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Research paper

How to develop fifth-generation district heating and cooling in Sweden? Application review and best practices proposed by middle agents

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A B S T R A C T

Sweden has an ambitious plan to fully decarbonise district heating by 2030 and to contribute with negative emissions of greenhouse gases in 2050. The vagaries of the energy market associated with climate, political, and social changes entail cross-sectoral integration that can fulfill these national targets. Fifth-generation district heating and cooling (5GDHC) is a relatively new concept of district energy systems that features a simultaneous supply of heating and cooling using power-to-heat technologies. This paper presents best practices for developing 5GDHC systems in Sweden to reach a consensus view on these systems among all stakeholders. A mixed-method combining best practice and roadmapping workshops has been used to disseminate mixed knowledge and experience from middle agents representing industry professionals and practitioners. Four successful implementations of 5GDHC systems are demonstrated and the important learned lessons are shared. The best practices are outlined for system planning, system modeling and simulation, prevailing business models for energy communities, and system monitoring. A roadmap from the middle agents' point of view is composed and can be utilised to establish industry standards and common regulatory frameworks.

1. Introduction

Heating and cooling of buildings are the largest energy-consuming sector in Europe and are responsible for 40% of the total final energy consumption and about 36% of related greenhouse gas (GHG) emissions (European Commission, 2020). The EU adopted in 2019 the *Clean energy for all Europeans* package which sets ambitious targets to reach climate neutrality by 2050. In the short-term, the package has a binding target of at least 32% renewables in the EU energy mix by 2030 and to improve energy efficiency by almost one-third (European Commission, 2019). Sweden is an early mover on sustainable clean energy as it adopted in 2017 the national climate policy framework which aims at reaching zero net emission of GHG by 2045 (Government Offices of Sweden, 2018). The country has also an energy policy with a promising target to achieve 100% renewable electricity

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Nomenclature

5GDHC	Fifth-Generation District Heating and Cooling
BHE	Borehole Heat Exchanger
BM	Business Model
BMC	Business Model Canvas
CHP	Combined Heat and Power
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
DSS	Decentralised Substation
ESCO	Energy Services Companies
GHG	Green House Gases
HCF	Heat Carrying Fluid
HP	Heat Pump
TPA	Third-Party Access

production by 2040 (Government Offices of Sweden, 2016). One way to attain the national and European targets could be the development of innovative solutions, especially with cross-sectoral integration between the heat and power sectors.

District heating and cooling (DHC) systems are regarded by the EU Strategy on Heating and Cooling as effective solutions to decarbonise the building sector (European Commission, 2016). Globally, district heating (DH) has high implementation rates around 50% in Iceland, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Russia, and northern China — while district cooling (DC) is more common in the Middle East and the USA (Werner, 2017b). The systems can integrate renewable energy sources such as geothermal and solar while offering flexibility in the energy system by coupling the heat and power sectors to cheaply produce and store thermal energy. DHC have been developed through different generations that are mainly characterised based on the temperature levels of the heat carrying fluid (Lund et al., 2014). For DH, steam was used in the 1st generation and was replaced in the 2nd generation by high-temperature water above 100 °C (Werner, 2017b). The water temperature was reduced to about 80 and 60 °C in the 3rd and 4th generations, respectively (Pellegrini and Bianchini, 2018; Lund et al., 2018). On the other hand, DC was introduced in the 1st generation as a pipeline refrigeration system to supply cooling to the food industry and in the 2nd generation as a supplier of comfort cooling to buildings (Østergaard et al., 2022). Refrigerants were replaced by water in the 3rd generation and as renewable energy sources became possible to integrate into the system, the 4th generation was realised.

Prompted by increasing cooling demands due to climate change and urbanisation, a new generation referred to as 5th generation district heating and cooling (5GDHC) has emerged to supply simultaneous heating and cooling to connected prosumers who are producers and/or consumers of thermal energy (Buffa et al., 2019; Revesz et al., 2020; Calise et al., 2022). The network in this generation operates at temperature levels typically below 40 °C whereby decentralised heat pumps (HPs) and/or mechanical chillers adjust the network temperature to the desired building supply temperatures. Such a new and advanced district energy system transforms thermal grids into electricity-dominated grids, which in turn supports the uptake of renewables and offers flexibility in power grids (Paiho et al., 2018). Like any emerging technology, DHC need to undergo a sociotechnical change in order to provide political and public acceptance in addition to technical solutions for wider implementations of 5GDHC systems.

A sociotechnical change within the energy sector with the aim of decarbonising buildings can be induced by either the common *top-down* or *bottom-up* approaches (van Vuuren et al., 2009). In the top-down approach, governmental agencies with legislative power enact policies and frameworks to lower carbon emissions. These policies are employed by the means of codes, standards, and regulations[1] which are communicated between different stakeholders and further down to citizens. The bottom-up approach stems instead from the efforts exerted by individuals and small to medium organisations to create a change. A complementary *middle-out* approach adds a new perspective that can further assist the process of reducing carbon emissions (Janda and Parag, 2013). The middle-out approach encompasses industry professionals and practitioners who are referred to in the remainder of the paper as 'middle agents' representing architects, engineers, district heating companies, property owners, and builders who can all be drivers of change towards greener DHC systems (Horsbøl and Andersen, 2021).

Since middle agents interact with all agents involved in the transition towards greener DHC systems, they can influence a change in three distinctive but compatible directions: (i) *upstream* towards policymakers by providing expertise and feedback to governmental bodies, (ii) *downstream* towards citizens by offering advice on techno-economically feasible solutions, and (iii) *sideways* towards peer professionals by promoting and improving the industry (Horsbøl and Andersen, 2021). Accordingly, middle agents can have three indicative modes of influence: (i) by *enabling* (or disabling) the implementation of new technology, (ii) by *mediating* to modify or adapt the technology to suit specific situations, and (ii) by *aggregating* the gained experience from several projects (Janda and Parag, 2013). Perspectives from middle agents on a certain technology can be elaborated through organised participatory discussions.

An established way of organising participatory discussions in the energy sector is through workshops (Horsbøl and Andersen, 2021; Thomas and Rosenow, 2020). A best practice workshop is tailored to collect, collate, and disseminate mixed knowledge with experience and examples of effective technical solutions. A group of middle agents participate in a series of presentations and discussions on a certain topic to share lessons from other implementations, explore existing challenges, and refine best practice methods. In the course of a best practice workshop, a roadmapping workshop intended for business strategy and innovation can also be carried out. Robert Galvin, who was the CEO of Motorola at the time roadmapping was established, defines the method as: "A 'roadmap' is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field" (Galvin, 1998). Several tools can be exploited to conceptually align the gained technological and functional perspectives during a best practice workshop, with visual roadmapping templates being the most common (Phaal et al., 2015). In the context of developing 5GDHC in Sweden, a roadmapping exercise engages middle agents in a collaborative work to analyze the underlying key drivers and sociotechnical challenges with the aim of establishing a route towards effective implementation.

This paper targets to answer the question of *how to develop 5GDHC systems in Sweden* and uses a mixed-method approach

[1] We distinguish between the three expressions on the basis that *codes* provide guidelines with or without mandatory compliance, whereas *standards* elaborate the industry requirements and create a common language to meet the codes, and that *regulations* incorporate both codes and standards and require industry compliance by law.

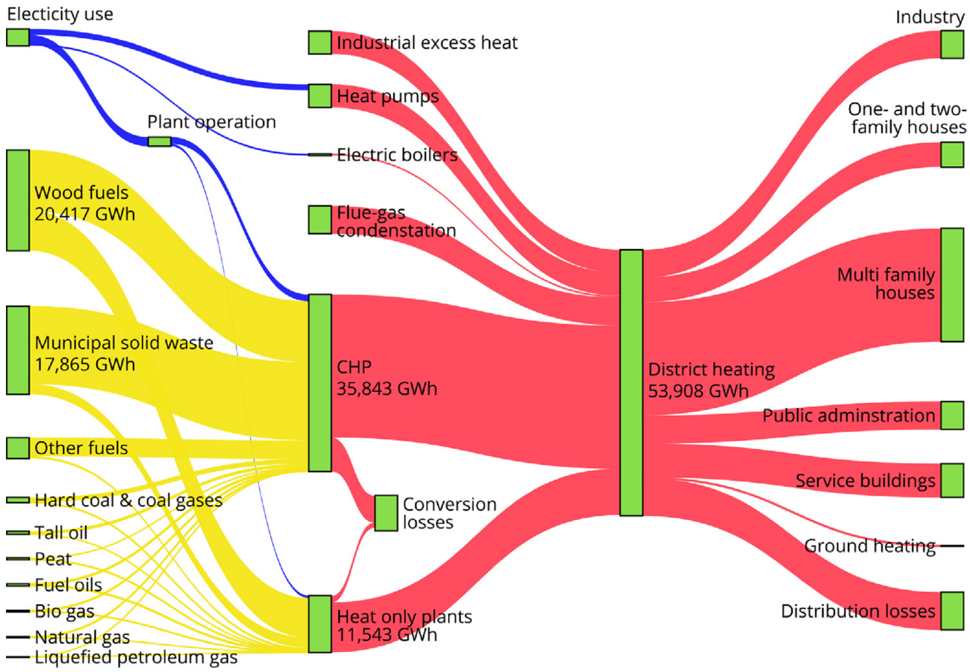

Fig. 1. Sankey diagram for the Swedish district heating energy balance in 2020. The width of connecting bars is proportional to the quantity of heat flow measured in GWh. Different nodes in the energy balance are illustrated in green rectangles. Yellow and blue bars correspond to fuel and electricity input, while red bars denote heat flows from heat sources to final deliveries. Conversion losses are derived from actual plant efficiency. Data source: Statistics Sweden and the Swedish Energy Agency (Energimyndigheten, 2020). . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

combining a best practice workshop and a roadmapping workshop for business innovation. The best practices are proposed by middle agents who are participating in the Interreg project COOLGEOHEAT (www.coolgeoheat.eu) titled *Shallow geothermal energy — the green and effective heating and cooling grids of the future*. The project aims to increase the production of renewable shallow geothermal energy in 5GDHC systems by (i) developing a thermo-hydraulic model to support the dimensioning of 5GDHC systems, (ii) analyzing operational data from existing 5GDHC systems in Sweden and Denmark, (iii) describing economic models based on certain forms of ownership and business transactions, and (iv) disseminating best practices for effective implementation of 5GDHC systems in Sweden and Denmark. This paper focuses on the Swedish market by aligning the workshop outcomes with the latest findings in the literature.

After the introduction section, the paper takes its point of departure in a review of DHC in Sweden concerning the current situation of the heating and cooling market, existing business models (BMs) and pricing mechanisms, types of system ownership, and the combination between DHC and HP technologies. Section 3 describes the methods used for designing the best practice and roadmapping workshops. Section 4 presents the findings of the workshops mainly in the form of proposed best practices from system planning to implementation and monitoring. Conclusions and outlook are finally outlined in Section 5.

2. Review of district heating and cooling in Sweden

2.1. Heating and cooling markets

Swedish DH has a long success story that started in Karlstad in 1948 aiming first to develop central heating systems for emerging industries and later in the 1970s to heat homes in the so-called The Million Homes Programme[2] (Werner, 2017a; Magnusson, 2016). To this day, about 500 DH systems exist in 283 municipalities with over 23 000 km of pipe length delivering about 60% of all heating to buildings. Fig. 1 shows a Sankey diagram for the Swedish district heating energy balance in 2020. On the left side, yellow bars represent different fuel inputs showing the predominant biomass and municipal solid waste with respective 45 and 39% of the total fuel input. Electricity is also used to generate heat through large-scale HPs and boilers as denoted by the blue bars. Red bars indicate heat flows that are mainly produced by Combined Heat and Power (CHP) and heat-only plants. The red bars on the right show the deliveries to end-consumers with multi-family houses, service buildings, and public administration being the three largest consumer groups. The diagram also shows the latest reported national statistics of network distribution losses which amount to about 14% (Energimyndigheten, 2020).

By contrast, Swedish DC was introduced in the 1990s and currently exists in 42 cities with a total network length of 660 km (Energiföretagen Sverige, 2022). A total delivery of 1 TWh was reported in 2020 to provide comfort cooling in malls and buildings as well as process cooling for data centers and freezing equipment (Energimyndigheten, 2020). The two largest DC systems exist in Stockholm and Gothenburg. The Stockholm system is one of the largest in Europe with an installed capacity in 2020 of 270 MW and total delivery of 335 GWh and a pipe length of 250 km (Jangsten, 2020). The system has three sources of cold production with different shares: waste cold from HPs used in DH (55%), compression and absorption chillers (27%), and seawater free-cooling (18%) with accounted distribution losses of 8% (Stockholm Exergie, 2020). The Gothenburg system has a capacity of 70 MW with a pipe length of 30 km and mainly operates with absorption chillers that utilise available waste heat from incineration plants. Free cooling from the river is also available in winter.

The long-established DHC in Sweden has led to a well-developed and efficient system. Compared to other European countries, Sweden has an ambitious plan to fully decarbonise district heating by 2030 and to contribute with negative emissions

[2] The Million Homes Programme achieved its goal of building modern and affordable one million new housing dwellings between the period 1965 to 1974. More details about the project can be found in Ref. Hall and Vidén (2005).

equivalent to −115.6 g/kWh of GHG emission in 2050 (Euroheat & Power, 2022). The transition towards negative emissions is expected to take place by producing heat mainly from bioenergy with carbon capture and storage (BECCS) and waste incineration technologies.

2.2. Business and price models

The majority of existing DH systems in Sweden are 3rd generation technology relying on conventional BMs with a clear distinction between the customer and the utility company (Lygnerud, 2019). In such a workflow, the utility company is responsible for heat production and distribution in addition to system maintenance. The utility company partners with fuel providers to operate the production plant(s) that it owns. The value created for the customer is realised in the delivered heat and hot water and the communication between the customer and the utility company is established through invoices.

The pricing mechanism in existing DH systems often uses the marginal cost method which is utilised in deregulated heating markets to determine the price of DH (Energiforsk, 2017). The marginal cost reflects the cost of generating one more unit of heat through DH. Since the DH price depends on the supplier's marginal cost, suppliers are motivated to reduce costs by: (i) maintaining good infrastructure conditions, (ii) investing in better equipment, and (iii) implementing energy-efficiency measures. A survey was conducted to investigate 237 different price models used by 80 DH companies in Sweden (Song et al., 2017). Generally, the survey findings showed that DH price typically includes the following four components:

1. *Fixed cost* that the user pays each month for being connected to DH. The fixed cost is proportional to the customer's peak load and is therefore divided into different incremental levels.
2. *Capacity cost* that is charged to cover the cost of maintaining a certain level of capacity for peak load and investment in new facilities. A price for a unit of load demand (SEK/kW) is usually set by the DH company and the cost is determined based on the customer's actual or estimated peak load.
3. *Energy cost* that includes all costs for heat production covering fuel cost, labor and operation cost, energy, and carbon emission taxes.
4. *Flow cost* that reflects the cost of delivering a volume of hot water to the customer. This price component motivates customers to improve energy efficiency in their buildings to reduce the required volume of water and consequently the pumping cost.

Findings from the previously mentioned survey showed that energy and capacity costs constitute more than 95% of the total cost. Fixed and flow costs on the other hand are usually added to reduce financial risks taken by the DH company due to the high investment and, therefore, are seen as less transparent. Prices for heating and hot water in each Swedish municipality have been reported annually since 1996 by the 'Nils Holgersson' group (Holgersson, 2022). The latest published report shows that the average DH price in 2021 was 887.9 SEK/MWh including VAT with a 1.2% annual increase compared to the previous year. Since the current BM used in many of the existing DH systems already generates profit for utility companies, there is a resistance to shift to BMs that adopt the prosumer concept (Lygnerud, 2019).

2.3. Forms of ownership

Before the Swedish DH market was deregulated on 1 January 1996, DH systems were owned and operated by municipalities that were not allowed to make profits. After market internationalisation and liberalisation, DH systems were sold to either private or municipality- or state-owned companies. Figures from 2014 show that DH existed in 283 out of the 290 Swedish municipalities where 51% of these systems were municipality-owned, 20% had private owners, 4% were state-owned, and the rest of the systems were jointly owned (Magnusson, 2016). The period between 1996 and 2005 experienced the largest redistribution of Swedish DH ownership. The three big market players (E.ON, Fortum, and Vattenfall) benefited from internationalisation and expanded in the market through acquisitions. For instance, the Finnish Fortum bought Stockholm Energi around the year 2000 while the German E.ON bought Sydkraft in 2002.

There was some risk of oligopoly in the early 2000s when prices increased rapidly after Fortum bought Stockholm Energi and Vattenfall bought Uppsala Energi, which led to subsequent protests and requests for competition through third-party access (TPA) (Magnusson, 2016). After national investigations, the government proposed the bill commonly known as 'Fjärrvärmelagen' obliging owners of DH systems to permit access to the DH network to entrants who want to sell heat (Riksdag, 2022). The proposed bill was issued in 2008 but was only passed in 2014 (Magnusson, 2016; Lygnerud, 2018).

2.4. Combining district and HP technologies

Power-to-heat solutions such as HPs were promoted in Sweden in the 1980s after the oil crisis and due to the resulting surplus of electricity from 12 new commissioned nuclear reactors (Averfalk et al., 2017). HPs started to play an economic role in contrast to CHP plants that are typically expensive to run on winter days when electricity is mainly produced from wind. Large-scale HPs[3] produced about 10% of the total heat production in the Swedish DH system in 2020. Meanwhile, small HPs exist in more than half of all Swedish single-family houses and have an overall share of about 25% of the heating market (Johansson, 2017). HPs are therefore considered the main competitor for DH in Sweden. Lygnerud et al. (2021) argue that there is a trend for customers in private and multi-family houses "converting from DH to individual HPs, triggered by cost savings and increased autonomy". These customers maintain the connection to DH to cover peak loads only while running the HP to provide the base load. This situation induces DH operators to change their business from selling a product, i.e., heat to selling services. Moreover, a window of opportunity is opened with combined DHC and HP technologies instead of viewing them as competing technologies. Such a combination is optimally realised in 5GDHC systems where the network temperature is reduced without deteriorating the system performance and whereby decentralised HPs adjust the network temperature to the desired supply levels. Moreover, the combination of DHC and HPs is estimated to cover up to 85% of the heating market and thus DH suppliers can gain more profits by setting a price lower than the market price.

The above discussion from the review provided in this section can be summarised in four main points. First, Swedish DHC is regarded as one of the most efficient systems in the world and has a key role in decarbonising the building sector. Second, the internationalisation of the Swedish energy market has created a good atmosphere for negotiation between different suppliers and possible joint ownership of DHC systems. Third, several arguments have been identified to motivate DHC suppliers to change their BMs and pricing mechanisms to adopt the prosumer concept dedicated to energy communities. Fourth, the combination of DHC and HP technologies reduces production costs, increases energy efficiency, and contributes to sustainable cities.

[3] We adopt the definition provided by Averfalk et al. (2017) that a heat pump is classified 'large' when it has an installed capacity larger than or equal to 1 MW.

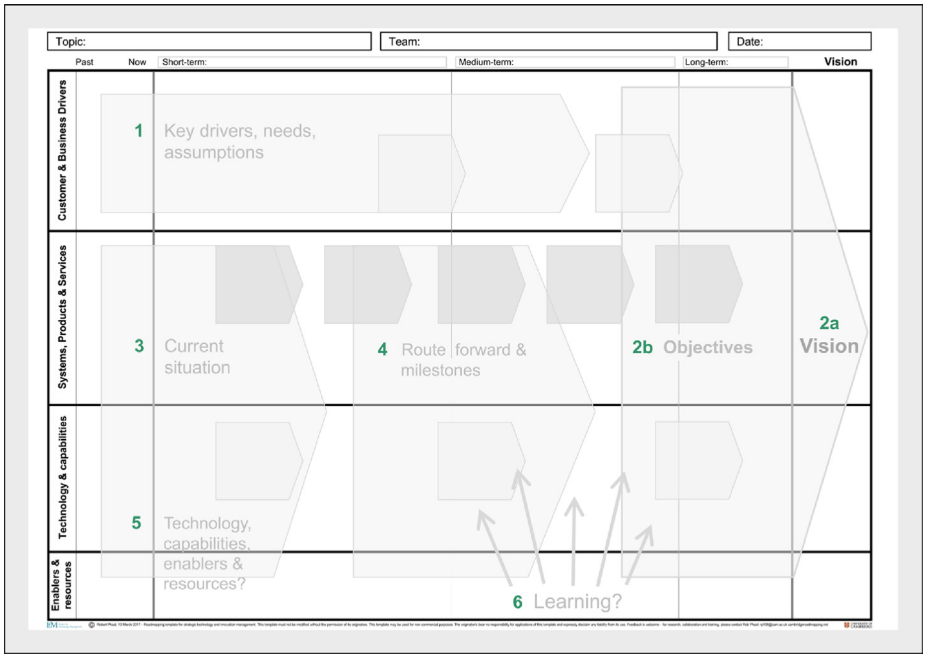

Fig. 2. Used template for the roadmap workshop which incorporates self-explanatory process steps.
Source: Adopted from Ref. Cambridge Roadmapping (2022).

3. Method and materials

A mixed-method approach combining best practice and roadmapping workshops is used in this study to envisage the development of 5GDHC systems in Sweden. The workshops were carried out by inviting middle agents involved in the COOL-GEOHEAT project to form a ubiquitous understanding of 5GDHC systems and to share learned lessons from existing implementations. The workshops took place during a full working day at the Faculty of Engineering at Lund University in Sweden and were divided into two main parts: (i) presentations of existing 5GDHC systems in Sweden and (ii) roadmapping for business innovation. The first part aimed to exchange gained knowledge and experience and to identify key challenges and industry requirements. In the second part, a roadmapping template was used to visually align the key drivers behind 5GDHC systems and technology requirements with future outlooks.

3.1. Design of best practice and roadmapping workshops

A total of 19 professionals and other stakeholders participated in the workshops. The workshops were divided into two main parts. The first part consisted of a series of seven presentations where each speaker was given 20 min for presentation followed by a 10-min of Q&A session. A moderator was responsible for documenting the workshop minutes and to facilitate the Q&A session. The second part was intended to perform a roadmapping workshop after the participants were divided into three distinct groups based on their background experience. The groups covered (i) *System planners*, (ii) *District heating companies*, and (iii) *Heat pump experts*. The moderator first explained the instructions for performing the roadmapping workshop using the digital roadmapping wall chart shown in Fig. 2 and obtained from Ref. Cambridge Roadmapping (2022).

In general, all roadmapping templates share a common structure to address different questions related to the discussed topic. Processes one and two in Fig. 2 aim to respectively answer the *why* and the *what*. The current situation is described in process three to address the *who* and the *where*. In processes four and five, the *how* is addressed by mapping the route forward and by listing the required capabilities and resources. Finally, learned lessons from different milestones are aggregated as shown in process six. Each group used a separate digital template and was asked to join its respective break-out room for about 30 min. Digital post-it notes were utilised to document the respective group's main discussion themes related to the development of 5GDHC systems according to the group's expertise. A group leader was assigned to document the discussion notes and present the group's roadmap after the workshop was finished.

3.2. Data collection and interpretation

The presentations from middle agents including the Q&A sessions in addition to the roadmapping workshop were audio and screen recorded and later on transcribed. Throughout the roadmap workshop, each group used a separate digital roadmap wall chart which was synchronised to a cloud for subsequent thematic analysis of the group discussions. Thematic analysis is particularly useful to identify discussion points that follow specific patterns. The main themes discussed in each group were then juxtaposed with themes discussed in the other groups to elicit common patterns across all middle agents.

4. Findings from the best practice and roadmapping workshops

This section presents the findings of the workshops with respect to suggested technical solutions, thematic analyses and proposed best practices.

4.1. Multiple technical solutions for 5GDHC systems

The middle agents presented and discussed four different case studies across Sweden that are summarised in Table 1 together with project key challenges. Each case has a unique technical solution for the shared energy concept that is presented in the following four subsections.

Table 1
Summary of four case studies of 5GDHC in Sweden sorted by project starting year.

Case study	Location	Project starting year	Total heated space area[a] [m^2]	Space use	Actual or estimated heating demand[b] [MW, GWh/year]	Actual or estimated cooling demand[b] [MW, GWh/year]	Energy source	Range of HCF[c] temperature [°C]	Key challenges
Embassy of Sharing	Malmö	2022	61,901	52% office, 46% residential, 2% retail	2.0 MW, 2.2 GWh	1.1 MW, 0.4 GWh	111 borehole heat exchangers with 30,525 m of active depth	5–20	• coordination between consultants • capacity for peak load • deviation between estimated and actual amount of shared energy • adequate size of BHE • control strategies for the three-way valve • requirements for connecting new buildings
ectogrid™	Lund	2018	105,755	43% office, 11% lab, 4% sport center, 4% restaurant, 38% other	1.5 MW, 4.2 GWh	1.0 MW, 1.2 GWh	Reversible air-source HP and a 150 m^3 accumulator tank	5–40	• capacity for peak load • real-time system monitoring • data collection and management • HP failures • complexity of system design, commission, and operation
Hästskon	Stockholm	2017	56,799	68% office, 16% retail, 6% restaurant, 3% residential, 7% other	1.5 MW	3.0 MW	Aquifer consisting of two cold wells and four hot wells	2–17	• low competence • many sources of error due to multiple subsystems • adaption of building distribution systems • development of beneficial BMs
NUS	Umeå	2014	330,000	Hospital	1.1 MW, 7.0 GWh	0.9 MW, 5.0 GWh	202 borehole heat exchangers with 42,250 m of active depth	9–17	• capacity for peak load • low competence • business risks • development of beneficial BMs

[a]Heated spaces are defined according to the Swedish National Board of Housing, Building and Planning Regulations (BBR) as the area of temperature-controlled spaces intended to be heated more than 10 °C (Boverket, 2020).

[b]Presented figures indicate deliveries from the 5GDHC system excluding deliveries from auxiliary systems such as connection to conventional DHC networks.

[c]HCF = Heat Carrying Fluid at the district source loop.

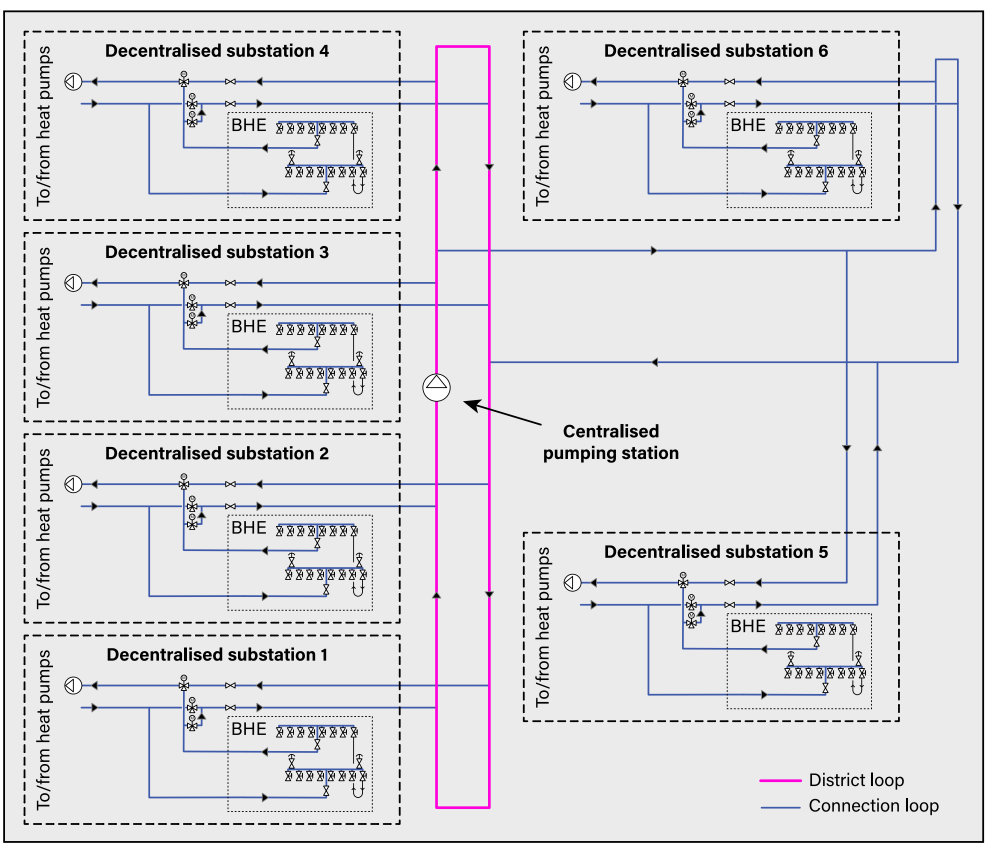

Fig. 3. Schematic diagram of a 5GDHC solution with one-pipe network topology, unidirectional mass flow, and DSS connected in series. The energy source is borehole heat exchangers.

4.1.1. Case study 1: The Embassy of sharing in Malmö

The new neighborhood in the Hyllie district consists of 6 decentralised substations (DSS) that supply both heating and cooling to 7 buildings with different space use. The system layout illustrated in Fig. 3 presents the mechanism for sharing energy flows between DSS through a geothermal energy sharing system. Here, each DSS is equipped with several borehole heat exchangers (BHE) that provide heating and cooling throughout the year, whereby HPs adjust the temperature of the heat carrying fluid (HCF) to the desired supply temperatures. The three-way

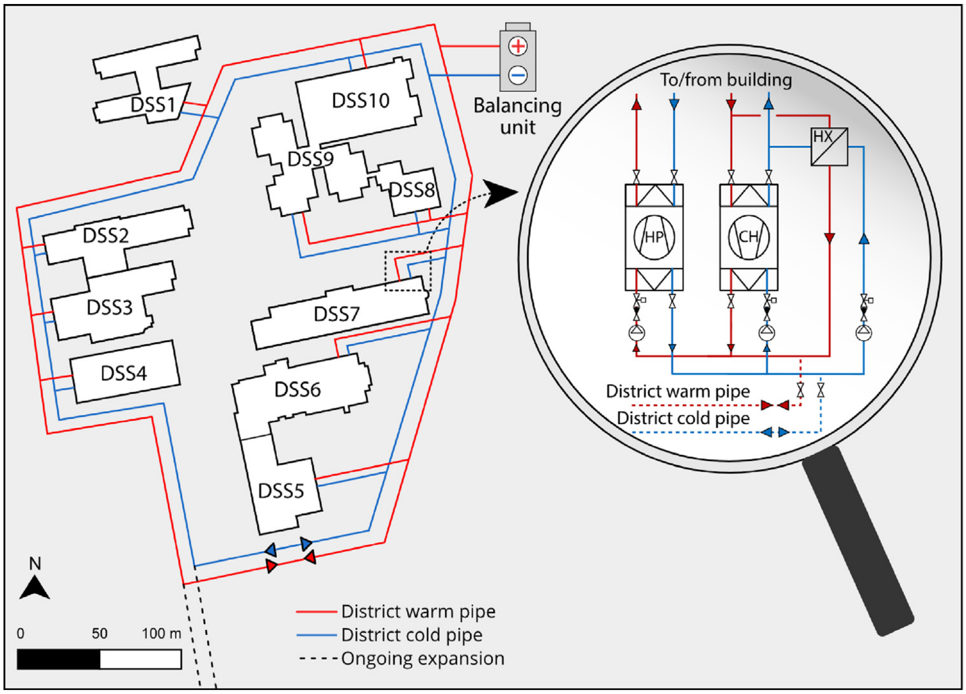

Fig. 4. Schematic diagram of a 5GDHC solution with two-pipe network topology, bidirectional mass flow, and DSS connected in parallel. The balancing unit incorporates a reversible air-source HP and a large accumulator tank.

valve is controlled such that it injects/extracts energy into/from a one-pipe loop (commonly referred to as the reservoir network (Sommer et al., 2020)) to balance the system demands.

4.1.2. Case study 2: ectogrid™ in Lund

The system is patented by E.ON Sverige AB (Rosén and Resoenqvist, 2018) and is regarded as the first Swedish district network with simultaneous heating and cooling demands and bidirectional energy flows (Abugabbara et al., 2022). Currently, the system connects 10 buildings whereby energy is shared at three stages. In the first intra-balancing stage, each DSS is equipped with a HP, a chiller, and a free-cooling heat exchanger that share energy flows with each other as shown in the magnified part in Fig. 4. In the second inter-balancing stage, the excess heat or cold from each DSS is shared with other connected buildings through a bidirectional two-pipe network. To balance the demands across the entire network, a balancing unit finally injects/extracts heat into/from the network. The balancing unit incorporates a large reversible air-source HP (ASHP) and a 150 m^3 accumulator tank for short-term storage. The sophisticated thermal interactions between buildings are controlled and monitored by ectocloud™, which is a control system based on Microsoft Azur cloud platform (Lindhe et al., 2022). The system is controlled based on several key performance indicators to improve system performance, minimise energy cost, and reduce peak demand.

4.1.3. Case study 3: Hästskon in Stockholm

The two blocks Hästskon 9 and Hästskon 12 located in the centre of Stockholm are typical examples of integrating several subsystems for increased synergy. The main energy source consists of an aquifer thermal energy storage with 2 cold wells and 4 warm wells as shown in Fig. 5. Cooling is mainly provided by the 2 water chillers and the refrigerant coolers in addition to conventional DC. Heating sources are realised in the available waste heat from server rooms, waste heat from chillers, and conventional DH. After its operation in 2016, cooling was provided solely by the aquifer and the purchased energy from conventional DH was reduced by about 68%. Ongoing system expansion includes connecting the adjacent property Jakob Större 18.

4.1.4. Case study 4: The Norrlands Universitetssjukhus (NUS) in Umeå

The geothermal system installed at the university hospital in Umeåcovers about 90 and 30% of the respective annual cooling and heating demands while the rest is provided by conventional DHC (Granmar, 2017; Puttige et al., 2022). The system illustrated in Fig. 6 consists mainly of three HPs with one being used for domestic hot water production and is connected in series with the other two HPs (Walfridson, 2022). Overall, the system has two chillers, three connection points to conventional DC, and four borehole thermal energy storages that have been expanded since 2014 to reach a total of 202 boreholes. In summer, heat from the space cooling loop and the available heat from HPs are injected into the BHE, while in winter the BHE act as a heat source. The components of the 5GDHC network operate in an economic sequence for simultaneous production of heating and cooling by optimising the buildings' power demands and power supply from DC.

4.2. Thematic analyses

The main discussed themes during the best practice and roadmapping workshops are presented herein for each corresponding group. An overview of the themes superimposed on the roadmapping wall chart is presented in Fig. 7 with more details deliberated below.

Group 1 — System planners: the group oriented their discussion towards the description of the current situation and on elaborating the key drivers. What was initially highlighted is the current lack of enough players on the market for the shared energy concept that is essential to gain momentum. The group also pointed out the current challenges in coordinating projects with the shared energy concept while knowledge still needs to be increased. From the group's viewpoint, focusing on improving knowledge would create common parlance between project partners which would ultimately facilitate coordination. Additionally, the group raised the challenge related to system control, especially controlling the valves for thermal energy exchange between

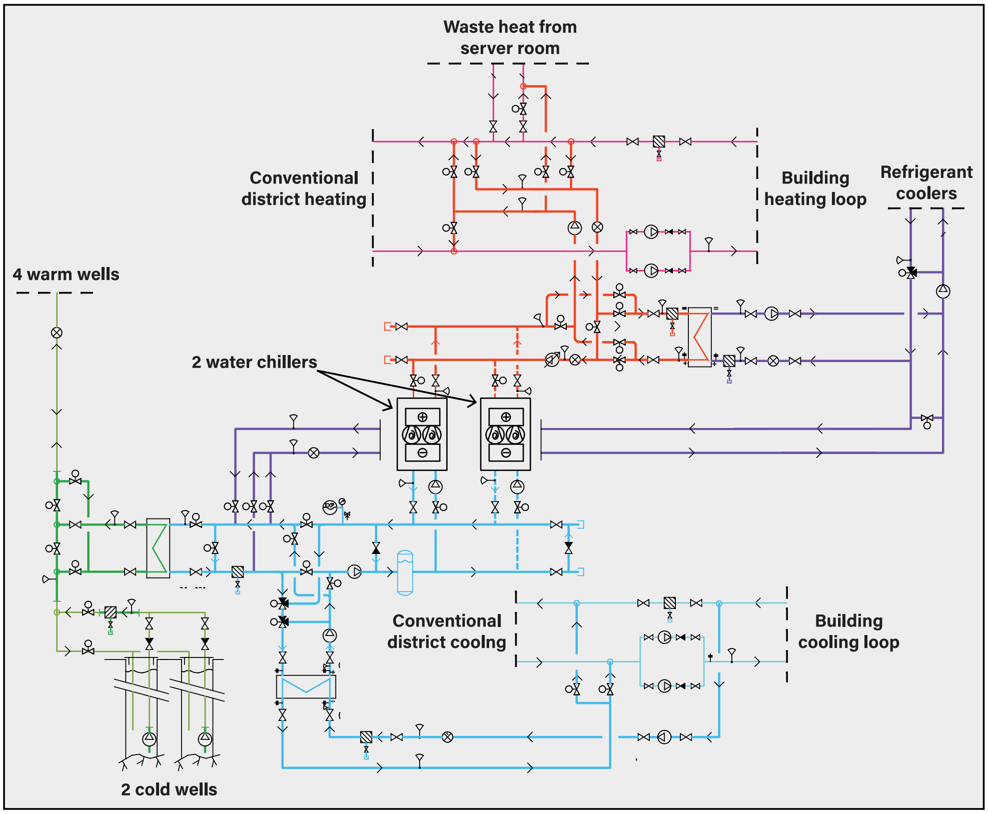

Fig. 5. Schematic diagram of a 5GDHC solution with aquifer thermal energy storage, waste heat recovery, and established synergy with existing conventional DHC systems.
Source: Adapted from Sweco, see Ref. Revholm (2013).

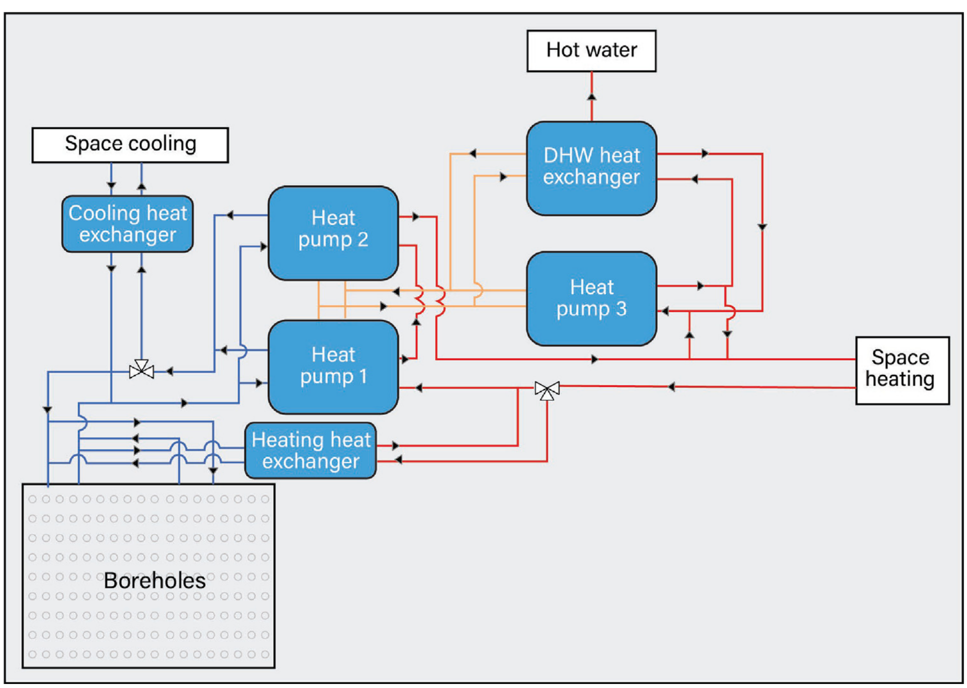

Fig. 6. Illustration of the 5GDHC system at NUS.
Source: Adapted from Ref. Puttige et al. (2020).

the DSS and the district network as depicted in the schematic shown in Fig. 3.

While mapping the route forward for business innovation, the group anticipated the challenge of connecting new buildings to the district network since many questions related to this point remain unanswered. For instance, the already existing challenge of balancing the demands between prosumers is aggravated when a new building is connected to the network. The difficulties in

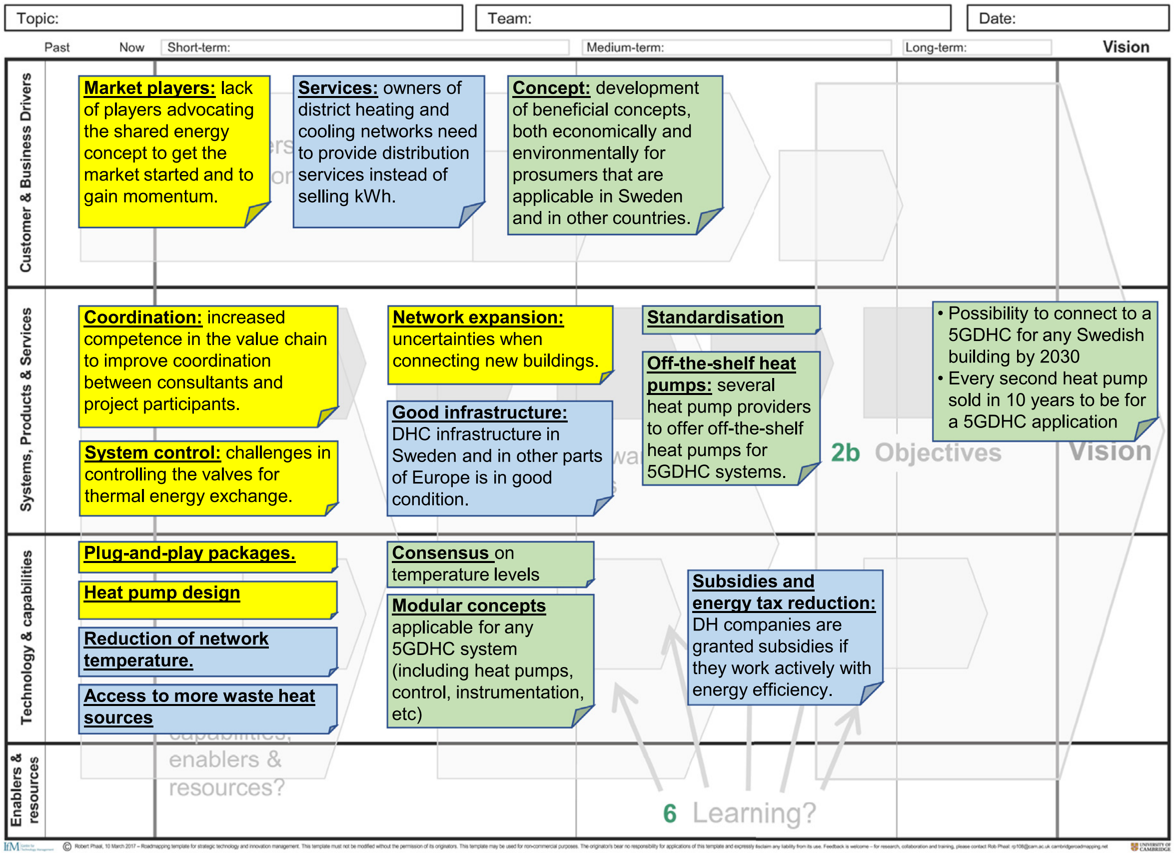

Fig. 7. Summary of the main discussed themes in the roadmapping workshop. Different colors denote themes discussed by each of the three groups: yellow = system planners, blue = district heating companies, and green = heat pump experts. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

estimating the demand profiles for new buildings with high certainty add a new layer of complexity for ensuring reliable system operation.

When discussing technology and capabilities, system planners put forth the need for developing plug-and-play packages for 5GDHC systems that can be easily assembled on-site. The group accentuated this point as it would improve trustworthiness and reduce uncertainties during system commissioning and operation. To achieve this, the group recommended developing better HPs customised for 5GDHC systems that have low-temperature lifts.

Group 2 — District heating companies: the participants in this group decided to not focus their discussion on defining a vision that only relates to 5GDHC systems. Rather, the group discussed three important points that could be interesting for the development of DHC networks and the development of societies in general. These points encompass TPA, network temperature reduction, and energy subsidies.

First, the group looked at the fact that DH companies are used to running their business based on selling units of energy, i.e., kWh. However, the participants believe that this would soon change as aspects of sustainability are integrated into the industry. This implies that DH companies need to shift their business towards providing services, particularly through TPA to existing networks. This would benefit all players on the market after DH companies begin to offer such services given that the infrastructure in Sweden and other European countries is already in good condition.

Second, in order to make TPA more practical, the group pointed out the existing issue of operating DH networks at high-temperature levels. This would naturally limit the possibility for low-grade waste heat sources to gain access to the network. For instance, sewage networks are the closest waste heat source available to DH networks since both coexist in urban areas and are probably located in the vicinity of each other (Pelda and Holler, 2019). However, available temperatures from sewage networks are typically around 35 °C which would require DH operators to lower the network temperature for better utilisation of similar waste heat sources.

Third, the group underlined the slow rate of change in DH businesses due to the dilemma between low motivation to increase efficiency and existing governmental subsidies that make the energy cost relatively cheap for DH companies. This is currently changing as sustainability is integrated into the industry which necessitates business transformation. The group suggested that "DH companies can be granted subsidies if they work actively with energy efficiency". Another suggestion was to inaugurate a new governmental agency that would be responsible for making controls and random checks for sustainable heat production and distribution. As such, the industry is motivated to improve energy efficiency by the tacitly increased subsidies.

Group 3 — Heat pump experts: the participants in this group exerted more effort in defining a vision since HPs are an intrinsic component of 5GDHC systems. The formulated vision constitutes two parts: (i) offering the possibility for any Swedish building to be connected to a 5GDHC system, and (ii) increasing sales such that every second HP sold in 10 years is for a 5GDHC application. This ambitious vision necessitates the development of economically and environmentally beneficial concepts for prosumers during the short- and medium-term. It was noted that these concepts should also be applicable in other countries since Sweden has a relatively small market. The participants emphasised providing clear key performance indicators that are easy to understand by end-customers and not only technicians.

To realise the vision, the group highlighted the need for offering off-the-shelf HPs suitable for 5GDHC applications since the performance of traditional HPs deteriorates when operated with low-temperature lifts due to issues in the expansion valve. Moreover, developing industry standards is an essential part that would benefit all involved in the daily practices of 5GDHC systems. The standards also allow reaching a consensus on the expected range of network temperature to design HPs more adequately.

Heat pump experts talked about the manufacturers who would need to develop modular HPs using a Lego-like approach including HP controls, instrumentation, and data management. The main advantage of such an approach is that the product is always available and can be customised for a specific application by only changing one or a few components. For example, it was revealed from the previously presented case studies that HPs in 5GDHC systems generally have issues in the expansion valve that deteriorate the HP performance. This issue is related to the higher source temperature which increases the capacity at the same size of the evaporator and condenser leading to incorrect refrigerant charge. Therefore, it would be more relevant to change the swept volume or to have two smaller compressors to better match the design of heat exchangers and the capacity of the expansion valve.

4.3. Proposed best practices

This section puts forward proposed best practices by the middle agents obtained from the workshop findings for developing 5GDHC systems starting from the planning stage up to system monitoring during operation.

4.3.1. Best practice for system planning

The technology behind 5GDHC is considered relatively new and findings from existing literature point to the lack of clear design guidelines for system planners (Gjoka et al., 2023; Volkova et al., 2022). The integration of social and political acceptance with possible technical solutions is required during the planning stage where several design options might be considered. The *ex-ante* and *ex-post* approaches are useful for considering the social, political, and technical barriers of these elements during the planning stage (Schubert et al., 2015). The ex-ante approach considers all the previous barriers at the same stage and only feasible options with regard to the three elements remain. It may be the case that successful design options arising from this stage are not technically or commercially viable. For example, a social acceptance of 5GDHC could be reached if the system guarantees full autonomy from other energy systems such as conventional DHC. This situation can lead to an oversized system that is difficult to finance. Therefore, the ex-post approach is recommended since only technically feasible options are assessed for their social and political desirability.

The communication tool between scientists, citizens, and policymakers to integrate social and political acceptance with feasible technical solutions can take the form of science cafés. In these cordial events, participants who are not experts in the technology are engaged in discussions and are on equal terms with scientists (Dallas, 1999). A colloquial language to encourage citizens to be part of an energy community based on the shared energy concept can evolve in science cafés designated for 5GDHC systems. Furthermore, they can be an ideal platform for establishing industry standards and designing training courses for certified installers of 5GDHC systems.

4.3.2. Best practice for system modeling and simulation

The feasibility of technical solutions during the design stage is evaluated with the aid of modeling and simulation. The middle agents recommend the use of Modelica language for modeling 5GDHC systems since it offers features, including, but not limited to (i) multi-domain modeling covering thermal, fluid, control, and economic domains, (ii) hierarchical modeling from small components up to the assembly of large district systems, (iii) ability to model bidirectional mass flows, (iv) ability to reuse and/or edit existing component models (object-orientation), (v) acausal modeling where no strict definition of input/output relationships is required, (vi) easy adoption of design changes since the system architecture is retained. Such recommended use of Modelica as a physics-based modeling and dynamic simulation approach for 5GDHC systems confirms the latest findings in the literature (Abugabbara et al., 2020, 2021; Abugabbara, 2021; Abugabbara and Lindhe, 2021; Mans et al., 2022).

Different use cases can be applied to the developed Modelica model during the project lifecycle. In the early design stage where no detailed representation of the system is required, the user may be interested in evaluating the system performance for a varying number of connected buildings. This poses a scalability challenge since Modelica models are connected through visual connection lines that can make the model prone to errors when the model becomes large. One way to circumvent this issue is to utilise array declaration which Modelica supports. Here, the model for DSS is vectorised and only one model for the distribution pipe is used with connection to each array element, i.e., the number of DSS. Thus, the model for the 5GDHC system consists of only three subsystem models: DSS, distribution pipe, and a balancing unit for heat injection and/or extraction. The interested reader can refer to Ref. Lawrence Berkeley National Laboratory (2022) for practical examples of this solution.

To use the model for real-time system monitoring and operation, it is recommended to first identify the required measured quantities needed for evaluating the system performance. These can be, e.g., heat flow rate, temperature, and volume flow rate at different spatial locations in the district system. Afterwards, it is necessary to standardise the method for data collection and preprocessing techniques to handle missing and unrepresentative data. Finally, Modelica runs in the continuous time domain and it is therefore important to pay attention to the selected method for data interpolation (between the measurement sampling frequency) and extrapolation (outside the measurement period). Data interpolation is crucial for validating variables that represent a time derivative such as heat flow rate, but of less importance for variables with conserved quantities such as energy.

4.3.3. Best practice for business models and ownership structure

The maturity of the Swedish DHC market along with market liberalisation has created an atmosphere with flourishing potential. Although market deregulation permits internationalisation and obliges DH companies to allow TPA, the middle agents confirmed the findings by Bürger et al. (2019) that a regulator is still needed, especially for 5GDHC applications, to minimise the cost for prosumers and to increase the share of renewable energy production. Because of the current minimal state intervention, the regulator plays a key role in overseeing the negotiations for TPA between owners of 5GDHC systems, which would otherwise be a voluntary and tedious process. Thus, it is important to design BMs that are likely to emerge in 5GDHC systems to identify the required regulatory frameworks.

To support the design of BMs for 5GDHC systems, the business model canvas (BMC) can be utilised. The BMC was developed by Osterwalder and Pigneur (2010) as a visual tool in which an organisation can design its BMs on nine building blocks for

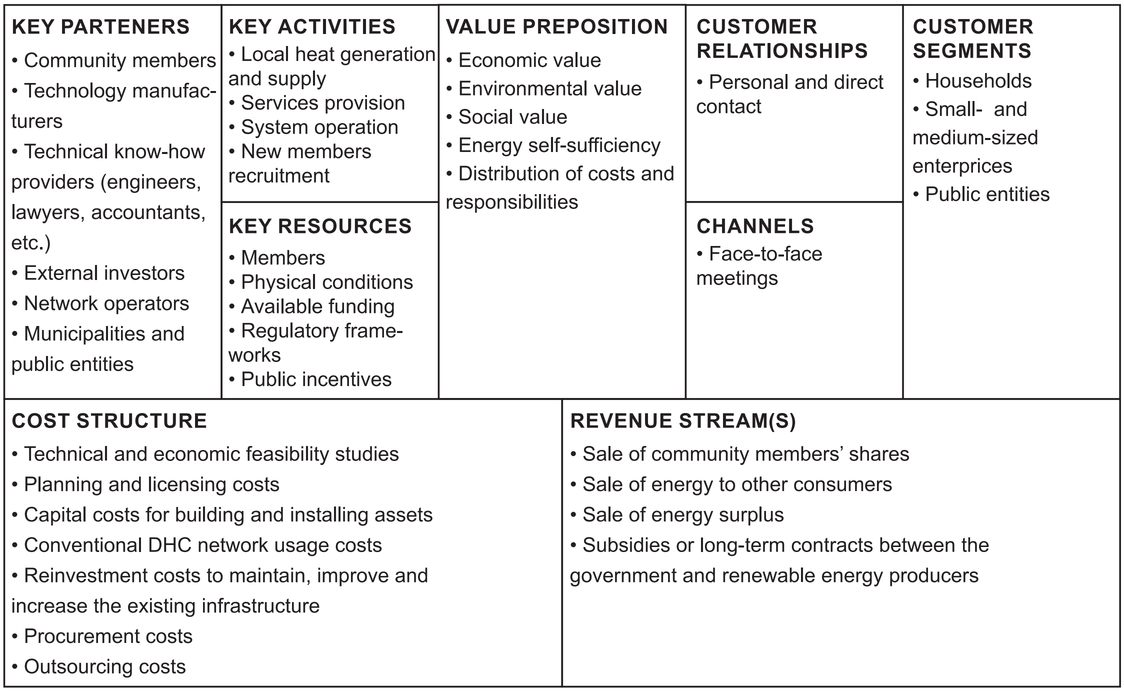

Fig. 8. Energy community business model canvas.
Source: Adapted from Ref. Reis et al. (2021).

different business dimensions. The BMC is vertically divided into two main parts, as shown in the BMC for the energy community presented in Fig. 8. The four blocks on the left including key partners, key activities, key resources, and cost structure show how value is created. The middle block, i.e., value proposition identifies the created values from the customers' perspective. The last four blocks on the right aim to address how value can be delivered and captured. Below we discuss three BMs for energy communities that are adapted from Reis et al. (2021) for 5GDHC applications.

Local energy markets: this BM would establish energy communities with peer-to-peer energy exchange between community members who would like to increase autonomy and reduce trading with external energy providers. Thus, pricing can be directly negotiated between community members and revenues would be equally distributed among them. All members shall be decision-makers whereby heat producers choose which consumer they sell their available energy to, and vice versa. A practical example of this application is seen in the case study Embassy of Sharing in which the seven connected buildings freely trade with each other in a fully decentralised way. However, challenges such as demand balancing, system control, and the requirement for an advanced trading platform to keep a record of energy and money transactions may limit the applicability of this BM.

Third-party-sponsored communities: this BM would enable community members to find sponsors who would become responsible for financing energy community projects. Available financing schemes for community members can be, e.g., grants and subsidies, private or public loans, leasing, and crowdfunding (Leoni et al., 2020). While representatives from the energy community can be involved in the decision-making process, the financing entity would be the main decision-maker in these projects since all financing risks are put on its side. The financing entity would hold assets of system ownership and would generate revenue through a long-term Public Purchase Agreement (PPA) with community members who benefit from cheaper and renewable energy.

Community ESCO: this BM would be realised when external energy services companies (ESCO) partner with energy communities to provide heat-as-service or comfort-as-service. ESCO are slightly different from ordinary energy companies or consultants in the sense that they can finance energy community projects. ESCO BM can take a variety of customised forms, out of which a practical example is presented in ectogrid™. In this case study, the energy company, i.e., ESCO selected a community of interest to implement a 5GDHC system and offered complete retrofit of all DSS by installing heat pumps, chillers, heat exchangers for free-cooling, pumps, valves, etc. The ESCO financed the project and owned the new infrastructure. In doing so, remuneration for ESCO existed in the guaranteed energy savings which were estimated in the ectogrid™ case to be around 60%. By the end of the binding contract period between ESCO and community members, the latter may choose between buying the entire system to run the business as local energy markets or continuing the community ESCO BM. The three discussed BMs need to be further investigated in their respective real cases at different heat tariffs and carbon taxes to assess the economic as well as environmental benefits of 5GDHC implementation (Pakere et al., 2023).

4.3.4. Best practice for system monitoring

Best practices for system measurement and verification are discussed herein based on lessons learned from the presented case studies. Firstly, in situations where multiple HPs are installed in one DSS, measurements from the thermal energy meter installed directly after the connection to the DSS should be used for model verification, energy audits and billing, and system performance evaluation. This is mainly because flow and temperature sensors in individual HPs do not necessarily represent the actual flow and temperatures entering and leaving the DSS since mixing between different streams usually occurs. Secondly, a best practice for correcting synchronisation errors between measurements is to shift or resample the measurements. Shifting is recommended when two time series are out of phase, while resampling to a common time frame is suitable when different intervals are used. These approaches would circumvent the practical issues arising when the controllers recording the timestamp are not connected to the internet and/or unable to use internet clock time. Finally, significant improvements in the system performance can be attained by employing heat pump control strategies that allow stable refrigerant charge through the expansion valve. To ensure correct control and operation of the heat pump, it is recommended to follow the latest guidelines for instrumentation and data management published by the International Energy Agency IEA HPT Annex 52 in Ref. Davis et al. (2021).

5. Conclusions and outlook

The paper presented proposed best practices by middle agents for developing 5GDHC systems in Sweden based on findings from workshops. Four different case studies were demonstrated to highlight the variety of technical solutions that 5GDHC systems can incorporate, including, e.g., one- and two-pipe network topology, uni- and bi-directional mass flows, and several energy sources. The main key challenges found in all presented case studies are the sophisticated control of energy exchange between connected buildings, the system capacity to cover peak load demand, the undefined requirement for connecting new buildings, and the need for well-established and beneficial BMs.

A roadmap was composed by the workshop participants who were divided into three groups consisting of system planners, district heating companies, and heat pump experts to analyze the current market situation and to provide an extended look at the future. It was found that wider implementation of 5GDHC systems entails technological development in HPs as well as in providing purchased packages, which would consequently create more jobs, boost the economy, and contribute to low-carbon cities.

The best practice for planning 5GDHC systems requires first identifying a set of technically feasible solutions which could then be evaluated for their political and social desirability. It is essential to include policymakers and citizens together with systems experts in this process to promote energy communities. Based on the demonstrated case studies, three BMs for energy communities are presented for cases of full autonomy (local energy markets), with a sponsoring agent (third-party-sponsored), or when a company provides services (community ESCO). The Modelica language is recommended for the modeling and simulation of 5GDHC systems due to its capabilities in modeling such systems including thermohydraulic, control, and economic aspects. Approaches for correcting synchronisation errors between measurements may involve shifting when two time series are out of phase, or resampling when different intervals are used.

Although the study focused on the Swedish DHC market, the best practices can be explored and adapted to suit specific market needs. The study findings are novel in the sense that they provide fresh insights into the current and future situation of the Swedish DHC. It is recommended that the main development efforts of 5GDHC systems should be focused on the following four major topics: (1) standardisation to elaborate industry requirements, (2) legislation and training courses for certified installers, (3) provision of purchase packages, and (4) promotion of joint ownership and TPA.

CRediT authorship contribution statement

Marwan Abugabbara: Conceptualization, Literature review, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Signhild Gehlin:** Methodology, Project administration, Review and editing. **Jonas Lindhe:** Review and editing. **Monica Axell:** Review and editing. **Daniel Holm:** Review and editing. **Hans Johansson:** Review and editing. **Martin Larsson:** Review and editing. **Annika Mattsson:** Review and editing. **Ulf Näslund:** Review and editing. **Anjan Rao Puttige:** Review and editing. **Klas Berglöf:** Review and editing. **Johan Claesson:** Review and editing. **Morten Hofmeister:** Review and editing. **Ulla Janson:** Review and editing. **Aksel Wedel Bang Jensen:** Review and editing. **Jens Termén:** Review and editing. **Saqib Javed:** Project administration, Resources, Supervision, Review and editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript..

Declaration of competing interest

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

Data availability

Data will be made available on request

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