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Survey of 53 Fifth-Generation District Heating and Cooling (5GDHC) Networks in Germany

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Fifth-generation district heating and cooling (5GDHC) networks are a promising technology to decarbonize the heating and cooling supply of buildings and districts. Up to today, only a small number of 5GDHC networks have been built, mostly in Switzerland and Germany. As a result, there are substantial uncertainties and knowledge gaps in the planning and operation of 5GDHC networks. Herein, a survey is conducted among utility companies and engineering offices to collect data on 53 5GDHC systems in Germany, including technical, economic, and political key figures and design decisions. Results show that 5GDHC networks are mostly planned for small new build districts (less than 100 buildings). The most frequent heat sources are horizontal geothermal collectors (used in 23 networks) and geothermal probes (17 networks). 74% of the surveyed networks provide not only heat but also cold. Typical network temperatures are in the range of −5–20 °C. The survey results show that the price models as well as political design decisions, such as the obligation to connect to the network, vary strongly among the districts.

1. Introduction

The decarbonization of the heating and cooling supply of buildings is one of the most challenging tasks of the energy transition. To reduce fossil fuel heating technologies such as gas or oil boilers, they must be replaced with renewable heat sources such as solar thermal collectors, geothermal energy or ambient air. Since connecting every building to its own heat source, like a geothermal field, is expensive, fifth-generation district heating and cooling networks (5GDHC) are increasingly built. They are also called anergy networks[1] (in Switzerland: Anergienetze), ambient loops,[2] tampered water loops (in French: Boucle d'eau tempérée), cold district heating[3] (in German: kalte Nahwärme), or balanced energy networks.[4] A summary of the different terms and a classification of different systems are presented in refs. [5,6]. In contrast to conventional district heating, the supply temperature of 5GDHC networks is too low to heat a building directly. Therefore, decentral water-to-water heat pumps are installed in every building to raise the temperature of the heat to the required level. Thus, 5GDHC networks serve as a provider of low-temperature ambient heat for building heat pumps. The low operating temperatures lead to major advantages: First, the heat losses of the network are often negligible, and depending on the ground and network temperature, substantial heat gains can be achieved. Second, 5GDHC networks cannot only provide heating but also cooling energy. Facing increasing cooling demands in residential and commercial buildings, this is considered a major advantage over conventional district heating systems. In contrast, the planning process of 5GHDC networks is more complex than for conventional district heating systems: First, the heat pumps in the buildings and their characteristic operational behavior have to be taken into account. Second, the balancing effects of heating and cooling demands have to be considered to determine the residual thermal demand of the district. Third, the calculation of heat losses (or gains) is more complex in the case of uninsulated plastic pipes which thermally interact with the surrounding ground. In addition, there is only limited experience in planning 5GDHC networks and only a small number of engineering companies have gained actual experience with this type of heat network. As a result, there are no general design guidelines available for 5GDHC systems in contrast to conventional district heating systems.[7] This means that the planning and dimensioning of 5GDHC systems is often subject to a substantial level of uncertainty, leading to a preference for proven technologies by decision-makers. In the following, we provide a brief overview of existing literature about the planning of 5GDHC networks.

1.1. Literature Overview

There are many theoretical studies on 5GDHC systems, which mainly focus on the development of simulation[4,8–11] and mathematical optimization models.[1,12] Some studies present operational optimization models,[13,14] while other publications provide real-world experience from a practical planning perspective: Zeh et al.[15] discuss the planning of the 5GDHC network in

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Wüstenrot (Germany) and their experience with installing the first large-scale agrothermal collector with a used land area of 4400 m^2 and a depth of 1.5 m. The Wüstenrot district is also discussed by Brennenstuhl et al.[16] They also provide detailed information about two other geothermal collector systems in the cities Neustadt am Rübenberge and Bad Nauheim. Then et al.[17] provide a technical description of the 5GDHC network in the district Largarde-Campus in Bamberg, in which geothermal probes and horizontal collectors as well as sewage water is used as the heat source. Vetterli et al.[18] present monitoring data for the Suurstoffi district in Rotkreuz (Switzerland). They analyze how the water network temperature develops over 3 years of operation. The current status of the minewater project in Heerlen (Netherlands) is presented by Verhoeven et al.[19] They elaborate on future network expansion plans and how the business case of this project is realized. In general, there is a lack of design guidelines for 5GDHC systems as discussed by Boesten et al.[7] First approaches have been presented by Revesz et al.,[20] who provide a holistic design approach for 5GDHC systems on a conceptual level. Pass et al.[21] and Wirtz et al.[22] introduce two different concepts to quantify the demand balancing in 5GDHC systems and to support design decisions in the early planning phase.

For conventional district heating and district cooling networks, comprehensive statistics exist as shown in refs. [23,24] For 5GDHC systems, however, there is only very little data and only two publications are available, which provide an overview of the technology usage: Reiners[25] shows a map with 22 5GDHC networks in Germany and indicates which heat source is used for every system. The data has been collected from publicly available sources. In his list, 7 systems use geothermal probes and 7 systems groundwater or water from old mines (especially in the Ruhrgebiet area in Germany). However, the data is from 2019 and except for the heat source, he does not provide any further details about the systems. In addition, Buffa et al.[26] present a list of 40 5GDHC networks in Europe with 15 systems in Germany, 15 in Switzerland, and 5 in Italy. They find that the heat sources are very diverse, ranging from geothermal energy to surface water (river, sea, or lake), to excess heat or ambient air. They also provide data on the network temperatures, which range from 0 to 35 °C. Twelve systems are operated with fixed temperatures and 16 networks with seasonal shifting temperatures. In the article by Zeh et al.,[15] the 5GDHC systems surveyed by Buffa et al. are visualized on a map.

The literature review shows that there is no overview of currently operated 5GDHC systems in Germany or Europe and that the literature mainly focuses on the investigation of individual case studies which makes it difficult to derive general conclusions or design guidelines.

1.2. Contributions

The main contribution of this article is an analysis of survey data of 53 5GDHC networks in Germany. The conduction of the survey has multiple objectives: Listing use cases of successful 5GDHC projects proves to decision-makers that 5GDHC systems have been successfully implemented in many cases in the past. This helps to build confidence in the technology and encourages decision-makers to implement innovative, emission-free district energy systems. Second, a comprehensive project list increases the visibility of 5GDHC networks and shows district design engineers how other 5GDHC districts have been planned in the past, including what key performance indicators have been achieved (e.g., primary energy factors) or which technologies and heat sources have been used. Third, the list of 5GDHC systems can support district design engineers in the planning process, since they can identify districts where systems with similar boundary conditions (e.g., specific combination of heat sources) have been implemented and can reach out to the respective planners. Lastly, the survey data is also a contribution to identify best practices and general design guidelines for 5GDHC networks, e.g., with respect to network temperatures or pricing models. In summary, the conducted survey helps to increase the global visibility and penetration of 5GDHC networks.

2. Method

In this section, we describe the survey, which was sent out to district planners and engineers: In Section 2.1, the questions and multiple choice options of the survey are described. Then, in Section 2.2, we explain how the 5GDHC districts have been identified and selected for the survey.

2.1. Survey and Questions

The goal of the survey is to cover the most relevant aspects of 5GDHC networks, ranging from technical aspects and key figures to political aspects. Basic information of the districts are the district name and city, the (planned) year of commissioning, and the operator of the 5GDHC network. To characterize the network and operation, the network temperatures and the pipe type were surveyed. The size of the system is quantified by the network length as well as the number of connected buildings. In many cases, 5GDHC networks were planned for newly built areas. Therefore, the share of new and existing buildings (floor area) is an interesting key figure for 5GDHC networks as well. One of the most important aspects of 5GDHC networks is the used heat source. The participants could select from a list or describe the heat source in a text field. The survey contains additional questions regarding the ability of the network to provide cooling energy, a district-wide obligation to connect to the network, the ownership of the decentral heat pumps, and the price model for heat and cold. All survey questions are listed in the Appendix.

2.2. Conduct of the Study

Districts with a 5GDHC network have been identified using a web search and a search in scientific literature as well as presentations at conferences and seminars. The goal was to identify a large number of 5GDHC networks, however, the total number of 5GDHC systems in Germany is unknown. The participants were contacted by email and asked to participate in the survey provided as a Google Form in German. The survey was conducted between September 2021 and May 2022. The participants were allowed to provide estimations (e.g., for network length) if exact numbers were not available or the system was not built yet. As a result, the authors cannot guarantee that all provided data is completely accurate. In the survey, only 5GDHC networks were included (no conventional district heating systems). For this purpose, the definition of 5GDHC systems by Buffa et al.[26] has been applied. This means that district heating networks that provide heat directly to buildings throughout the year, i.e., without decentral heat pumps, are not considered a 5GDHC network. Also, district cooling networks (with the primary goal of providing cold) are not included, although their network temperature is in the same range as 5GDHC systems.

3. Results

In the following, the data of all 53 surveyed 5GDHC networks is presented. First, general information about the districts is provided (Section 3.1). In Section 3.2, the technical data of all networks are listed and visualized and then the political design decisions are presented in Section 3.3.

3.1. General Information

In **Table 1**, the key facts of all surveyed 5GDHC districts are listed. In most cases, the operators are city utilities (municipalities) or energy utility companies, such as E.ON,[27] EnBW,[28] or Energiedienst.[29] Twenty networks are already in operation, 12 are commissioned or planned to be commissioned in 2022, and 8 networks are planned to start operation in 2023. **Figure 1** provides an overview of the (planned) year of commissioning of the districts (the 5GDHC network from 1981 is not depicted). The increasing number of projects is an indication of the growing interest in 5GDHC networks in recent years. However, it should be noted that recently planned projects tend to be over-represented in this study due to the better availability of information and technical planners.

3.2. Technical Data

In **Table 2**, the technical parameters of the networks are listed. In some districts, the number of buildings and the network length has been estimated by the survey participants since no exact data is available. The network temperatures range from −5 to 75 °C (c.f. **Figure 2**). Usually, networks with 75 °C are not considered fifth but fourth-generation district heating (4GDH) networks. However, these networks are operated in summer as a 5GDHC network and in winter as a 4GDH network and are therefore a hybrid network type. In this study, the networks in Bedburg, Berlin-Tegel, Bodenmais, Dollnstein, Flehingen, Haßfurth and Kerpen are identified as hybrid 5GDHC/4GDH solutions. The other 5GDHC networks are operated below 40 °C during all seasons. Some networks use constant temperatures in the warm and cold pipe throughout the year, others have a temperature window that depends on the load situation of the network, the ground temperature, or the temperature of the heat source (e.g., in the case of river water). The network temperature strongly affects the pipe type: Networks with higher temperatures tend to use insulated pipes, since otherwise heat losses become dominant. As a result, the hybrid networks use insulated pipes. In contrast, if the network temperature is close to the ambient temperature level, insulation is usually omitted. Without insulation and with low network temperatures, heat gains from the surrounding soil to the pipe become relevant. Heat gains can make up a substantial share of the heat load of the district, especially for districts with low heat density. Since most of the networks are operated close to the ground temperature, plastic pipes are the most frequent pipe type (42 of 53 networks). In some cases, both types, plastic and steel, as well as both insulation types, with and without insulation, are used in a network, for example, in the district in Herne.

The network lengths vary within a wide range: The smallest network has a single length of 150 m (Achern). This network connects 4 buildings with a central heat source. The largest 5GDHC network has a length of 12.5 km (Berlin–Tegel). Other districts with large networks are Schleswig (Berender Redder, 13.9 km, 199 buildings), Soest (7.3 km, 417 buildings), Gelting (6.6 km, 118 buildings), Warendorf (5.5 km, 180 buildings), Bamberg (5.5 km, 60 buildings), and Nieby (4.9 km, 49 buildings). The network length of 32 districts (60%) is below 2 km.

The majority of projects are new build districts. Only in 10 districts, the share of newly built buildings (floor area) is smaller than 100%. One reason is the low-temperature requirements of underfloor heating systems in new residential buildings, which result in high heat pump efficiencies. Another reason is that for new built districts, natural-gas-based solutions are often not an accepted solution anymore.

The heat sources, the heating capacity, the provision of cold as well as the primary energy factors are listed in **Table 3**. 5GDHC networks are supplied by a wide range of heat sources (c.f. **Figure 3**): In 23 of the 53 districts, horizontal geothermal collectors are installed. For a detailed review of geothermal collectors, we refer to ref.[15] If geothermal collector tubes are installed in multiple layers and in close proximity, the surrounding ground freezes in winter. This further increases the heat potential and is often described as earth ice storage. An earth ice storage is used, for example, in the district in Schleswig (Wichelkoppeln). The second most common heat source is (vertical) geothermal probes, which is used in 17 districts. They usually reach depths of 100–200 m. Another proven heat source, that is available in every district, is ambient air. Ambient air can be used in combination with an air-source heat pump or an air-to-water heat exchanger. Ambient air is used in 9 surveyed districts. In 5 districts, sewage water is used as the heat source. Especially for urban areas, sewage water is a promising heat source: Sewage water has a largely constant temperature throughout the year and can be used directly to heat a 5GDHC network. A further very promising heat source is waste heat: Waste heat can result from a variety of different processes and buildings: Industrial processes, data centers, process cooling in commercial buildings (e.g., supermarket), or from space cooling. Since space cooling of connected buildings is usually an integral function of the 5GDHC network, it is not considered an explicit heat source in this study. In 6 districts, waste heat is used as a heat source: In Shamrockpark in Herne, for example, waste heat from a nearby industrial site as well as a data center is used to cover the district's heating demands. Other examples are the two districts in Jülich, where waste heat from a data center and a supercomputer are used. In the district in Meitingen, industrial waste heat from a large industrial site is used to cover the heat demands

Table 1. List of all surveyed 5GDHC networks in Germany.

City	District	Year of commissioning	Operator
Achern	Arealnetz Lott	2022	EnBW Energie Baden-Württemberg AG
Bad Nauheim	Bad Nauheim Süd	2021	Stadtwerke Bad Nauheim
Bamberg	Lagarde-Campus	2023	Stadtwerke Bamberg
Bedburg	Ressourcenschutzsiedlung Kaster	2022	E.ON Energy Solutions GmbH
Berlin-Tegel	Urban Tech Rep./Schumacher-Q.	2026	Green Urban Energy GmbH
Bodenmais	Bodenmais	2017	
Damme	Westlich der Bahn	2022	Energiegenossenschaft
Dollnstein	Dollnstein	2014	Kommunalunternehmen Dollnstein
Dorsten-Wulfen	Barkenberg	1981	OET Kälte & Wärme GmbH
Eckernförde	Projekt Noorblick	2018	Schleswiger Stadtwerke GmbH
Emmerthal	Solarsiedlung am Ohrberg	2020	Energieservice Westfalen Weser
Fischerbach	Sonnematte	2013	Bürgerenergie Fischerbach
Flehingen	Seniorenwohnpark Eden	2020	EnBW Energie Baden-Württemberg AG
Friedberg	Afrastraße	2019	Lechwerke AG
Gelsenkirchen	Wohnen am Stadtteilpark Hassel	2023	Grüne Quartiere GmbH
Gelting	Geltinger Bucht	2018	Schleswiger Stadtwerke GmbH
Gensingen	Westlich der Alzeyer Straße	2022	EDG Rheinhessen-Nahe mbH
Gutach-Bleibach	Alte Ziegelei	2018	Bürgerenergie Bühl
Haßfurth	Osterfeld II/III	2016	Städtische Werke Haßfurt
Herne	Shamrockpark	2023	Shamrock Energie GmbH
Hilter	Erkingshof	2022	Teutoburger Energie Netzwerk eG
Husby	Bregning-West	2019	Schleswiger Stadtwerke GmbH
Ilsfeld	Steinhäldenweg II	2016	Gemeinde Ilsfeld
Jülich	Brainergy Park	2023	Brainergy Park Energie GmbH
Jülich	Forschungszentrum	2022	Forschungszentrum Jülich GmbH
Kerpen	Vinger Weg	2021	Stadtwerke Kerpen/E.ON
Königsmoos	Bgm.-Bitterolf-Straße	2022	Bürger-Energie-Gen. ND-SOB-AIC-EI
Königsmoos	Kirchfeld	2023	Bürger-Energie-Gen. ND-SOB-AIC-EI
Maikammer	Eulbusch III	2022	Pfalzwerke AG
Mainz	Alte Brauerei	2023	Süwag Grüne Energie und Wasser AG
Meitingen	Meitingen	2018	Wasserwerk Meitingen
Murg	Auf Leim	2021	Energiedienst AG
Neustadt a. Rübenberge	Hüttengelände	2020	Stadtwerke Neustadt
Nieby	Geltinger Birk	2017	Schleswiger Stadtwerke GmbH
Reichenbach a. d. Fils	Grünes Leben am Schafhaus	2022	NaturStromWärme GmbH
Rendsburg	Eisspeicher-Quartier	2018	Stadtwerke Rendsburg GmbH
Rieseby	Heidegarten	2019	Schleswiger Stadtwerke GmbH
Rottenburg	Öchsner II	2022	Stadtwerke Rottenburg am Neckar
Salzgitter-Thiede	Am Bahnhof	2023	WEVG Salzgitter GmbH & Co. KG
Schallstadt	Weiermatten	2021	Energiedienst AG
Schifferstadt	Max-Ernst-Straße	2016	Stadtwerke Schifferstadt
Schlier-Unterankenreute	Am Bergle	2022	EnBW/Technische Werke Schussental
Schrobenhausen	Kellerbergbreite	2023	Bürger-Energie-Gen. ND-SOB-AIC-EI
Schleswig	Berender Redder	2015	Schleswiger Stadtwerke GmbH
Schleswig	Wichelkoppeln	2021	Schleswiger Stadtwerke GmbH
Soest	Soester Norden	2022	Stadtwerke Soest
Troisdorf	Bergheim	2019	Stadtwerke Troisdorf

Table 1. Continued.

City	District	Year of commissioning	Operator
Troisdorf	Eschmar West	2019	Stadtwerke Troisdorf
Warendorf	In de Brinke	2021	WEV Warendorfer Energieversorgung
Werther	Lehmkuhle	2022	Energiegenossenschaft Helmetal eG
Wiesbaden-Biebrich	Am Parkfeld	2022	ESWE Versorgungs AG
Winsen (Luhe)	Am Luhedich	2023	Stadtwerke Winsen (Luhe)
Wüstenrot	Vordere Viehweide	2011	Gemeinde Wüstenrot

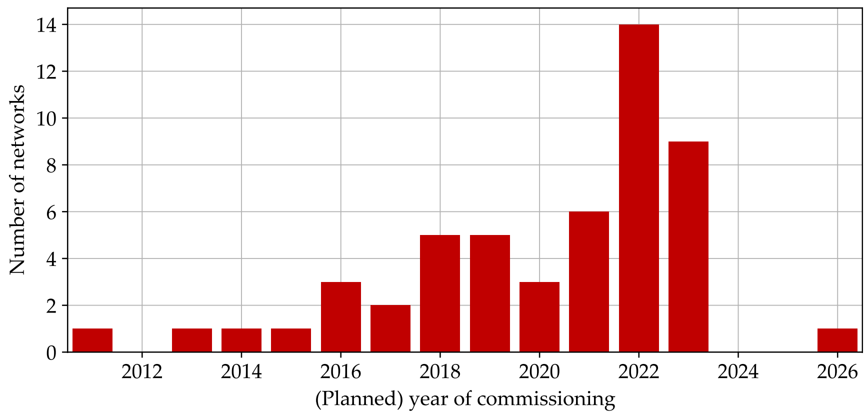

Figure 1. Overview of the (planned) year of commissioning of the surveyed districts. The network from 1981 is not depicted.

of the 5GDHC district. Other heat sources are river water, wells and groundwater, or the return pipe of a conventional high-temperature district heating network. Using the return pipe of a district heating network to supply a 5GDHC network increases the temperature difference between the supply and return pipe, and thus reduces the pump work of the district heating network. Buffa et al. find in their study that 65% of the investigated 5GDHC networks are connected to only a single heat source and the rest uses multiple heat sources.[26] This finding is close to the data of this study, where 57% (30 of 53) of the districts have a single heat source.

The cumulated heating capacity of all heat sources/generation units of a district varies largely from 50 kW (Achern) to 43 MW (Berlin–Tegel). While a crucial advantage of 5GDHC networks over 4GDH networks is the possibility to provide cold with the same infrastructure, the cooling supply is not realized in every district. In 39 of the 53 districts, the 5GDHC network also covers the buildings' cooling demand. In contrast to that, most of the hybrid 5GDHC/4GDH networks do not provide cooling. Also, the districts in Meitingen and Jülich (FZ) are supplied with waste heat at around 30 °C, and therefore do not provide cold.

The surveyed primary energy factors (PEFs) span a large interval from 0.1 to 0.5. Since no formal definition of the PEF was given to the participants of the survey, it is not possible to comprehend the underlying calculation of the provided PEF values. However, in Germany, the calculation is usually conducted according to the German AGFW standard (FW 309)[30] and it can be assumed that most of the surveyed values are based on this standard. Consequently, the surveyed data allows drawing the following conclusions: In most districts, for which a PEF value has been provided, it is between 0.4 and 0.5. If ambient heat (e.g., from geothermal sources with PEF = 0) is used as a heat source, the PEF of the network is predominantly affected by the electricity demand for the hydraulic pumps and decentral heat pumps. For example, a PEF of 0.45 is obtained when geothermal heat is used and a heat pump coefficient of performance of 4, and a PEF for electricity of 1.8 (according to the German standard) is assumed. A PEF of 0.45 is in line with typical 5GDHC networks that use a single geothermal source such as Hilter (0.46), Rottenburg, (0.42), Neustadt am Rübenberge (0.45), Salzgitter-Thiede (0.45), Soest (0.44), Warendorf (0.47), and Winsen/Luhe (0.45).

3.3. Political and Economic Data

Besides technical design parameters, political factors are also important for a successful implementation of a 5GDHC network. An overview of the surveyed data is given in **Table 4**. The municipality has to decide whether there is an obligation to connect to the 5GDHC network or not (German: Anschlusszwang). In 27 districts, an obligation to connect is imposed, in 22 this is not the case. In the districts, Achern and Flehingen, the entire district is developed by a single company. In Meitingen, a connection to the network is compulsory in some parts of the district. With the obligation to connect, the building owners cannot choose which heating system they want to install and must connect their building energy system to the thermal network. In some cases, building owners are hesitant to connect to a thermal

Table 2. Technical specifications of surveyed 5GDHC networks: "W": winter operation, "S": summer operation, "P": plastic, "S": steel, "unins.": uninsulated, "ins.": insulated.

Network	Network temperatures [°C]	Pipe type	Network length [km]	Number of buildings	Share of the newly built area
Achern	2–23	P/ins.	0.15	4	100%
Bad Nauheim	W: −2, S: 16	P/unins.	6	120	100%
Bamberg	6	P/unins.	5.5	60	70%
Bedburg	W: 45–50, S: 12–15	P/unins.	1.88	110	100%
Berlin-Tegel	W: 40, S: 20	P/ins.	12.5		90%
Bodenmais	W: 65–75, S: 20–35	P/ins.	0.95	19	0%
Damme	6–15	P/unins.	1.5	75	100%
Dollnstein	W: 65–75, S: 20–35	S/ins.	1.8	35	0%
Dorsten-Wulfen	12/6	P/unins.	3	40	0%
Eckernförde	9	P/unins.	4.2	10	100%
Emmerthal	12/8	P/unins.	1	65	100%
Fischerbach	−5–20	P/unins.	1.8	24	100%
Flehingen	W: <45, S: 20/15	P/ins.	1.2	52	100%
Friedberg	10.5/8.5	P/unins.	0.65	20	100%
Gelsenkirchen	0–19	P/unins.	1.5	60	100%
Gelting	9	P/unins.	6.6	118	100%
Gensingen	14	P/unins.		80	100%
Gutach-Bleibach	−5–20	P/unins.	2.8	36	100%
Haßfurth	20–50	P/ins.	4.6	80	100%
Herne	22/12	S/ins., P/ins.	2	24	50%
Hilter	10/6	P/unins.	1	44	100%
Husby	9	P/unins.	1.63	19	100%
Ilsfeld	20/13	P/unins.	1.2	35	100%
Jülich (Brainergy Park)	12/8	S/ins.	3.7	86	100%
Jülich (FZ)	20–40	S/ins.	0.6	8	12.5%
Kerpen	W: 40/35, S: 20/15	P/ins.	1.2	78	100%
Königsmoos (B.-B.-Str.)	W: 8/2, S: 15/8	P/unins.	1.6	40	100%
Königsmoos (K.)	16	P/unins.	1.3	32	100%
Maikammer	3–10	P/unins.	0.65	37	100%
Mainz	W: 14/10, S: 10/6	P/unins.	0.5	24	100%
Meitingen	30/22	S/ins., P/ins.	0.9	35	94%
Murg	W: 10/6, S: 12/6	P/unins.	1	52	100%
Neustadt a. R.		P/unins.	0.92	56	100%
Nieby	9	P/unins.	4.9	49	100%
Reichenbach a. d. Fils	9	P/unins.	1	41	100%
Rendsburg	9	P/unins.	0.5	3	15%
Rieseby	9	P/unins.	3.15	45	100%
Rottenburg	8	P/unins.	1	55	100%
Salzgitter-Thiede	12/6	P/unins.	1.15	45	100%
Schallstadt	W: 6–12, S: <25	P/unins.	2.2	50	95%
Schifferstadt	W: 6, S: 15	P/unins.	0.53	41	100%
Schlier	0–12/−3–9	P/unins.	0.66	35	100%
Schrobenhausen	15.5	P/unins.	2.5	65	100%
Schleswig (B. R.)	9	P/unins.	13.9	199	100%
Schleswig (W.)	9	P/unins.	2.9	60	100%
Soest	−2–12	P/unins.	7.3	417	100%

Table 2. Continued.

Network	Network temperatures [°C]	Pipe type	Network length [km]	Number of buildings	Share of the newly built area
Troisdorf (B.)	12/8	P/unins.	0.45	38	100%
Troisdorf (E. W.)	12/8	P/unins.	0.5	57	100%
Warendorf	5–20	P/unins.	5.5	180	100%
Werther	8	P/unins.		33	100%
Wiesbaden-Biebrich	14	P/unins.	2	26	100%
Winsen (Luhe)	12/6	P/unins.	0.85	61	100%
Wüstenrot	W: 1, S: 16	P/unins.	0.5	23	100%

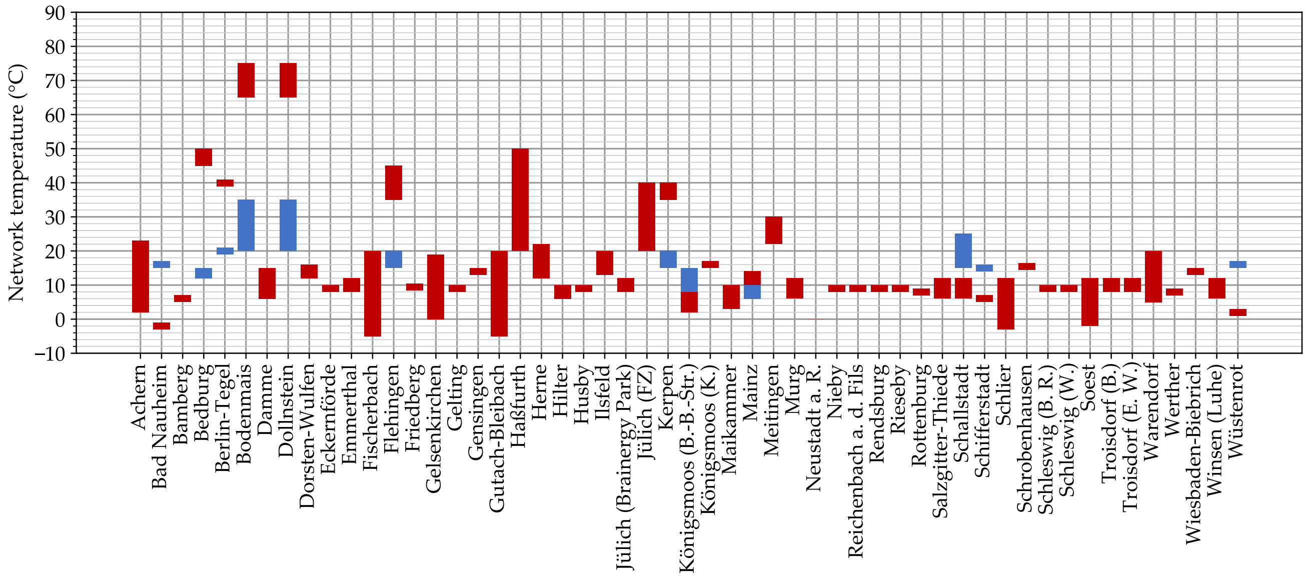

Figure 2. Operational temperatures. Blue intervals indicate summer operation mode. Averaged temperature values are visualized with an interval of 2 K. For open intervals (< or >), an interval of 10 K is visualized.

network because the network operator has a de facto monopoly on the heat supply in the district. From an energy and economic perspective, a connection obligation makes sense, since a high connection rate reduces the heat supply costs for all buildings.

Another political design parameter is the ownership of the decentral heat pumps. Decentral heat pumps are either owned by the network operator or by the building owner. Due to the current subsidy policy in Germany, in most cases, it is beneficial if the network operator covers the investments of the heat pumps since then, the heat pumps are part of the publicly subsidized district energy system. In the surveyed districts, the heat pumps are owned by the network operator in 29 cases, in 18 systems they are owned by the building owner. In the district in Emmerthal, the operator owned the heat pumps for the first 20 years, now they are owned by the building owners. The transition of ownership from the network owner to the building owner after a certain time period is a typical agreement in 5GDHC networks in Germany.

In conventional district heating systems, the price policy is usually similar: The consumer pays a base and energy price (for the supplied heat at the substation) and, in some cases, a capacity price for the peak power. An energy price is charged in all systems, since a higher heat demand leads to higher fuel and operational costs for the network operator. 5GDHC networks offer more flexibility for designing price models: At first, it must be decided, where the billing boundary is located: The useful heat behind the heat pump, the low-temperature heat from the network, or just a flat rate service for supplying heat. Due to the ambient heat sources in 5GDHC networks, the operational costs of the network itself are very low and consist of maintenance costs as well as electricity costs for the hydraulic pumps. In most surveyed 5GDHC networks, the billing boundary for delivered heat is at the condenser of the heat pump (34 districts). The price models vary across the surveyed networks: The most widely used price model for heat supply is charging a base price (€ year^{-1}) as well as an energy price (€ kWh^{-1}) (30 districts). In 9 districts, a capacity charge (€ kW^{-1}) applies. Another 8 districts have a flat rate model and only charge an annual base price that depends on the expected annual heat demand. For example, in the districts of Fischerbach and Gutach-Bleibach, the annual base price depends on the building area. In the district in Dorsten-Wulfen, the supplied heat at the evaporator is charged based on a liter price for cold water. In Reichenbach a. d. Fils, cold water from the network is charged with a base price, and the electricity costs for the heat pumps are covered by building owners. Since the Wüstenrot

Table 3. Heat sources, central heating capacity, provision of cold and primary energy factor: "Geothermal collectors" mean near-surface horizontal geothermal collector systems.

Network	Heat source	Heating capacity [kW]	Cooling supply	Primary energy factor
Achern	River water, ambient air	50	Yes	
Bad Nauheim	(Double-layer) geothermal collectors	1400	Yes	
Bamberg	Geothermal probes and collectors, sewage water	3200	Yes	0.22
Bedburg	Geothermal collectors, ambient air, sewage water	425	Yes	0.49
Berlin-Tegel	Geothermal collectors, lake water, ambient air,	43 000	Yes	<0.3
	Combined heat and power [unit] (CHP), boiler, biomass, sewage water,			
	Waste heat (industry, heating plant), aquifer storage			
Bodenmais	Solar thermal, biomass (CHP or boiler)	400	No	
Damme	Geothermal probes	171	Yes	
Dollnstein	Solar thermal, groundwater, CHP, boiler	980	No	
Dorsten-Wulfen	Wells	300	No	0.25
Eckernförde	Geothermal collectors, PVT, biomass	275	No	
Emmerthal	Waste heat (industry), boiler	370	No	
Fischerbach	Ice storage, ambient air, geothermal collectors		Yes	
Flehingen	Geothermal probes, CHP, boiler	380	Yes	
Friedberg	Groundwater	850	No	
Gelsenkirchen	Geothermal probes, ambient air	550	Yes	0.33
Gelting	Geothermal collectors	423	Yes	
Gensingen	Geothermal probes	570	Yes	
Gutach-Bleibach	Ice storage, ambient air, geothermal collectors		Yes	
Haßfurth	Solar thermal, CHP, boiler	825	No	0.4
Herne	Waste heat (industry and data center), CHP	3000	Yes	0.4
Hilter	Geothermal probes		Yes	0.46
Husby	Geothermal collectors	85	Yes	
Ilsfeld	Return pipe district heating	250	No	0.1
Jülich (Brainergy Park)	Ambient air, boiler, ice storage	5900	Yes	
	Waste heat (industry and data center)			
Jülich (FZ)	Waste heat (supercomputer), CHP	2000	No	
Kerpen	Ambient air, CHP, boiler	850	Yes	0.44
Königsmoos (B.-B.-Str.)	Geothermal probes	272	Yes	0.3
Königsmoos (K.)	Geothermal probes	270	Yes	
Maikammer	Geothermal probes and collectors		Yes	
Mainz	Wells	500	Yes	0.5
Meitingen	Waste heat (industry)	500	No	0.35
Murg	Geothermal probes	330	Yes	
Neustadt a. R.	Geothermal collectors	1000	Yes	0.45
Nieby	Geothermal collectors, biomass	302	Yes	
Reichenbach a. d. Fils	Geothermal collectors		Yes	
Rendsburg	Ambient air, ice storage	196	Yes	
Rieseby	Geothermal collectors	215	Yes	
Rottenburg	Geothermal collectors	250	Yes	0.42
Salzgitter-Thiede	Geothermal collectors	120	Yes	0.45
Schallstadt	Sewage water	700	Yes	
Schifferstadt	Geothermal probes	160	Yes	0.4
Schlier	Geothermal probes	270	Yes	0.4
Schrobenhausen	Geothermal probes	520	Yes	

Table 3. Continued.

Network	Heat source	Heating capacity [kW]	Cooling supply	Primary energy factor
Schleswig (B. R.)	Geothermal collectors, boiler	943	Yes	
Schleswig (W.)	Geothermal collectors, PVT, earth ice storage	300	Yes	
Soest	Geothermal collectors	2820	Yes	0.44
Troisdorf (B.)	Geothermal probes	950	No	0.49
Troisdorf (E. W.)	Geothermal probes	1000	No	0.49
Warendorf	Geothermal probes and collectors	2400	Yes	0.47
Werther	Geothermal collectors			
Wiesbaden-Biebrich	Sewage water	430	No	0.45
Winsen (Luhe)	Geothermal collectors	170	Yes	0.45
Wüstenrot	Geothermal collectors	140	Yes	

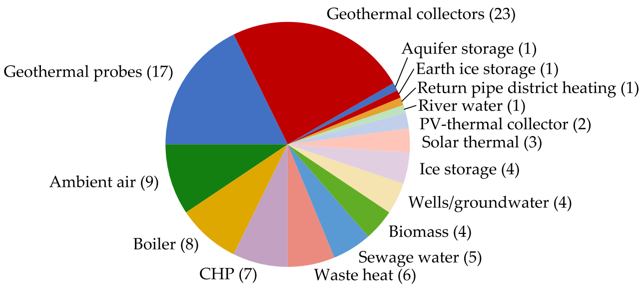

Figure 3. Heat sources for 5GDHC networks. The numbers in brackets indicate in how many districts this heat source is used.

district was part of a research project, heat is supplied for free and only a one-time fee was charged. In general, a one-time connection fee is charged in many districts, however, no data has been surveyed in this regard.

The provision of cold is often for free (11 districts). Keeping cooling prices low can be beneficial to incentive a high cooling demand in summer to regenerate geothermal sources. Other operators charge a base price (8 districts) or a base and energy price (8 districts).

In two districts (Bainergy Park in Jülich and Berlin–Tegel), prosumer buildings are connected to the network which receives a compensation for the feed-in of heat. Only a few values have been provided by the participants regarding the levelized costs of heat. Since the underlying cost calculation is not comprehensible for the authors, the values cannot be compared with each other and therefore, the data is not presented in this paper.

Several points have been mentioned by the participants regarding the regulations or legal provisions that are considered obstacles to the development of 5GDHC networks: One central problem is the use of an appropriate heat carrier fluid. Currently, a water–glycol mixture is widely used for 5GDHC networks. However, glycol but also alternative heat carrier fluids like bioethanol are classified as harmful to the environment in Germany (classified as Wassergefährdungsklasse 1). This classification leads to difficulties in the regulatory approval process. In some cases double-walled pipes have to be installed which has a substantial impact on the efficiency of 5GDHC networks: Heat gains from the ground, which can make up to 20% or more of the total heat source capacity (according to statements of survey participants), are substantially reduced. This means heat sources have to be sized larger which increases the investment cost and necessary installation area. In addition, the complex regulations and additional fees for self-used photovoltaic electricity is another regulatory obstacle for 5GDHC networks (decentral PV power is ideally used by decentral heat pumps in the same building[31]). Other difficulties are long approval processes for subsidy applications or complex geological regulations for geothermal probes with a depth of more than 100 m (application of Bergrecht regulations in Germany).

4. Conclusions

In this article, survey data of 53 5GDHC networks in Germany are presented and analyzed. A large number of 5GDHC networks and the fact that some utility companies (e.g., Stadtwerke SH) have multiple systems in operation show the high potential of 5GDHC networks. The data shows that 5GDHC networks are increasingly built in recent years and many projects are currently planned or under construction. The network temperature data shows a large variety of different concepts that have been realized: Some networks are operated at temperatures below 0 °C, and others use different temperature modes in summer and winter, resulting in hybrid 4GDH/5GDHC networks. A typical temperature band of −5 to 20 °C can be identified, although 5GDHC networks exist with higher temperatures, often driven by high-temperature heat sources. About 4 out of 5 networks use uninsulated plastic pipes. 60% of the networks have a total length of less than 2 km and the largest network has a length of 12.5 km. However, in the future, even larger 5GDHC networks are expected. In the surveyed districts, less than 1 out of 5 networks supply existing buildings, all other districts are newly built. This share is likely to increase as well, since 5GDHC networks have a high potential to also contribute to the decarbonization of existing districts. Heat sources of 5GDHC networks are very diverse and 15 different heat sources are observed in the surveyed districts: The most frequent heat source are geothermal collectors (43%) and geothermal probes (32%). Since solar thermal collectors provide temperatures above the network

Table 4. Political design decisions and pricing models: "Condenser": Heat at condenser of heat pump. "Evaporator": Heat at evaporator of heat pump. "B": Base price (€ $year^{-1}$), "E": energy/volumetric charge (€ kWh^{-1}), "C": Capacity price (€ kW^{-1}).

Network	Compulsory connection	Owner of building heat pumps	Billing boundary (heat supply)	Price model (heat)	Price model (cold)
Achern		Netw. operator	Condenser		
Bad Nauheim	No	Netw. operator	Condenser	B/E	free
Bamberg	Yes	Netw. operator	Condenser	B/E	E
Bedburg	No	Netw. operator	Condenser	B/E	B/E
Berlin-Tegel	Yes	Netw. operator	Evaporator	B/C	B/C
Bodenmais	No	Netw. operator	Condenser		
Damme	No	Building owner	Evaporator	B	B
Dollnstein	No	Netw. operator	Condenser	B/E/C	
Dorsten-Wulfen	No	Building owner	Evaporator	E	
Eckernförde	Yes	Building owner	Condenser	B/E	
Emmerthal	Yes		–	B	
Fischerbach	Yes	Netw. operator	–	B	
Flehingen		Building owner	Condenser	B/E	B/E
Friedberg	No	Building owner	Evaporator	E/C	
Gelsenkirchen	Yes	Netw. operator	Condenser	B/E/C	B
Gelting	Yes	varies	Condenser	B/E	free
Gensingen	Yes	Building owner	–	B	
Gutach-Bleibach	Yes	Building owner	–	B	
Haßfurth	No	Netw. operator	Condenser	B/E	
Herne	Yes	Netw. operator	Condenser	E/C	E/C
Hilter	Yes	Netw. operator	Condenser	B/E	B/E
Husby	Yes	Building owner	Condenser	B/E	free
Ilsfeld	No	Building owner	Evaporator	B/E	
Jülich (Brainergy Park)		Netw. operator	Condenser	E/C	E/C
Jülich (FZ)	No	Netw. operator	Condenser		
Kerpen	No	Netw. operator	Condenser	B/E	B/E
Königsmoos (B.-B.-Str.)	No	Netw. operator	Condenser	B/E	B/E
Königsmoos (K.)	No	Netw. operator	Condenser	B/E	B/E
Maikammer	No	Building owner	–	B	
Mainz	Yes	Netw. operator	Condenser	B/E	
Meitingen		Netw. operator	Condenser	E	
Murg	No	varies	–	B/E	free
Neustadt a. R.	Yes	Netw. operator	Condenser	B/E	free
Nieby	Yes	Building owner	–		
Reichenbach a. d. Fils	Yes	Building owner	–	B/E	free
Rendsburg	Yes	Netw. operator	Condenser	B/E	free
Rieseby	Yes	Building owner	Condenser	B/E	free
Rottenburg	Yes	Netw. operator	Condenser	B/E	B
Salzgitter-Thiede	No	Netw. operator	Condenser	B/E	B
Schallstadt	No	varies	Evaporator	B/E/C	B/E/C
Schifferstadt	Yes	Netw. operator	–	B	B
Schlier	Yes	Netw. operator	Condenser	B/E	B/E
Schrobenhausen	No	Netw. operator	Condenser	B/E	B/E
Schleswig (B. R.)	No	varies	Condenser	B/E	B/free
Schleswig (W.)	Yes	Building owner	Condenser	B/E	free
Soest	Yes	Netw. operator	Condenser	B/E	B

Table 4. Continued.

Network	Compulsory connection	Owner of building heat pumps	Billing boundary (heat supply)	Price model (heat)	Price model (cold)
Troisdorf (B.)	Yes	Building owner	Evaporator	B/E	
Troisdorf (E. W.)	Yes	Building owner	Evaporator	B/E	
Warendorf	No	varies	Condenser	B/E/C	B
Werther	Yes	Building owner	–	B	
Wiesbaden-Biebrich	No	Netw. operator	Condenser	E/C	
Winsen (Luhe)	Yes	Netw. operator	Condenser	B/E	B
Wüstenrot	No	Building owner	–	free	free

temperature of 5GDHC systems, they are rarely installed (in the survey solar thermal is only used in 3 hybrid networks). 74% of the 5GDHC networks supply cold as well, which shows that 5GDHC networks are a promising approach to also decarbonizing the cooling supply in urban areas. Some survey results are specific to German regulations: The primary energy factor of 5GDHC systems is usually between 0.4 and 0.5, and in 27 networks building owners are obliged to connect to the network. Due to subsidy regulations, the decentral water-to-water heat pumps are owned by the network operator in most cases (29 districts). The price models are diverse, ranging from a one-time connection fee to a complex price system with a capacity price. Price models for the provision of cold tend to be less complex with either an energy and base price or no fee at all.

In addition to the data surveyed in this study, in future works further technical aspects can be included in technical surveys about 5GDHC networks. This comprises the heat carrier fluid used in the network, the usage types of the supplied buildings (residential, commercial, etc.) as well as a classification of the network (one-pipe/two-pipe system, directional/nondirectional medium flow, meshed/tree topology). Furthermore, any kind of cost data is interesting to survey, e.g., levelized cost of heat, or the compensation for heat feed-in. However, the conduction of the survey for this article shows that companies are usually not willing or not able to provide detailed cost data about their systems.

Based on the survey results, 5GDHC networks appear to be a proven technology, especially for newly built districts. The next step in the technology development is to generally prove the viability and profitability of districts with an existing building stock. Compared to large district heating networks, all surveyed 5GDHC networks are considered only local solutions for small to medium-sized districts. Although 5GDHC networks could be also feasible and suitable for large city districts with thousands of buildings, this has not yet been shown or proven in real-world districts. Also, the idea of meshed clusters of multiple interconnected 5GDHC networks has not been realized yet. However, as more and more 5GDHC projects are built, it is likely that interconnected grids will be planned in the future since they offer additional efficiency potential.

Appendix

All survey questions are listed in the following:

General district data

- District name
- City
- Year of commissioning
- Operator

Technical data

- Network temperatures
- Which pipe type is used?
  1. Steel pipe (insulated)
  2. Plastic pipe (insulated)
  3. Plastic pipe (uninsulated)
  4. Other
- Network length (supply and return pipe counted only once)
- Number of connected buildings
- Share of new build area
- Used heat sources:
  1. Geothermal energy (e.g., probes)
  2. Near-surface geothermal energy (e.g., horizontally installed collectors)
  3. Solar thermal energy
  4. PV-solar thermal hybrid collectors (PVT)
  5. River water
  6. Lake or seawater
  7. Ambient air (e.g., for air-source heat pump)
  8. Return pipe of district heating network
  9. Deep geothermal energy (depth > 1000 m)
  10. Combined heat and power unit
  11. Boiler (e.g., natural gas/biogas)
  12. Biomass (CHP or boiler)
  13. Sewage water
  14. Waste heat (industry)
  15. Waste heat (power/heating plant)
  16. Waste heat (data center)
  17. Waste heat (supermarket)
  18. Waste heat (shopping center)
  19. Other
- Installed heating capacity (energy center or central heat source)
- Central heat or cold storages
  1. Heat storage (water tank)
  2. Aquifer storage
  3. Geothermal field
  4. Ice storage (frozen water)
  5. Earth ice storage (frozen soil)
  6. Other

- Are the buildings supplied with cooling energy by the network? (yes/no)
- Primary energy factor
- Levelized costs of heat (€-ct kWh^{-1})

Political and economic data

- Is there an obligation for the buildings to connect to the network? (yes/no)
- Who is the owner of the (decentral) building heat pumps?
  1. Building owner
  2. Network operator
  3. Varies from building to building
  4. Other
- Where is the system boundary for billing the supplied heat?
  1. Heat at the evaporator of the heat pump (network side)
  2. Heat at the condenser of the heat pump (building side)
  3. Other
- Price model for the heat supply
  1. Base price (€ $year^{-1}$)
  2. Energy price (€ kWh^{-1})
  3. Capacity price (€ kW^{-1})
  4. Free of charge
- Price model for the cooling supply
  1. Base price (€ $year^{-1}$)
  2. Energy price (€ kWh^{-1})
  3. Capacity price (€ kW^{-1})
  4. Free of charge
- If previous questions do not apply, a short description of the price model
- Are there buildings that receive compensation for feed-in of waste heat into the network (e.g., industry companies, data centers)?
- From your point of view, are there any regulations or legal provisions that are an obstacle to the development of 5GDHC networks?

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

5GDHC, energy network, cold district heating, district cooling, district heating, kalte Nahwärme

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