank until it is needed to cool buildings at night.
- Phase change material (PCM) storage: PCM storage systems store thermal energy by melting and solidifying a PCM. PCMs are materials that have a high latent heat of fusion, which means that they can absorb or release a lot of thermal energy without changing temperature (Faraj et al., 2020). PCMs can store more thermal energy per unit volume than water, which means that PCM storage systems can be smaller and more compact than sensible heat storage systems. PCM storage systems typically use a PCM that has a melting point in the range of 5–15 °C. This means that the PCM will melt during the day as it absorbs heat from the surrounding environment. The melted PCM is then stored in a tank until it is needed to cool buildings at night.
- Adsorption storage: Adsorption storage systems store thermal energy by adsorbing water vapor onto a solid desiccant material, such as silica gel (Roumpedakis et al., 2020). The stored energy is then released by desorbing the water vapor from the desiccant material. Adsorption storage systems are still under development, but they have the potential to be the most efficient type of cooling storage technology.

5. Transmission

The transmission lines in a 5GDHC system consist of an extensive network of underground pipes, which interconnect cohesive areas to form a unified DH grid (Fallahnejad et al., 2018). These pipelines facilitate the transfer of warm water or cooling to consumers, while also allowing the transport of cooled or hot water to other local sources within the network.

5.1. Transmission temperatures

In the past, geothermal grids were primarily implemented on a small scale, catering mainly to the provision of hot water rather than DH or domestic heating (Lygnerud et al., 2019; Schmidt et al., 2017). The majority of existing DH systems are non-compliant with energy efficiency standards and suffer from technological obsolescence. Conversely, low supply temperature DH systems, such as 4GDH and 5GDHC, offer significant advantages over conventional high supply temperature DH systems, including the sustainable reduction of heat loss and the utilization of renewable energy sources and surplus heat (Gudmundsson et al., 2021). Some notable benefits of low-temperature grids compared to previous DH systems include:

- Substantially reduced energy requirements for both hot water supply and space heating.
- Robust and efficient low-temperature grid that lowers investment expenses.
- Minimal heat dissipation from the pipes to the ground due to the lower temperatures involved.
- Effective utilization of low-grade waste heat and integration of various decentralized energy sources.
- Contributes to the development of a smart grid, offering high flexibility and scalability as renewable sources become more prevalent.

The objective of 5GDHC aligns closely with the latest trends in DH, emphasizing lower network temperatures, decentralized substations, and simplified system architectures. 5GDHC grids demonstrate remarkable adaptability and are well-suited for operation in cold climates. In contrast, current third-generation DH systems suffer from significant energy waste, with over two-thirds of the initial exergy content in the fuel being lost as heat during the generation process, which is solely utilized for DH purposes (Dorotić et al., 2019). Consequently, these systems exhibit an annual exergy efficiency ranging from 15% to 18%. In contrast, 4GDH and 5GDHC systems offer significantly improved exergy efficiency and greatly enhance the utilization potential of low-grade heat. However, the lower temperatures and pressures involved in these systems introduce two notable challenges in piping: moisture-related issues (Akhmerova et al., 2020) and the growth of legionella (Toffanin et al., 2021). These are primary areas of research interest.

5.2. Transmission equipment

Heat loss and friction loss are the primary sources of energy dissipation in DH network pipelines. Heat loss typically accounts for 5%–20% of the transmitted energy and can be influenced by various factors, including pipe length, external conditions, and insulation quality (Chicherin et al., 2020). On the other hand, friction loss ranges from 100 to 250 Pa/m and is affected by the pipe material's roughness (Wang et al., 2018). Maintaining a minimum pressure in the network at all times is essential to prevent problems such as cavitation.

5.2.1. Pipeline types

Previous generations of DH systems typically relied on a two-pipe network consisting of supply and return pipes (Li and Nord, 2018). In contrast, 5GDHC systems can utilize two primary pipeline configurations:

- Single-pipeline setting: Also known as reservoir networks, single-pipeline systems use a single pipe to distribute and collect thermal energy (von Rhein et al., 2019; Khosravi and Arabkoohsar, 2019). This configuration typically requires larger pipe diameters and longer lengths than two-pipe networks. However, single-pipeline systems offer a number of advantages, including lower investment costs, reduced heat loss, and increased flexibility.
- Twin-pipeline setting: Twin-pipeline systems use two separate pipes, one for supply and one for return. This configuration is more common in existing DH systems, but it can be more expensive to install and maintain than single-pipeline systems.

In the single-pipeline mechanism of 5GDHC, consumers' heating or cooling demands are met through a single pipeline grid. Within this system, a WSHP directly draws or discharges the heat transfer fluid from the same pipeline to meet the heating or cooling requirements. On the other hand, in the twin-pipeline mechanism, heat transmission in 5GDHC networks involves extracting warm water from one pipe, using a WSHP to extract the heat, and then directing the cooled water to a separate cooler pipe. To meet the cooling demand, the reverse process is applied. Sommer et al. (2020) conducted a comparative analysis of the two pipeline mechanisms used in 5GDHC systems for multiple consumers. Their study found that the single-pipe setting required half the length of pipes and a nearly 95% increase in diameter compared to the twin-pipe configuration, resulting in higher hydraulic pump consumption. Additionally, the single-pipeline mechanism showed a minimal increase of less than 2% in energy consumption (including both heat pumps and hydraulic pumps) compared to the twin-pipeline networks. Based on these findings, it can be concluded that the single-pipeline setting is well-suited for small grids with low flow requirements. However, in larger grids, heat and hydraulic losses are higher, requiring greater consumption from both circulation pumps and HPs to compensate for these losses. Therefore, the twin-pipeline configuration is considered a more favorable choice for large-scale DH grids.

Recently, Alsagri et al. (2019) proposed a triple-pipeline configuration as an alternative to the twin-pipeline setup for transmitting and distributing heat in DH systems in Europe. The triple-pipe configuration introduces an additional supply line to optimize the network's performance during peak heat demands. The authors demonstrated that the triple-pipe setting significantly reduces heat loss rates, resulting in lower operating costs for the entire system. Furthermore, several innovative piping schemes have been proposed in recent years and have found applications in the market. For instance, Millar et al. (2020) proposed a four-pipeline mechanism, while a flexible corrugated pipe design has been introduced to eliminate joint appearance and enable service over longer distances (Al-Obaidi, 2019). Some of the new pipe types incorporate internal moisture detection mechanisms and utilize polyurethane foam insulation to extend their lifespan. These pipes typically range in diameter from 25 to 100 cm (Elleuchi et al., 2019). However, it is important to note that the initial investment required for implementing these advanced pipeline systems can be substantial, and the high operating costs associated with increased hydraulic pump usage may make these configurations less attractive for 5GDHC applications.

5.2.2. Pipeline material

While the market offers a wide range of pipe types and materials, the most commonly used pipe materials in previous DH systems that operate at high temperatures and pressures (above 90 °C and 16–25 bars) are typically aluminum, copper, or steel (Kim and Kim, 2018). However, due to the low operating temperatures in 5GDHC networks, which eliminate thermomechanical stresses, it is now possible to use third-generation pipe-grade polyethylene (PE) materials, such as PE 100 or PE 100-RC, without the need for insulation.

PE 100 is commonly used in drinking water supply networks, and requires a sand bed for backfilling. In contrast, PE 100-RC eliminates the need for a sand layer (Risitano et al., 2020). PE 100-RC exhibits exceptional characteristics such as a long lifespan, crack resistance, and robustness against point loads or stresses (Neuberger and Adamovskỳ, 2019). These attributes facilitate rapid and cost-effective installations while accommodating various network geometries. Furthermore, the use of PE 100-RC eliminates the need for pipe welding, expensive inspection equipment (such as X-ray or ultrasound), and complex on-site pipe insulation. However, it is important to note that compared to previous generations of DH systems, the pipes used in 5GDHC often require a larger diameter to transport the same heat load, which can result in higher energy consumption by the pumps.

5.2.3. Pipe diameter

As discussed in the previous section, 5GDHC systems operate at lower temperatures than previous generations of DH systems. This requires a higher circulating flow rate, which leads to larger pipe diameters in the distribution network and increased operational costs for hydraulic pumps. To address this issue, Zeng et al. (2016) introduced a genetic optimization-based mathematical model to determine the optimal pipe diameter, considering factors such as initial investment, operation, and maintenance costs of the hydraulic loop. Their experiments showed that both fluctuating electricity prices and nominal flow rates influenced the optimal pipe diameter.

5.2.4. Circulating pumps

In addition to the pipe network, a DH grid comprises multiple components, such as circulating pumps, sensors, and control equipment. Circulating pumps play a crucial role in maintaining stable pressure within the system, ensuring smooth water flow at the desired rate throughout the pipe grid (Gong et al., 2019). Additionally, these pumps help to reduce friction loss, heat loss, and the required elevation for water delivery to buildings. Since the energy demand of the water varies dynamically due to external factors, modern pumps incorporate variable speed drives to optimize overall efficiency.

Heat loss is a significant source of loss in the system, accounting for approximately 5%–20% of the energy delivered (Chicherin et al., 2020). Several factors affect heat loss, including pipe insulation, external conditions, and transmission length. Maintaining a minimum pressure in the pipelines is essential to prevent problems such as cavitation, which can lead to friction loss due to pressure head loss caused by friction. Friction loss typically ranges from 100 to 250 Pa/m (Sarbu et al., 2019).

Innovative circulating pump configurations have been developed to optimize electricity consumption in 5GDHC networks. One such configuration is to use distributed variable-speed pumps (DVSPs) installed in each prosumer's substation, replacing the conventional central circulating pumps (CCCPs). For example, Wang et al. (2017) proposed implementing DVSPs in local substations of 5GDHC networks, along

Table 6
Comparison of various aspects of the direct and indirect connection approaches.

Direct connection	Indirect connection
Primary and secondary heating sides are the same	Primary and secondary heating sides are separated
Low temperature heat supply and return	The primary side is flexible and can function at any temperature or pressure
No requirement for decoupling interface or junction	Heat exchanger and auxiliary apparatus are required
No requirement	Substation is referred
Low heat losses	High heat loss
Suitable for small-scale supply	Suitable for large-scale supply
Economical	High capital cost

with a new hydraulic regulation algorithm to adjust the pumps to their designated frequencies, effectively preventing hydraulic oscillation. Their experimental results demonstrated a substantial reduction in power consumption of up to 90% compared to the original CCCPs.

6. Distribution

The DH substation plays a vital role in current DH systems, linking the main grid to a building's local substations (Buffa et al., 2020). In this configuration, the main DH grid and its heating system are referred to as the primary heating side, while the local substation within a building, along with its heating system and water, are considered the secondary side. Various components of the distribution grids can influence the heat distribution process in a 5GDHC system, and these components are described in detail in the following subsections.

6.1. Connection approach

Two approaches can be employed to establish a connection between the DH grid and a local node: direct and indirect approaches (Zhang et al., 2021). Table 6 outlines these approaches. The indirect connection method, currently the dominant approach for large-scale supply, uses a heat exchanger to separate the primary and secondary heating fluids (Werner, 2017a). However, this approach incurs high heat loss within the network. In contrast, the direct connection method ensures lower heat loss by utilizing low-temperature heat supply and return, resulting in energy savings for small-scale supply. Compared to the indirect connection, the direct connection method is more cost-effective and offers the additional advantage of reducing initial investment requirements.

Two approaches can be employed to establish a connection between a DH grid and a local node in the DH network: direct and indirect approaches (Zhang et al., 2021). These approaches are outlined in Table 6. Currently, the indirect connection method is predominantly used for large-scale supply, where a heat exchanger is employed to separate the primary and secondary heating fluids (Werner, 2017a). However, this approach is associated with high heat loss within the network. On the other hand, the direct connection method ensures lower heat loss by utilizing low-temperature heat supply and return, resulting in energy savings for small-scale supply. Compared to the indirect connection, the direct connection method is more cost-effective and offers the additional advantage of reducing initial investment requirements.

6.2. Pipeline topology

Previous DH systems were predominantly designed with local conditions in mind, resulting in a variety of piping layouts and grid topologies. In general, there are two primary grid topologies: linear and

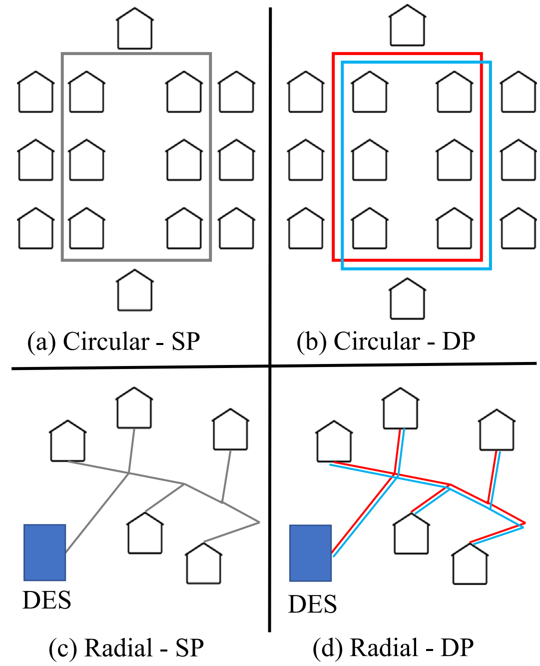

Fig. 5. Standard 5GDHC grid topology. Note: SP stands for single-pipeline setting and DP is a twin-pipeline system.

circular layouts (von Rhein et al., 2019) (see Fig. 1). The linear grid configuration features a centralized district energy system (DES) at its core, which can consist of a boiler for heating or a chiller for cooling purposes. The DES serves as the central hub from which pipes extend and connect to the surrounding buildings.

The circular topology, on the other hand, is characterized by multiple heat sources and offers enhanced security of supply. Its primary feature is the closed-loop main pipeline (Garbai and Jasper, 2017). Given that 5GDHC systems are designed to accommodate a large number of prosumers connecting to the heating and cooling sources, the circular setup is considered the optimal choice (Huber et al., 2021). Furthermore, the circular topology is particularly effective in managing high demand diversity, as it enables a balanced supply and demand of heating/cooling throughout the year. However, it should be noted that the piping and trenching requirements for the circular topology are significantly higher compared to the linear setup, resulting in a higher investment cost. Thus, there exists a potential trade-off between investment costs and energy efficiency that needs to be carefully considered during the early development phase (Ho et al., 2021) (see Fig. 5).

6.2.1. Heat exchanger

Heat exchange is the process of transferring thermal energy between two substances or mediums with different temperatures. It is a fundamental process in many engineering applications, including DHC systems. In DHC substations, the most commonly used liquid-to-liquid heat exchangers are the shell and tube heat exchanger (STHE), shell and coil heat exchanger (SCHE), and plate heat exchanger (PHE) (see Fig. 6) (Wang et al., 2021). In larger buildings, multiple heat exchangers can be connected in parallel to meet the heating or cooling demands. The STHE is the most widely used type, featuring a large shell housing bundles of precisely spaced tubing that facilitate efficient heat transfer (Rashidi et al., 2022). The tubing in STHE is typically made of stainless steel to prevent fouling damage. In contrast, the PHE consists of a series of parallel plates stacked together, creating channels for fluid flow between them (Zhang et al., 2019b). While STHE offers superior heat transfer performance, it requires more space and manual management during load shifting than PHE. The heat

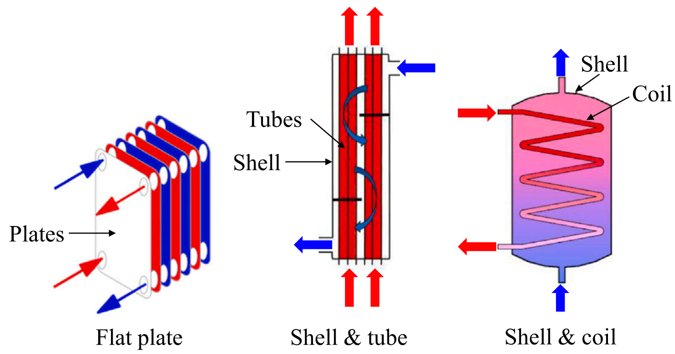

Fig. 6. Common heat exchanger configurations.

transferred from the primary heating fluid in the heat exchanger to the secondary heating fluid is then distributed to the building's space heating system, often using central heating radiators.

For example, Singapore is a tropical country with a hot and humid climate, resulting in a high demand for cooling in homes and businesses (Deng et al., 2019). Traditional air conditioners can be expensive and energy-intensive, so Singapore has invested in a DHC system to reduce its reliance on them. The DHC system uses heat exchangers to transfer heat between a primary fluid and a secondary fluid. The primary fluid is heated or cooled at a central energy plant and then distributed to individual buildings through a network of pipes. The secondary fluid is then used to heat or cool the buildings, depending on the season (Sun et al., 2021). Singapore's 5GDHC system has been very successful in reducing the country's reliance on traditional air conditioners, as well as its energy consumption and greenhouse gas emissions.

Two primary fluid flow patterns in heat exchangers are counter-flow and parallel-flow (Mansoury et al., 2019). In a counter-flow configuration, the two fluids exchange thermal energy while flowing in opposite directions within the heat exchanger. For example, in the PHE, one fluid flows from top to bottom while the other flows from bottom to top. In the STHE, one fluid flows inside the shell while the other flows inside the tubes in the opposite direction. In parallel-flow fluid transfer, both fluids flow in the same direction and exchange heat as they pass through the exchanger. The counter-flow heat exchanger offers several advantages over its parallel-flow counterpart. It achieves higher thermal transfer rates, allows the outlet temperature of one fluid to be closer to the inlet temperature of the other, and can operate for both cooling and heating purposes (Alam and Kim, 2018).

7. Future scenarios

This section thoroughly explores and analyzes the key considerations for major stakeholders involved in the planning, design, and management of 5GDHC networks. The discussion covers crucial topics such as climate change, electricity prices, and renovation plans, which are categorized to highlight the diverse pathways towards the future.

7.1. Stabilizing heating and cooling demands in 5GDHC networks

One advantage of 5GDHC networks is their ability to provide both heating and cooling services, which can partially balance heating and cooling demands within a district (Ma et al., 2020). This results in two distinct balancing processes: intra-building demand balancing and inter-building demand balancing. Intra-building demand balancing focuses on effectively balancing the heating/cooling demands within a specific structure. Inter-building demand balancing aims to achieve a balance between the heating/cooling demands of different buildings. The fundamental principle remains the same in both cases: waste heat from the cold supply can be used as a heat source by harnessing it at the heat pump's evaporator (Reynolds et al., 2019). This approach offers two benefits: first, the waste heat is not dissipated (recooled), and second, less external heat is required for the heat pump's evaporator.

Balancing heating and cooling demands within buildings can be achieved when they occur simultaneously. This can be done by installing either a heat exchanger or a chiller, both of which generate waste heat that can be partially or fully utilized by the heat pump at its evaporator. As a result, the amount of waste heat injected into the 5GDHC network and the heat drawn from the network are reduced (Allen et al., 2021). This leads to a situation where, at any given time, either only surplus heat is supplied to the network or only heat is extracted from the network.

If at any given time, at least one building supplies heat to the 5GDHC network while another building draws heat from the network, it indicates a balance between the buildings. In an ideal scenario of perfect balance, the total heat supplied and drawn across all buildings would be equal. This equilibrium would result in no mass flow passing through the energy hub, achieving complete thermal balance within the district. However, this ideal case is rarely achieved, and the energy hub is typically responsible for meeting the remaining heating or cooling demands (Dang et al., 2019; Minh et al., 2022).

7.2. Climate change

DH systems are a primary energy infrastructure in numerous urban areas worldwide. However, previous generations of DH systems have significantly contributed to greenhouse gas emissions, exacerbating climate change (Ivner and Viklund, 2015). With rising global temperatures, the demand for cooling is projected to increase by approximately 50% in the 2050s compared to the 2020s (Larsen et al., 2020).

The impacts of climate change on DH systems have been extensively studied using various simulation models. This survey uses the Rossby Centre atmospheric climate model projections (RCA4), developed by the Swedish Meteorological and Hydrological Institute (SMHI), as the primary model for examining these impacts. For a comprehensive analysis of RCA4, please refer to Kjellström et al. (2016). RCA4 was specifically chosen because of the significant presence of a large-scale DH system in central Stockholm, where nearly 90% of the city's buildings are interconnected with the DH network (Levihn, 2017). To accurately estimate the future trend of greenhouse gases and aerosols, multiple scenarios were considered, taking into account critical socio-economic factors such as rapid population growth and advancements in technology and economy.

Fig. 7 illustrates the projected annual mean temperature for the Stockholm area based on the RCP8.5 high-emissions scenario, which represents a future where insufficient efforts are made to reduce greenhouse gas emissions. The projections demonstrate significant temperature changes in northern Europe due to the escalating effects of global warming. The upward trend in temperature over time is inevitable, emphasizing the urgent need for effective measures to address climate change.

In the coming years, global temperatures are expected to rise, with even more significant increases projected in the distant future. Modeling results indicate that both observed temperatures and model outputs exhibited annual fluctuations of over ±2 °C during the 1961–1990 period. From 1990 to 2010, the fluctuations predominantly exhibited an upward trend in both observed and projected temperatures. Looking ahead to the projected temperatures until 2100, the model indicates that the increasing temperature trend persists and presents a concerning indication of higher amplitude. The graph highlights that even the coldest years towards the end of the 21st century are hotter than the hottest years in the reference period.

Climate change is expected to significantly impact heating and cooling demands, with a projected 13% reduction in heating demand and a 50% increase in cooling demand in the 2050s compared to

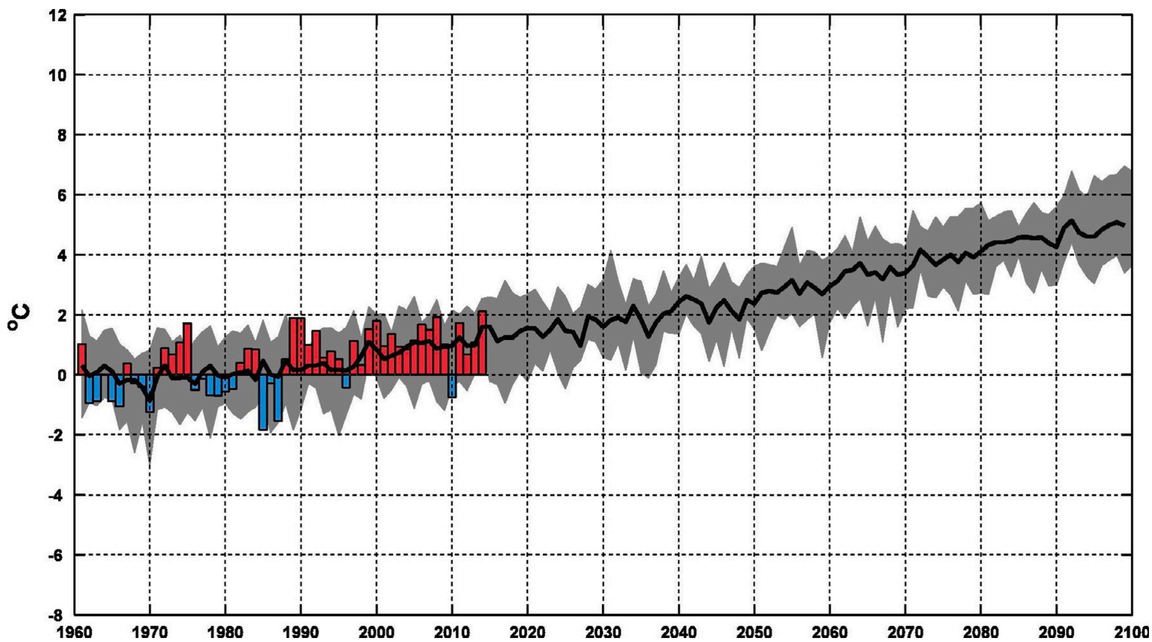

Fig. 7. Annual mean temperature projection of Stockholm County (Sweden) until 2100. Note: The red and blue bars denote observed temperatures by SMHI, whereas the black line (ensemble mean) and gray region (maximum and minimum temperatures from any ensemble member) are generated from the RCA4 ensemble model under the RCP8.5 scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the 2020s (Isaac and Van Vuuren, 2009). These statistics reinforce the observation that Nordic countries will experience higher cooling demands than heating demands, which will substantially impact the applications of 5GDHC networks (Hirvonen et al., 2020). Consequently, in addition to the primary goal of achieving net-zero emissions by 2050, alternative approaches need to be considered. One such approach is building innovation, which has the potential to significantly reduce energy consumption levels. Research published by Savvidou and Nykvist (2020) suggests that energy consumption can be reduced by up to 50% by 2050 compared to 1995 through behavioral, technological, and structural improvements. Key renovation measures include replacing low-efficiency building components, implementing advanced insulation technologies for the exterior building envelope, installing heat recovery ventilators, and improving indoor air tightness (Andrić et al., 2018).

7.3. Prices and costs of 5GDHC networks

7.3.1. Heat prices of existing districts with 5GDHC network

In the 5GDHC grid, each local substation typically incorporates a WSHP, and therefore, the energy costs for consumers include both electricity and heating/cooling energy expenses (Long et al., 2021). This emerging trend of active prosumers within the 5GDHC grid generates profits by trading excess heat with the operators of the 5GDHC system. Various new business models have been proposed to address the unique requirements of 5GDHC systems, aiming to streamline billing processes by either combining electricity consumption and thermal energy usage into a single bill for substations or treating heating and cooling services as a unified offering.

For research purposes, some 5GDHC systems have made their costs transparent to end customers, enabling a closer examination of the cost structure. For example, Table 7 presents cost information from three different heat suppliers in Germany. All three 5GDHC systems charge a one-time connection fee of approximately 10,000 € to cover the operational costs of the heat source. Additionally, they charge an annual base price to cover the operation and maintenance expenses of the entire plant and network. Finally, customers must pay an energy bill calculated based on the heat consumed (price per kWh). It is worth noting that the bill may include a flat rate or no charge for cooling supply throughout the year. Additionally, Table 7 provides sample annual bills for a typical single-family house, as provided by the 5GDHC companies.

The price information sheet for AggerEnergie includes a comparison with other heating systems. The one-time connection fee is approximately 4.64 € per square meter of property area. The base price is 132 € per year, and the energy price is 6.9 cents per kilowatt hour. The annual cost for a single-family house with an 8 kW heating capacity in the AggerEnergie 5GDHC network is 2481 €. In comparison, the annual cost for a decentralized heat supply based on ground-source heat pumps with deep drilling is 2800 €, and the annual cost for using air-source HPs is 2200 €. While air-source heat pumps are affordable and cost-effective, outdoor units can generate disturbing noise emissions and have a higher risk of unexpected failure.

7.3.2. Price adjustment clause

The initial investment in 5GDHC networks represents the largest portion of the total costs, while consumption-based costs, such as electricity for circulation pumps and heat pumps, decrease in later operation (Wirtz et al., 2022). As a result, simplified pricing models are commonly used. For example, in the newly developed 5GDHC network in Gensingen, Germany, building owners pay a flat rate of €80/kW/year (net, as of 2021) to join the district heating and cooling network. However, the rate increases significantly to €400/year for a connection capacity of 5 kW. Additionally, the pricing model includes a price change clause, whereby 20% of the flat rate tariff increases linearly with the German index of collectively agreed hourly earnings in the overall economy.

$$FR = FR_0 \cdot \left(0,8 + 0,2 \cdot \frac{L}{L_0}\right)$$

Flat-rate pricing for heating and cooling is common in 5GDHC networks. The cost of cooling is typically covered through an annual payment or provided free of charge, as shown in Table 7. Providing free cooling complements the use of waste heat in the summer, enabling the creation of a geothermal probe field. While investment costs pose a significant challenge to the development of sustainable 5GDHC networks, new business models and active engagement of prosumers can overcome these obstacles (Gjoka et al., 2023).

Table 7
Example heat prices for three 5GDHC networks in Germany (as of 2022, errors reserved). Note: €/a indicates €/annum, Ct/kWh stands for cents per kilowatt hour, and MWh is megawatt hour.

Name	Base price	Energy price	Cooling price	Connection fee	Example costs (single-family house)	Heat price per kWh (plus connection fee)
APURStadtwerke SH (APURStadtwerke, 2022)	420 €/a	8.27 Ct/kWh	Free	13,650 €	998.97 €/a (4.8 kW, 7 MWh/a)	14.8 Ct/kWh
Stadtwerke Warendorf (Stadtwerke, 2022)	119 €/a	11.7 Ct/kWh	100 €/a	11,705 € (incl. cooling)	1458 €/a (5.5 kW, 9.3 MWh/a)	15.6 Ct/kWh
AggerEnergie (AggerEnergie, 2022)	132 €/a	6.9 Ct/kWh	Na	4.64 €/m^2 (land area)	2481 €/a (8 kW, 13 MWh/a)	19.1 Ct/kWh

7.3.3. Are 5GDHC networks more expensive?

While 5GDHC offers numerous advantages in terms of a clean and environmentally friendly heat/cooling supply, the economic feasibility is the most critical factor when considering the adoption of new DH systems. Additionally, as 5GDHC technology is still in its early stages of development, there is uncertainty regarding its competitiveness against existing DH systems (Maragna et al., 2022). Providing a definitive answer is challenging because the costs are heavily dependent on the unique conditions of each neighborhood, including factors such as the type and size of available heat sources. For a detailed examination of the factors influencing the economic viability of low-temperature networks, please refer to a report published by Gudmundsson et al. (2021).

Most technical planners specializing in 5GDHC believe that there are no inherent economic disadvantages associated with 5GDHC networks (Bilardo et al., 2021). In fact, some planners even consider 5GDHC to be a more cost-effective option when compared to conventional heat networks or decentralized solutions. It can be assumed that prior to the implementation of any 5GDHC projects, an economic efficiency analysis was conducted, which included a comparison of the 5GDHC supply with standard heating networks or decentralized supply solutions. The fact that 5GDHC networks have been successfully realized indicates that either the network was the most economically viable option or had only minor economic disadvantages (Jebamalai et al., 2022).

One crucial factor often overlooked when assessing the economic efficiency of 5GDHC networks compared to other networks is the availability of free cooling services. The demand for cooling services is projected to increase significantly in the coming years due to the frequency of extreme heat waves (Song et al., 2017). For example, a recent economic feasibility study comparing 5GDHC networks with conventional heating networks in Denmark and the UK found minor cost advantages of 5GDHC over conventional heating networks (Volkova et al., 2022). However, the study overlooked several important factors, such as cost savings associated with free passive cooling and the potential advantages of using electricity from solar power systems or subsidy programs.

8. Conclusion

Although certain technologies within the 5GDHC domain have been used successfully for decades, the concept of 5GDHC networks for district heating and cooling supply is still in its early stages of development. This survey aims to emphasize the pressing need for 5GDHC as a crucial technology in future sustainable energy systems and to promote greater acceptance of 5GDHC systems.

The survey conducts a comprehensive SWOT analysis of 5GDHC technology and carefully categorizes and describes its essential components, including heat sources, thermal storage, transmission networks, and distribution networks. It examines representative CHP heat sources, emerging renewable sources, and their potential contributions to heating or cooling supply within the 5GDHC network. It also explains various heat storage technologies, integral to 5GDHC, and details the vital components and configurations of transmission and distribution networks. Finally, based on the information discussed throughout the study, the survey addresses several future scenarios concerning the main stakeholders involved in 5GDHC networks.

A review of recent publications on 5GDHC reveals a significant increase in research activity since 2015. While previous studies have examined important aspects of 5GDHC, there has been a notable emphasis on integrating 5GDHC within smart energy systems and facilitating cross-sectoral and renewable energy integration. The in-depth analysis of critical 5GDHC components provided in this survey establishes a solid foundation for future 5GDHC modeling and feasibility studies. Drawing inspiration from data shared by other surveys, this study also addresses the barriers and drivers that influence the primary stakeholders involved in 5GDHC projects. Experts consider 5GDHC a suitable solution for the future sustainable grid. While developed concurrently with 4GDH technology, 5GDHC is not intended to replace 4GDH in the future but rather offers a more efficient solution for heating and cooling grid systems.

CRediT authorship contribution statement

L. Minh Dang: Writing – original draft, Investigation. **Le Quan Nguyen:** Formal analysis. **Junyoung Nam:** Data curation. **Tan N. Nguyen:** Validation. **Sujin Lee:** Conceptualization, Software. **Hyoung-Kyu Song:** Writing – review & editing, Visualization. **Hyeonjoon Moon:** Supervision.

Declaration of competing interest

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

Data availability

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

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