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Articles

A review of the current status and development of 5GDHC and characterization of a novel shared energy system

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Abstract

This review presents the status and outlook for shared energy systems (SES) and fifth-generation district heating and cooling (5GDHC). It provides an overview of the technical and functional knowledge encompassing design and development, operational and system architecture, and control and decision support systems of these technologies. The review also presents different tools and models found in the literature for design, simulation, feasibility, high-level control, and business incorporates legal and social barriers that risk being forgotten. The review identifies existing research gaps and challenges that need to be addressed in the further development of SES and 5GDHC. Finally, the article presents and characterizes a new energy solution built in Lund, Sweden. The characterization is performed in line with the definitions of 5GDHC and SES.

Introduction

Background

Access to energy is an important foundation in the evolution of today's modern society. Energy is a facilitator for the development of technologies, products, and societies. However, a large proportion of energy sources is based on fossil fuels, which have far-reaching negative effects on our environment and future opportunities. To mitigate these effects, the energy sector faces the major challenge of transitioning to a more sustainable operation.

Heating and cooling represent 50% of the final energy use within the European Union (EU) (European Commission 2016). Only 18% of this energy is based on renewable energy sources, while 75% is based on fossil fuels and 7% is based on nuclear technology. With the goal of the Paris agreement being to keep global warming well below 2 °C compared to preindustrial levels (Delbeke et al. 2019), we must replace fossil energy with efficient and renewable sources to lower the emission of greenhouse gases.

There seems to be no universal solution to this challenge, which will impact all levels of society. A mix of measures is required as part of the energy transition, including energy efficiency, planning measures, and utilization of renewable and recycled energy. The European Commission published in 2016 the first strategy to strategy provided a framework for integrating efficient use of energy by decreasing leakage of energy and maximizing the efficiency and sustainability of cooling and heating systems. One method to achieve this is the reuse of excess energy flows within the community.

It is difficult to recover low-exergy thermal sources from current common heating and cooling solutions. Low-temperature energies, for example, excess energies from industrial processes, supermarket refrigeration, and chillers for comfort cooling, are commonly wasted. These energy sources have the potential to recover energy for use in neighboring buildings with complementary demands. However, this requires a different approach when designing new energy solutions within the community.

Common heating and cooling solutions can be categorized into two types: either a centralized solution, such as district heating and cooling, or a local solution in each individual building, such as a boiler, chiller, or heat pump. In Sweden, district heating accounts for 58% of the total delivered energy for space heating and hot water in households and commercial buildings (Energimyndigheten 2020). The remaining heating demand is supplied by local solutions.

Each solution has its advantages and disadvantages. The centralized solution is large in scale and preferably combines heating, cooling, and electric power production. Due to the scale and professional operation, cheaper energy sources can be used, which are untenable for local systems. An example could be the combination of a boiler fueled by wood chips or household waste for heating with a heat-driven cooling machine or electrical heat pump for cooling. Even though it is a complex solution, the operation and maintenance required by the end customer are very low. However, a grid is required to distribute the thermal energy from the production unit to the customer, requiring high initial investments and complicated permit processes. The distribution grid for heat has a high temperature (generally between 60 and 120 °C), suffering from thermal losses, while cooling is supplied through a parallel low-temperature grid. Though the centralized solution is highly impacts on the served community. Such systems are also referred to as traditional or first-to-third generation district heating systems.

Local solutions adapt the temperature to the individual building and require a more refined energy source, for example, electrical heating, gas, or wood pellets. The local equipment, such as a boiler, is not as advanced or efficient as the centralized solutions. Local solutions normally lack equipment for exhaust treatment but have no distribution losses. They also require more attention from the customer compared to centralized solutions. The unit and any support equipment (e.g., chimney, fuel container) occupy space in the building and necessitate a higher capacity of electrical power, gas, or other types of fuel supplied to the place of use. Thus, even though the local solutions do not require a grid for transporting thermal energy from the production unit to the customer, their use increases the cost of operating, maintaining, and developing the electricity and gas grids.

With this in mind, one alternative could be to create a system that is a mix of local and centralized solutions, benefitting from both technologies. A promising example is a thermal-based shared energy solution (SES). It can consist of a small, low-temperature district heating and cooling grid with bidirectional energy flows, which supplies buildings integrating local heat pumps that increase the temperature as required. Such a solution allows for grid temperatures closer to ground temperatures, which increases the ability to recover excess energy flows and also has lower distribution losses. Furthermore, the SES enables sharing of energy flows between connected buildings. With a centralized control strategy, low-temperature energy from one building can be used as an energy source in another. This kind of SES solution has several names, but a recent popular term is a fifth-generation district heating and cooling (5GDHC) system.

Introduction to the general concept of the shared energy system

Shared energy systems (SES) are energy solutions that enable exchanges of energy flows between buildings or processes. A typical example of SES is industrial and supplying other connected buildings with any surplus electric energy. On a community level, it might be a thermal grid allowing recovery of low-temperature (50–70 °C) excess heat from a process or jointly owned grid-connected solar panels, often referred to as the fourth generation of district heating (4GDH).

Another upcoming SES-based community solution involves connecting together buildings with different energy demands, which allows the buildings to complement each other’s needs instead of fulfilling these demands locally by primary energy sources. An example would be linking a supermarket, some residential buildings, and an office building together by an uninsulated, two-pipe distribution system, illustrated in Figure 1. The supermarket´s refrigeration and freezing plant generate heat, the residential buildings have heating demands, and the office has both heating and cooling demands for climatization. The office building will first locally recirculate heat that appears from its cooling demand. The remaining heating demand in the office building and the heating demand of the residential buildings are covered by the recovery of excess heat energy from the supermarket supplied through the grid. By using this heat energy, the office and residential buildings in effect provide cooling to the supermarket's equipment. Through the use of local heat pumps and cooling machinery, each building's temperature demand is locally fulfilled and the temperature in the distribution system can fluctuate freely and is often near the ground temperature.

Fig. 1. Principle structure of a thermal SES.

to the system. This enables the system to save unbalanced thermal energies over time and discharge them when demands occur. By linking opposite thermal demands together and using local heating and cooling machines, the need for primary energy is lowered. Such SES solutions are referred to as 5GDHC.

Previous reviews and aims of the study

District heating and cooling (DHC) systems have been a topic of active research, with several review articles published covering different aspects of these systems. Rezaie and Rosen (2012) reviewed traditional district energy systems from technical, economical, and environmental perspectives. Werner (2017) studied the status of the first to the fourth generation of district heating and cooling, considering the market, technical, supply, environmental, institutional, and future contexts. Guelpa and Verda (2019) presented a critical review of thermal energy storage in DHC systems. Talebi et al. (2016) reviewed system and component modeling approaches for traditional district heating systems with a specific focus on load prediction. Sarbu, Mirza, and Crasmareanu (2019) also surveyed the modeling and optimization approaches for district heating systems with a particular emphasis on the heat distribution network. Olsthoorn, Haghighat, and Mirzaei (2016) provided a review of existing studies on the modeling and optimization methods for the third- and fourth-generation district heating systems in terms of computation, precision, and degree of output certainty. Allegrini et al. (2015) presented an overview of existing models and modeling approaches for district energy systems and associated software tools that address district-level energy systems. Vandermeulen, van der Heijde, and Helsen (2018) reviewed the literature on advanced control for thermal networks for 4GDH systems. Odgaard and Djørup (2020) described various regulatory regimes for price regulation in traditional district heating systems. Guelpa and Verda (2021) reviewed the existing literature on demand-side management in district heating systems. The study by Schmidt et al. (2017) highlights the benefits of low-exergy systems and provides a good understanding of both the possibilities and the challenges of low-temperature district heating. The

Most of the existing reviews focus on traditional first-to-third generation DHC systems. A few recently published review articles provide a general background of the SES and 5GDHC technology. Existing reviews of 5GHDC characterize the low-temperature energy solution, present facilities (Buffa et al. 2019; Pellegrini and Bianchini 2018) or different suitable simulation tools (Abugabbara et al. 2020), and fault detection (Buffa et al. 2021). Nevertheless, a thorough review of literature related to technical and functional knowledge of SES and 5GDHC systems encompassing evolution and development, operational and system architecture, modeling methods and approaches, control and decision support systems, and social and legal aspects is lacking.

This review article aims to summarize the recent knowledge on SES and 5GDHC systems in the context of high-level control solutions, business models, simulation tools (including the platforms they are based upon), and the legal and sociological challenges of implementing these systems. It also intends to extend the previous reviews on 5GDHC systems by providing an updated overview of different 5GDHC solutions to highlight the development and current knowledge of these technologies, clarifying further the terminologies related to 5GDHC solutions, and presenting references to new 5GDHC cases.

The article includes the categorization of a new variant of a 5GDHC solution called ectogrid™ that is under development. The categorization is performed based on the findings from the review.

Literature review

Method

The literature study was based on articles retrieved from LUB-search, which is Lund University's scientific database, connecting more than 25,000 different scientific

February 22, 2021.

Table 1. Keywords used in the literature review and the resulting articles.

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If the search gave broad initial hits, the articles were first limited through the addition of relevant keywords using the "and" function. Then they were filtered out based on publication year (interval) and by topic. The articles obtained during the initial selection process and supplementary search numbered 1671 pieces. After a multistage selection based on whether the article was related to an SES or 5GDHC solution, there were 44 articles of interest. The selection process is illustrated in Table 1.

Results

This section presents the results of the literature review. It starts with a historical recap of the evolution of district heating. Then the results from the review are presented. The articles are sorted into six groups based on the main topics of the article and are presented and commented on in the following.

Evolution of district heating systems

District heating solutions have a long technical history. The first generation was created in the United States between 1870 and 1880 (Pellegrini and Bianchini 2018; Long 2018; Lund et al. 2014) and was based upon high-temperature steam, <300 °C, as an energy carrier (Long 2018; Kadir and Özkan 2018; Averfalk 2014). The second generation used pressurized water with operating temperatures up to 150 °C (Averfalk 2014).

third generation started development during the 1970s (Pellegrini and Bianchini 2018) and consists of prefabricated pipes with insulation. The temperature level in the supply line is usually below 100 °C. A temperature range between 70 °C and 120 °C is specified by Averfalk (2014).

The fourth generation is in ongoing development and works with lower grid temperatures than the third generation. The study of Pellegrini and Bianchini (2018) refers to a Danish facility that was built in 2012 with two types of fourth-generation district heating, one operating with a temperature range between 50 °C and 70 °C called low-temperature district heating (LTDH) and one operated with temperatures below 50 °C called ultra-low-temperature district heating (ULTDH). The ULTDH solution is complemented with a local heat pump for hot water production. The fourth-generation district heating system is described as a system that can handle both central and local energy production, energy stores, low system temperatures, and varying supply temperature (Schweiger et al. 2017). A comparison between the third and fourth generations of district heating has been performed by Lund et al. (2018). The comparison underlines the relative strengths and limitations of the two generations based on their technical and economic prospects. The main difference is the lower supply and return temperatures in the fourth generation, which lead to smaller heat losses from the grid. Moreover, secondary aspects, including possible integration of low-temperature excess and waste heat sources, and improved efficiencies of combined heat and power (CHP) plants, heat pumps, biomass boilers, and solar collectors, among others, are the key derivatives of the fourth generation.

The fifth generation of district heating is the most advanced generation of DHC systems. It is defined as a distribution system that works with temperature levels near the ground level, 12 °C to 30 °C in the grid (Kadir and Özkan 2018; Buffa et al. 2019). In fifth-generation district heating, each building has local heat pumps, which fulfill the required temperature level and power demand. The heat pump itself is connected to a low-temperature distribution grid from which it retrieves its energy. There are many driving forces for the development of the fifth generation. One is its thermal energy. Lastly, the grid can meet both cooling and heating demands with the same pipes.

The ASHRAE Handbook (2020) provides a more general categorization of the development of district heating systems into three broad categories of high-temperature hot-water, medium-temperature hot-water, and low-temperature hot-water systems. These systems correspond respectively to supply temperature classes of over 175 °C, between 120 and 175 °C, and lower than 120 °C. Under the ASHRAE categorization, the first and second generations of district heating principally correspond to high- and medium-temperature hot-water systems, respectively, whereas the third, fourth, and fifth generations all fall into the class of low-temperature hot-water systems. The two categorization schemes are, however, not fully parallel. For example, the upper temperature limit of 175 °C for medium-temperature hot-water systems is higher than the corresponding limit of 150 °C for the second-generation district heating systems.

Characterization of 5GDHC

There are several different names for solutions that can be categorized as 5GDHC. In the review article by Buffa et al. (2019), the following names are mentioned: FLEXYNETS, Anergy, LTDHC (low-temperature district heating and cooling), LTN (low-temperature network), and CDH (cold district heating). Other examples that can be added to that list are ectogrid^{TM} (Kadir and Özkan 2018), ULTDH (ultra-low-temperature district heating) (Pellegrini and Bianchini 2018), BEN (balanced energy network) (Song et al. 2019), and DESS (District Energy Shared System) (Perry and Ren 2013).

The plethora of names is due to the lack of a common definition and the marketing of different solutions for 5GDHC. FLEXYNETS is a 5GDHC system that arose from a Horizon 2020 project coordinated by Eurac Research in Italy. Anergy and ectogrid^{TM} are names for different commercial solutions of 5GDHC systems. A large Anergy system was built in Switzerland at ETH in Zurich. A pilot ectogrid^{TM} system is being

Canada.

Some names are used with both fourth- and fifth-generation systems, such as LTDHC, LTN, and CDH (Buffa et al. 2019). A presentation of a conceptual system design for CDH is performed by Pellegrini and Bianchini (2018) and corresponds to the 5GDHC definition of Buffa et al. (2019). This is based on traditional district heating and cooling solutions but with a cold distribution line. The authors describe the main parts, energy sources, distribution networks, subcentral parts, and control and metering of a CDH solution and its possibilities.

The literature review suggests that there are a few published solutions and that they lack a unifying name or definition. To avoid misunderstandings, a unifying name is needed and some evaluation or characterization factors are essential for defining these energy solutions. Buffa et al. (2019) have proposed a name based on the established generational term for district heating together with their definition of a 5GDHC system.

> A 5 GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with Water Source Heat Pumps (WSHP). It operates at temperatures so close to the ground that it is not suitable for direct heating purposes. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5 GDHC technology enhances sector coupling of thermal, electrical, and gas grids into a decentralized smart energy system.

There are different designs and technical solutions that correspond to the definition of 5GDHC. To sort them out from one another, a categorization of different 5GDHC temperature, and balancing units.

The numbers of pipelines are defined as follows:

- A one-pipe system is a solution where the medium is disposed of after use or a closed one-pipe system.
- A two-pipe system handles both cooling and heating within the same two pipelines.
- A three-pipe solution has one supply line with a high temperature and after using the water is fed back into a two-pipe system.
- A four-pipe solution is built up with a pair of pipes that maintain a temperature quality that can be applied directly. Then the second pair of pipes forms a grid where the temperature quality requires local finishing.

The second characteristic is based on energy and medium flow directions in the grid. The traditional grid solutions (first- to fourth-generation district heating) are classified as nondirectional energy flows and directional or nondirectional medium flows. In 5GDHC, the energy flows are instead bidirectional and the medium flow can be directional or nondirectional.

A 5GDHC with nondirectional medium flow appears in systems with decentralized pumps. Bidirectional energy flow with directional medium flow occurs in 5GDHC networks with central pumping and when there are both cooling and heating demands. Buffa et al. (2019) also present the result of an inventory of fifth-generation district heating plants in Europe. The inventory is based on the presented definition of 5GDHC.

Practical examples of SES and 5GDHC systems

There is a large variation in the technical execution of 5GDHC solutions. An early 5GDHC facility is the Whistler Athletes Village, built in 2009 for the Winter Olympics solution, a low-grade waste energy flow is recovered from both wastewater and buildings. The flow is then distributed through a two-pipe system that delivers both cooling and heating in the same pipeline.

The balanced energy network (BEN), built at London South Bank University, is evaluated by Song et al. (2019). The BEN has a cold energy carrier that is distributed centrally to local heat pumps. In this solution, there is no central balancing unit but local accumulators on the hot side of the heat pumps, which could allow for better power matching in the grid through peak shaving. Current buildings in the grid have very low cooling demands, which were not considered.

Anergy is a 5GDHC solution that originates from Switzerland, an example of such a solution is the facility at ETH Hönggerberg in Zurich that was built in 2013. A description and an initial evaluation of the Anergy system are presented in a report from ETH Zurich (2020). The facility consists of three underground energy storages with a total of 431 boreholes used for handling energy imbalances and storing excess energies between seasons. Fourteen buildings are connected through five clusters. Each cluster consists of local heat pumps and exchangers. Each cluster balances the energy demands within the cluster, and if that is not enough the imbalance is compensated by the three energy storages connected via a grid to all clusters. The grid is built as a supply loop. The grid enables energy exchanges between the clusters but also between the clusters and different energy storages. The energy storages aim to be as cold as possible at the beginning of the summer season to maximize the free cooling capacity and aim to be as warm as possible when the winter season starts. The grid consists of a three-pipe system: one warm pipe, one cold pipe, and a free cooling pipe that connects the energy storage with the clusters directly. The temperatures in the grid shift over the year, with the hot side varying between 8 and 22 °C and the cold side varying between 4 and 18 °C. An energy center is connected as a redundancy but also to fulfill peak demands.

Boesten et al. (2019) present a 5GDHC solution that characterizes a facility built in Heerlen, the Netherlands. An old district heating system based on a heat pump in small-scale industries. The system comprises various buildings with a total area of 200,000 m^2. Conditions and possibilities for 5GDHC plants were also addressed and the possibility of using an energy hub concept was also studied. The concept, known as a multi-energy system (MES), highlights the possibility of combining different generations of district heating solutions and connecting different renewable energy sources.

In the study of Kadir and Özkan (2018), two SES-based projects are presented. The first facility is in The Hague, the Netherlands. It uses seawater as a heat sink. The heat is exchanged either directly or through a heat pump in winter. The energy is then distributed to local heat pumps in the connected buildings. This facility only adds heat. The second facility serves Krommen Kelchbach district, Switzerland. It is a 5GDHC-based facility that distributes both cooling and heating through the same distribution lines. The working temperatures are between 8 and 18°C for heating and between 4 and 14°C for cooling. The energy is either directly exchanged for cooling delivery or refined via local heat pumps for heat delivery.

The 5GDHC solution ectogrid™ was developed by a European energy company. A pilot plant has been built in Lund, Sweden, and consists of a cold distribution grid supplying both heat and cooling within the same network. The temperatures in the hot and cold pipes of the grid are kept between 16 and 40°C and between 6 and 30°C, respectively. Local chillers and heat pumps are used to secure the right temperature level for the end user. It is categorized in detail later in this article.

Due to the lack of definition and a unifying name, there are many gray zones between 5GDHC and 4GDH solutions. For example, in the research report by Andrés et al. (2018), the possibilities of combining a fourth-generation district heating network with low-quality waste energy sources common in urban areas are assessed. One project located in Nice could be described as 5GDHC, where low-grade heat from sewage water is recovered and distributed through a local distribution system to properties using local combined cooling and heat pumps. The work was carried out within the European collaboration project “ReUseHeat.”

Similarly, upgrades to existing district solutions can resemble 5GDHC solutions. An upgrade to a district heating and cooling network on a university campus in Umeå, Sweden, was presented by Bäcklund (2018). The existing solutions consisted of a local energy distribution grid with both cooling and heating pipes, connected to the municipal district heating and cooling grid. Some of the buildings connected to the internal grid have installed combined cooling and heat pumps. The heat from the combined machinery is delivered to the individual buildings, but the evaporator side is connected to the entire cooling grid at the campus. This enabled sharing of cooling energy to other connected buildings and increased the seasonal coefficient of performance (SCOP) of the heat pump since both heating and cooling energies are utilized.

The variation in design could be due to different priorities in efficiency and availability, as well as other factors. Therefore, it is unlikely that there is one optimum 5GHDC solution.

Operational experience

Since the 5GDHC solution is a fairly new energy concept, there is a lack of reported operational experiences and operational data. The Anergy solution at ETH Hönggerberg in Zurich covered 81% of the heating and 87% of the cooling demand in 2016 (ETH Zurich 2020). The evaluation performed in 2018 shows that the annual coefficient of performance (COP) was between 5.8 and 6.2 for heating and between 9.7 and 12.8 for cooling (including the coverage from the energy central). The COP of free cooling goes up to 36.5. The maximum heat and cooling output from the heating and cooling unit is 6.5/5.3 MW.

The study by Sommer et al. (2020) has compared two types of low-temperature grids. The bidirectional grid (BG), a two-pipe solution with a cold and hot side and decentralized pumps, was compared with a new proposed reservoir network (RN), based on a distribution ring, a one-pipe solution with central pumping. The comparison was made due to a control problem being noticed in BG solutions built showed that the two solutions are nearly equivalent in terms of performance, with BG being a little more efficient as its temperature qualities are better and it also uses slightly lower pump energy when it is operated efficiently. In contrast, the RN solution can generate large pumping energy costs if constant flow occurs in the ring. The installation cost is lower in a ring-fed RN since only one pipe is installed instead of two.

Wang et al. (2021) analyzed the BEN solution. The energy solution was based on the central distribution of a cold energy carrier and local heat pumps. It is not a typical 5GDHC solution and it only supplies heat. Interestingly, the work includes an investigation of the thermal inertia of buildings and how local accumulators can be used for optimizing energy costs and carbon footprint. The analysis showed that the heating consumption for operating the BEN system is decreased by more than 70% compared to the more traditional natural gas boiler-based heating system.

The 5GDHC distribution solution is more complex than the former energy distribution solutions, so hopefully more findings and results will be published over time.

Modeling of 5GDHC

In more advanced district heating and cooling systems, peak shaving, thermal load balancing, emissions, and costs are challenges that may be addressed in new ways to gain efficiency and reduce emissions. In a review presented by Buffa et al. (2021), publications focusing on control strategies of 4GDHC and 5GDHC systems, based on model predictive control and machine learning algorithms, are summarized. The control strategies of a 5GDHC solution differ from 4GDHC and the more traditional solutions, and the review highlights those differences. It is also acknowledged that innovative DHC solutions require more sophisticated operations to function optimally, which can be helped by the use of appropriate mathematical models. Due to the complexity and multiple parties interacting within a 5GDHC, it is

Design and simulation

A balance of heating and cooling demand is required for a well-performing 5GDHC system. The feasibility of a system is dependent on the buildings and heating/cooling sources that will be connected to the grid. For new systems, this requires a complete assessment. Revesz et al. (2020a) used a techno-economical modeling tool to perform a feasibility study for a potential 5GDHC grid in the area of Islington in London. The feasibility study was performed in cooperation with local authorities. Two possible grids were identified based on the buildings in the area and an estimation of the different buildings' energy demands for cooling and heating. One of the grids utilized excess heat from the underground railway system combined with groundwater for both heating and cooling. The other grid utilized excess heat from data centers for heating and also groundwater for both heating and cooling purpose. The study concluded that there was a technical potential to develop two 5GDHC grids in Islington. However, neither grid met the profitability requirements set by Islington Council. Once a grid is established, the energy balance can be affected by the connection of additional buildings.

A modeling strategy for evaluating different types of central distribution systems was presented by Long (2018). The strategy was based on the reduced-order modeling framework (ROM). It was aimed at analyzing the consequence of connecting individual buildings to a 5GDHC grid. The model can be used for decision making and strategical work when expanding a 5GDHC grid. von Rhein et al. (2019) also presented the development of a software tool to evaluate whether a building has the right characteristics to be connected to a central 5GDH grid. The evaluation is performed on a building's energy profile, demand, and potential contribution to a network. The focus is on the development of a flexible hydraulic model for several buildings or a district. The outcome accounts for system performance, energy requirements, CO_2 load, and construction cost.

to optimize a 5GDH toward the lowest annual cost is presented by Wirtz et al. (2020). The tool handles several different types of energy sources and builds up an energy hub where energy sources and flows can be chosen. The tool was applied to a real case in Germany and is compared to a reference case based on individual building system solutions, with stand-alone HVAC systems. Comparisons were made based on economic, exergy efficiency, and environmental impact parameters. The results showed that in the present case an annual reduction of cost by 42% and of CO_2 emissions by 52% was possible to achieve while increasing exergy efficiency by 34.1%.

A study of how local heat pumps, combined with a thermal energy storage (TES) for the production of domestic hot water, can shift electrical peak loads and lower energy costs through a model for predictive control is presented by Buffa et al. (2020). The study used algorithms from artificial intelligence (AI) and uses ROM for predictions of the performance. In the study, 10–14% of the electrical consumption could be shifted to off-peak hours compared to a rule-based control. An interesting finding was that even though it was possible to shift electrical power demands to off-peak hours, the benefits of doing so must be investigated further. This was because the overload during off-peak hours resulted in lower COPs and higher thermal losses, which often reduced the economical savings from shifting the electrical loads to off-peak hours. This meant that the economic benefit of shifting 14% of the load in the study resulted in just 3.5% saving, based on their conditions for the calculations.

A novel design methodology for the development of a fifth-generation district heating system that combines both electrical and thermal factors with forecasting is presented by Revesz et al. (2020b). The work studied the possibilities for two facilities in central London to integrate different local energy sources, including energy from wastewater, data centers, supermarkets, geo-energy sources, the subway, and the sea. The methodology is based on a previous project, Green SCIES, which aimed to utilize various recycled and renewable energy sources within the grid while maximizing the use of renewable energy and promoting peak shaving. The authors compared different combinations of energy sources to see which is the most effective design, and the evaluation model tool is based on Energy PRO.

A simulation model of a stand-alone distribution network and its interaction between different buildings during operation is presented by Alisic, Paré, and Sandberg (2019). They see the buildings, connected to the network, as loading points that can deliver both cooling and heat, depending on their demands. The size of the load point depends on its power demand and the Carnot efficiency of the connected heat pump. The power demand is based on the room's internal load and its heat-emitting properties to the surroundings. The power demand is also affected by the current Carnot efficiency, which is due to temperature changes in the grid. The temperature in the grid depends on the power requirements of other connected load points and energy losses in the grid.

A proposed model for optimizing grid temperatures of 5GDHC systems was presented by Wirtz et al. (2021). The model, based on a mixed integrated linear program (MILP), is real-time capable and is designed for model predictive use. A comparison is made between two temperature control strategies of the grid. One was a direct cooling mode, that focuses on grid temperatures that could be used for direct cooling <14 °C on the cold side of the grid. The reference case operates with free-floating temperatures limited only by lower and upper temperature limits of 6 °C and 40 °C. The study presents a method for optimization of the grid temperatures regarding energy usage and costs.

A significant aspect of the design and simulation of 5GDHC is the choice of the modeling environment. A bibliographic analysis of modeling 5GDHC systems was presented by Abugabbara et al. (2020). The authors found that using Modelica in a new way for co-simulation of the district and building energy systems is a prevalent modeling approach. One of the challenges of using it for 5GDHC purposes is the modeling of the advanced control strategies. In a different study, von Rhein et al. (2019) noted that although EnergyPlus, ESP-r, and TRNSYS also have the capabilities modeling environment for both feasibility studies and design calculations of 5GDHC.

High-level control system

A high-level control system is the top level of the control system and coordinates subsystems in the equipment, external information, and business transactions. One of the challenges when building a 5GDHC system is the coordination between the connected facilities demands and supplies and to uphold the system efficiency. This is one of the main tasks for the high-level control system. Other important tasks for the high-level control system are peak shaving and securing the overall energy supply.

The 5GDHC systems are founded on the idea that buildings connected in a low-temperature grid can together achieve a better energy efficiency than one would gain individually. By linking buildings together, it is possible to share energy between different buildings and a type of energy symbiosis arises. This symbiosis requires a coordination of the energy demands, sources, and each stakeholder's requirements, known as a high-level control system. This creates the framework for trading strategies within the grid.

Research about the high-level control system identifies the need for important factors other than just technical coordination between the different buildings. It is easy to see the benefits of being able to exchange excess energy between buildings. However, there are factors to take into account in order to make it work. This could be the need for business models and handling different participants' agendas. Menneghetti and Nardin's (2012) optimization model is interesting because it not only optimizes for energy flows but also accounts for factors that influence the individual participants.

Another work with a similar approach is presented by Leong et al. (2017). The work is interesting from an optimization perspective as their experiences from an established eco-industrial park are valued. The facility described in the work is not a developed to optimize beneficial resource flows in EIP (eco-industrial parks) between the different stakeholders. Wastes, by-products, or products from one actor can be inputs to another actor connected to the EIP. The study presents an analytical method for managing the supply and demands of the stakeholders. The optimization is based on predefined criteria, including economic performance, environmental impact, connectivity, and network reliability. Each criterion is weighted in importance by each individual actor. The individual demands need to be coordinated with the whole distribution system for recovery and supply flows, which, in turn, aims to fulfill all demands appearing in the distribution system. The study describes a numerical method to evaluate the prerequisites for an EIP by optimizing the exchanges between the actors and trying to fulfill their demands, and still keeping an effective common whole. When there are deviations between what the EIP can supply and what each actor demands, they aim to keep it within an acceptable level, referring to each actor's individual weighting of the criteria. By mapping the demands and assets of an individual actor, and putting them in relation to the demands and assets of the other actors and the weighting of their demands, it is possible to optimize the entire system.

An optimization model has been developed by Meneghetti and Nardin (2012). The model was used to support the expansion of a distribution system. There is a facility management provider (FM) responsible for efficiently managing the "symbiosis" of energy sources, flows, and products. The FM role is important for balancing the demands and sources added to the grid to maintain the symbioses over the long term, and the model supports the FM with essential data for decision making.

Another example of a better common whole by minimizing energy demand is the work of Orehounig et al. (2014). The work applies an “energy hub” concept that looks at the incoming and outgoing energy flows to a system. The energy hub concept was developed by Power Systems Laboratory at ETH and is used for managing energy flows in large buildings, neighborhoods, cities, or countries. The study is about integrating different types of energy sources and providing a good

The energy hub concept might be applied as part of a 5GDHC to manage energy flows between buildings and storages.

In the work of Kadir and Özkan (2018), the possibilities of implementing an SES energy solution type ectogrid™ have been explored. The work is founded upon two questions: Are Germany and England ready for implementation of ectogrid™, and what will the costs be compared to choosing a 4GDH solution instead? To answer the first question, a market analysis was performed. In order to clarify the cost analysis, a "case model" was developed comparing CAPEX and OPEX between an ectogrid™ and a 4GDH solution. The comparison was based on three new buildings with 30 apartments each and a 7750-m^2 floor area.

Business transactions

One of the key characterizations of 5GDHC is the ability of connected buildings to be a supplier of energy to the grid in addition to being a consumer. This two-way transfer of energy requires financial modeling tools to manage the prices charged and received. In several literature studies, business transactions are combined with the high-level control strategies already described. An example of combining energy management and trading strategies is presented by Hussain et al. (2017). The authors investigated the possibility of designing building management systems (BMSs) that can also "trade" between each other to minimize the primary energy demand. The model includes the individual building, its energy production, the grid, and the production units connected to the system. In the study, the conditions for trade between each building are also reflected upon. This "system thinking" is essential in a 5GDHC system. The parameters chosen for control depend on the required strategies and parameters, such as lowest cost or greatest environmental benefit. One of the challenges with 5GDHC is to make the overall market work with the interaction of the individual buildings' own operation strategies. The authors made a theoretical approach based on the energy needs of three different buildings in Korea. The study covers BMS for electrical energy, heat, and cooling energy, as well as energy distributor and prosumers.

development of a "network controller" for 3GDH and 4GDH within a Horizon 2020 project. The controller is to be tested in a traditional district heating network in Rottne, Sweden, and in a low-temperature grid in Heerlen, the Netherlands. The goal for the controller is to achieve peak shaving and balancing of excess energy flows within the grid of both cooling and heat and the interaction with the energy market for maximizing the profit. An important part of the project is the ability to implement renewable energy sources and the use of energy thermal storage concepts. The controller should, based on the inputs and algorithms, self-learn and always optimize the system according to the desired parameters.

Trading strategies are an important factor that influences energy sharing and performance. The potential of distributed layer and peer-to-peer trading strategies for heating and cooling is presented by Li et al. (2021). The authors created a simplified distributed heating system and applied peer-to-peer techniques using IOTA cryptocurrency for financial transactions. The main objective for each peer was to maximize its profit. Bui et al. (2019) proposed a three-stage trading model for micronetworks to promote energy sharing and lower costs. The model includes both electrical and thermal exchanges between customers. The main priority is exchanging between customers that have opposing needs for electricity and heat. The second priority is selling the surplus to someone with demand but without anything to offer in exchange. The third priority is that if the internal energy production is cheaper than the energy from an external player, then the internal energy production is increased, if possible, and is sold within the microgrid. Some energy storage possibilities are also included in the trading model.

An interesting approach to creating a local market is the use of distributed layer technology with blockchain applications and peer-to-peer platforms. In several studies (Hrga, Capuder, and Žarko 2020; Mureddu et al. 2020; Klein et al. 2020; Sahin and Boynuegri 2020), a trading platform is studied based on these techniques. Even though they are focusing on local electricity production the

As discussed earlier, several studies have underlined the challenge of keeping the "grid community" satisfied while fulfilling all the individual demands. This challenge requires overall systems and strategies together with business models as drivers to succeed.

Legal and social barriers

New technical solutions face several challenges when coming to market. The development is initially performed by technicians focused on the technical challenges. Often, the need to influence societal factors can be neglected. These include adjusting legislation, planning regulations, and incentives. Furthermore, it is important to create public acceptance of a solution. Forgetting such parameters can delay the introduction to the market. A study about Danish energy planning (Chittum and Østergaard 2014) investigated whether overall energy planning is needed to enable the integration of renewable energy systems. The study identified legislation that has not been adapted and poor incentives as significant challenges.

A crucial part of 5GDHC future opportunities is how the legislation and drivers are adapted toward 5GDHC solutions being valued in the right way. For example, in the Swedish building legislation, the classification of waste energy exchange between interconnected buildings is a problem. The possibility for building a 5GDHC depends on whether the thermal waste energies are seen as free-flowing or distributed purchased energy for fulfilling the energy efficiency regulations. Another example is the regulated heat market in Denmark that restricts the possibility of selling excess energies between buildings if you are not a selected energy provider. A similar limitation influences the possibility of an SES solution that distributes electrical energy directly between different properties in Sweden since the electrical grid is regulated. A study by Chittum and Østergaard (2014) about energy plans points out the power of policy instruments and legislation and their influence on the development and introduction of new energy systems.

scale was raised in the study by von Wirth, Gislason, and Seidl (2018). If a solution is not socially accepted, the possible superiority of the new technology becomes insignificant. The study reviewed 15 articles related to the establishment and acceptance of distributed energy systems to define the drivers and barriers to their social acceptance. Little work was found on the acceptance of renewable energy both in general and as individual technologies such as wind power. No published work was found on the acceptance of combined systems with local distribution such as 5GDHC. Factors that were important for gaining acceptance of a concept include good anticipation and management of individuals' interests and potential conflicts. The study introduces three dimensions of social acceptance in the implementation of renewable energy: social policy acceptance, social acceptance, and market acceptance. The challenge of implementing new energy concepts is not only technical but largely psychosocial, which is easily underestimated.

Not underestimating the need of addressing legal challenges and social acceptance is vital when introducing new technologies/solutions. Legislations and drivers need to be managed. An energy solution is a part of the city and its infrastructure for a long time. Therefore, delivering a “distributed energy solution” is in many ways different from delivering other products. To be successful, it needs to navigate through political decisions and national legislations while still conserving its advantages.

Other findings

In this section, studies are presented that can be a source for inspiration but are not directly linked to 5GDHC.

A theoretical study of a combined cooling and heat distribution network with CO_2 as a distribution medium instead of water is conducted and presented by Weber and Favrat (2010). The network would then consist of a liquid side and a side where the CO_2 is in its vapor phase. Combining this with decentralized heat pumps and cooling machines enables two things: the extraction of both cooling and heat from and ORC technology. A discussion about the challenges of using CO_2 is provided. Also, a comparison of a CO_2 plant against a conventional energy solution is performed. The solution differs from the 5GDHC we are used to. However, it is founded on the same basic ideas, such as local temperature refinement, two pipelines for both cooling and heating, and the exchange of energy flows between buildings.

Costa et al. (2017) presented adaptive control and optimization methods from several district heating and cooling projects funded by European Union's Horizon 2020 research and innovation program. The study presents projects including Indigo and FLEXYNETS, among others. Indigo is a project that aims to improve the efficiency of district cooling through operation optimization. FLEXYNETS is the development of a 5GDHC system containing decentralized production with local reversible heat pumps and low-temperature distribution networks (10–20 °C). Other projects included in the study are E2district, InDeal, and H-Disnet. For these projects, the study describes control systems for production, distribution, storage, HVAC, and demand response systems, and optimization methods for improving energy efficiency and reducing the amount of fossil energy.

Tunzi et al. (2020) present a 4GDHC solution with temperatures around 45/25 °C that could be defined as a 5GDHC solution. The presented solution focuses on the integration of local energy sources and supplies both heat and cooling with the same two-pipes system. Local customers are connected to a distribution grid consisting of two pipe rings driven by main pumps. The connected customers retrieve energy from either the cold or warm ring depending on their demand. Local pumps secure the delivery to the connected customer. The design of the distribution grid differs from the traditional DH grid and 5GDHC solution. The solution of hot water supply is also special. The study compares their grid solution with a more traditional grid design.

Espagnet (2016) looked into thermal energy storage and its integration into a low-temperature district heating grid. The work relates to a fourth-generation district economic issues. Many different TES solutions are presented, such as water tanks, groundwater aquifer, borehole, rock tank, and phase changes of salt hydrates and metallics. This study provides a good orientation of TES techniques and their integration into a low-temperature grid.

Characterization of ectogrid

The ectogrid^{TM} is an upcoming energy solution. It is under development, and the first example has been built at Medicon Village in Lund, Sweden. It is a full-scale testbed that connects 12 buildings with a total area of 120,000 m^2 through a low-temperature, two-pipe thermal grid, enabling energy sharing between buildings. A balancing system, handling deviations in energy demands is also connected to the grid. A graphical illustration of the system is shown in Figure 2. There are several more ectogrid^{TM} solutions in the design phase throughout Europe, in Italy, Britain, the Netherlands, France, and Sweden.

Fig. 2. Pilot project for ectogrid^{TM} at Medicon Village, Lund, Sweden.

An ectogrid^{TM} consists of local cooling and heating machines (chillers and heat pumps) and circulation pumps. The pumps supply the machines with energy from the grid, and the temperature requirement is adapted locally to the individual building demands. The temperatures and the flows in the grid are therefore free to fluctuate and are only limited by material qualities or operational strategies. This distribution network. The grid consists of a cold pipe and a warm pipe that supply both cooling and heating.

The key components for local energy production are heating and cooling machines or a combination of these; a heat exchanger for free cooling; circulation pumps; and some fittings for both internal balancing and export of excess energy to the grid.

The preferred piping material for the grid is plastic pipes made of polyethylene (PE) due to the ease of installation and widespread knowledge of handling PE pipes compared to metal district heating pipes. However, using PE pipes also imposes certain restrictions on the permissible temperature levels in the grid. The desired service life of the PE pipes and their loss of strength at elevated temperatures restrict the upper temperature limit in the grid to 40 °C, whereas the risk of freezing in the heat pump evaporator confines the lower temperature in the grid to 6 °C. For applications with grid temperatures higher than 40 °C, PERT and PEX pipes provide alternate but more expensive options. The piping is normally uninsulated, but it is possible to backfill the piping trench with materials with different thermal characteristics and inertia to achieve different thermal characteristics.

The combination of local heat and circulation pumps enables control over temperature levels and flow in a somewhat different manner than in earlier DHC generations. For the previous DHC generations, the energy provider is largely dependent on the consumer's ability to return water at the appropriate conditions to enable adequate temperature difference (dT) for efficient operation of the district energy system (ASHRAE 2019). In 5GDHC, it is possible for the energy provider to effectively regulate supply temperatures, return temperatures, and temperature differences in the grid independent of the consumer. The presence of local equipment in buildings, including direct cooling heat exchangers, chillers, and heat pumps, opens up interesting possibilities for controlling the grid temperatures in both warm and cold pipes. It is, for example, possible to transfer more power to the grid by increasing the temperature difference even beyond the design values during the peak loads. This can be accomplished even without the need for all consumers the power distribution and energy performance.

The thermal storage system is a vital part of ectogrid™. It deals with imbalances in cooling and heating demands. The storage systems can consist of combinations of short-time storage such as water accumulators and seasonal storage like ATES or BTES solutions. The use of energy storage increases the possibility of utilizing all energy flows in ectogrid™.

Referring to the definition of 5GDHC provided earlier, the ectogrid™ can be defined as such a solution. The ectogrid™ has:

- A thermal energy supply grid.
- Hybrid substations with water source heat pumps (WSHP).
- A grid temperature that is free but operates normally close to ground temperatures.
- A low grid temperature, which allows recovery of excess energy with low thermal exergy.
- The possibility of using the same pipeline(s) for both heating and cooling demands.

The full categorization of ectogrid™ is a two-pipe 5GDHC solution with bidirectional energy flows and nondirectional medium flows that rests on an SES foundation. The grid operates with free temperature levels, and the pilot facility at Medicon Village uses a central short-time energy storage together with a grid consisting of uninsulated PE pipes.

The ectogrid™ is controlled and monitored by a high-level control system called ectocloud™. This works toward optimizing the whole grid, which is limited by individual buildings' restrictions and power demands. The ectocloud™ controls the grid, the local energy units, and the balancing units. The control system works

The ectocloud™ is based upon a Microsoft Azure cloud platform. It is used for planning, coordination, monitoring, and control, with the aim of optimizing the system. The optimization and control strategy is based on different key values, such as performance, peak shaving, energy cost, environmental footprint, and combinations of them all. To achieve this, the overall control system works with different forecasts (e.g., weather and energy market) and learns from historical patterns of the grid. It also collects and stores data for control, monitoring, and evaluation purposes. The overall system communicates with the locally placed subcontrol system, an energy manager that controls and influences local equipment such as heat pump(s), circulation pumps, and control valves. The ectocloud™ enables the usage of thermal inertia, the control of temperature levels in the grid, peak shaving, and more.

Even though it is stated that the temperature levels are free in the ectogrid™ grid, that should not be mistaken as uncontrolled. The freedom of choosing both the flow and the temperature levels in the grid makes it possible to base part of the operation strategies upon those parameters. For example, one can gain directional freedom by controlling the flow. With this, it is possible to create different temperatures in the grid, which then impact the efficiency of the local energy units and their power ability.

The business model for the ectogrid™ is aimed at providing flexible solutions where the customer can choose either a turnkey connection or installation themselves. In the turnkey connection, the grid owner owns and operates the local equipment. The customer is supplied with thermal energy at a cost that covers the supplied energy from the grid, capital costs of the local heat pump, and maintenance. Alternatively, the customers can own and operate the local equipment themselves and pay only for the purchased energy from the grid. These individual actors could potentially interact with the grid as part of a local energy market. However, the framework for peer-to-peer transactions is under further development.

Discussion and conclusions

The term "shared energy system" describes the interaction between buildings and their energy flows. For example, excess heat from one building can be recovered by another building through a grid that distributes the energy. One aim of this review article was to compare the basis of a shared energy system with other energy solutions using low-temperature grids. This turned out to be a challenging problem since there is no unifying name for energy solutions based on the SES principles. The general conclusion from the literature findings is that SES and 5GDHC rest on the same basic ideas of exchanging energy flows. 5GDHC forms a subgroup of SES, focusing on thermal interaction and low exergy flows.

The literature suggests there is a need for a unifying name and a definition for low-temperature grids and it leans toward 5GDHC. The definition of 5GDHC solutions proposed by Buffa et al. (2019) is the first step. It will almost certainly be developed and complementary subclassifications based on different technical distinctions, such as pipe design, material, temperature levels, and balancing, will appear in time. However, at present, there is a great deal of confusion about what constitutes a 5GDHC system (Lund et al. 2021; Gudmundsson et al. 2022). Some recent studies (Gudmundsson, Dyrelund, and Thorsen 2021; Gudmundsson et al. 2022) have made erroneous comparisons between 5GDHC and 4GDHC technologies, where the cooling potential and applications prospects of 5GDHC to provide simultaneous cooling have been inexplicably ignored. The key determinant of the 5GDHC is its ability to simultaneously provide heating and cooling with distributed heat pumps. This differentiation separates the fifth generation of DHC from the subgroup of the fourth generation for providing heating using decentralized heat pumps (e.g., ULTDH; Pellegrini and Bianchini 2018). Another differentiation between 5GDHC and the older generations of DHC is that, unlike previous generations, the temperatures in a 5GDHC grid are not explicitly related to the customer-side temperatures. In the first four generations of district heating, the network supply temperatures correspond to the temperature requirements of the most demanding customers

The practical applications of 5GDHC solutions are still in their nascent stage, and therefore, large variability in reported field practices exists. For example, the grid temperature levels in different 5GDHC solutions differ considerably (Krommen Kelchbach district: 4–18°C (Kadir and Özkan 2018), Anergy grid: 4–22 °C (ETH Zurich 2020), ectogrid™ 6–40°C). Moreover, the modernization and upgrading of older, more traditional, networks to 5GDHC-type solutions have also resulted in networks somewhat similar (but not always identical) to regular 5GDHC grids. For example, the grid at the university campus in Umeå (Bäcklund 2018) integrates an internal DHC grid with decentralized heat pumps, with the traditional DHC networks in a hybrid solution. The transformed grid at Heerlen (Boesten et al. 2019) is another example demonstrating the integration of several technologies in a hybrid solution.

In a 5GDHC solution, the energy exchanges between buildings are predominant and thus most of the energy production is located in individual buildings. This limits the need for central areas and also affects the need for permits. The power expansion follows the expansion of the system as more customers connect. Due to its scalability, the 5GDHC solution is faster both in getting to market and in generating turnover compared to a traditional district heating solution.

It is quite evident from the literature that further development of design and simulation tools and business models is needed. Currently, Modelica and EnergyPlus are among the most widely used modeling and simulation tools. One important thing to address is how to handle the individual participant's needs and wishes while at the same time keeping the grid attractive to everyone else connected to it. Additionally, how the business models handle expansions of the system and what that might entail for the ones already connected are important to explore. The 5GDHC solution must add so much value that it motivates the investment for building a grid and the central equipment.

An integral part of the 5GDHC technology is its high-level control system. Such a specialized control system is necessary for the flexible and robust application of control to serve as decision support are still lacking. Cryptocurrency-based transactions have been tried to facilitate energy and financial exchanges between different buildings of a 5GDHC grid, and the growing use of blockchain technology for energy transactions in 5GDHC settings is anticipated. An often overseen barrier in implementing 5GDHC solutions is the challenges presented by legislation and social practice. The energy market in many countries is a monopoly managed by state-owned enterprises, and trading or sharing of energy between private entities is illegitimate.

There is also a need for more studies addressing operational experiences and identifying the opportunities and challenges as concepts are further developed. The lack of studies relating to real case evaluation and operational experiences of 5GDHC articles is due to the youth of the technology. Even general experiences are of value in this early phase. Without this knowledge, it will take a much longer time to navigate toward stable and efficient 5GDHC solutions.

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Nomenclature	
BEN	building energy network
BG	bidirectional grid
BMS	building management system
CDH	cold district heating
DESS	district energy sharing system
DH	district heating
DHC	district heating and cooling
dt	temperature difference
EIP	eco industrial park
FM	facility management
G	generation

	low-temperature district heating
LTDHC	low-temperature district heating and cooling
LTN	low-temperature network
MES	multi-energy system or manufacturing execution system
MILP	mixed integrated linear program
PE	polyethylene
RN	reservoir network
ROM	reduced order modeling framework
SES	shared energy system
TES	thermal energy storage
ULTDH	ultra-low-temperature district heating
WSHP	water sourced heat pump

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