Early-Stage Feasibility Study of an Ambient-Temperature District Thermal Network: A Case Study in Denmark

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Abstract

District heating systems have been used for space heating and domestic hot water since the 1880s. Since then, the efficiency of these systems has been improved continuously. The aim of this work is to conduct an early-stage feasibility study to calculate the energy performance of an ambient-temperature district heating and cooling system serving a new urban area located in Denmark. Dynamic energy simulation models of buildings and district network components were developed using Modelica. Results show that the evaluation of the water temperature in the network is critical, as it must be lower than a certain value to enable compressor-less cooling. Furthermore, due to the small temperature difference between supply and return pipes, higher water flow rates are required with respect to a traditional DH network. In terms of primary energy, savings of about 41% can be achieved in comparison to a traditional DH network. This is mainly due to the ability of decentralized heat pumps to adapt the temperature of heat distribution to different uses.

Keywords: District heating and cooling, heat pumps, energy modeling and simulation

1. Introduction

In Europe, heating and cooling demand in the building sector is responsible for a share of about 40% of the overall final energy usage (European Commission, 2016). In most countries, the energy required for heating is larger by far than the energy used for cooling. However, factors such as global warming, proliferation of glass facades, thermal insulation and rising standards in comfort are leading to new scenarios. In fact, it is expected that by 2050 the heating demand will decrease between 20% and 30% and the cooling demand will rise of about three times compared to 2006 values (Joint Research Centre, 2011). This tendency is confirmed by the number of air-conditioning units installed in Europe, which increased with a growth rate of 3% per year since 1990s (Pezzuto et al., 2016).

District heating and cooling (DHC) systems have been acknowledged as a promising solution for the reduction of both primary energy consumptions and CO_2 emissions to cover the heating and cooling demand of buildings. District heating (DH) systems have been used for space heating and domestic hot water since the 1880s. Conventional DH systems consist of centralized plants that feed hot water or steam into pipes to distribute heat in urban areas. Such systems suffer from significant heat losses and low potential for integration of sustainable energy sources. In addition, in traditional DH systems the same piping network is typically not able to provide simultaneously both heating and cooling services to different buildings.

For these reasons, current research focuses on novel systems, which can reach high efficiencies by operating at temperatures close to ambient (Buffa et al., 2019). Such systems, which are also referred to as the 5th generation of district heating and cooling (5GDHC), enable covering both heating and cooling demands of buildings with the same pipeline. The 5GDHC technology is still in early stages of research and development, and few pilot sites and demonstration projects are currently being operated across Europe. Most of the previous studies have focused on the development of simulation models to evaluate the energy performance of 5GDHC systems.

Wirtz et al. (2020) proposed a novel methodology for designing and evaluating bidirectional 5GDHC systems. Based on linear programming, this design approach led to a cost reduction of 42% and caused 56% less CO_2 emissions compared to a reference case based on individual building systems. Calixto et al (2021), modeled an existing 5GDHC network located in Italy using both detailed and simplified modeling approaches. The results showed reasonable agreement between the two models, with the simplified model underestimating the overall electric consumptions by about 15% with respect to the detailed model. Allen et al. (2020) analyzed

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the energy performance of 5GDHC systems for a prototypical district located in Denver (USA). Results showed that radiant hydronic systems connected with 5GDHC systems achieved a source energy use intensity that was 49% lower than that of air-based systems and conventional district thermal energy systems.

This paper presents preliminary results from an early-stage feasibility study that aims to calculate the energy performance of a 5GDHC system serving a new urban area located in the municipality of Køge (Denmark).

2. Methodology

2.1 Building energy models

The urban area considered in this work is located in the municipality of Køge (Denmark), and it consists of about 85,000 m^2 floor area of residential buildings and 50,000 m^2 floor area of office buildings. The total annual heating and cooling demand is about 4 GWh and 0.7 GWh, respectively. To calculate hourly heating and cooling demand of the future buildings, four representative building energy models were developed: terraced house (TH), multi-family house (MFH), block apartments (BA) and office buildings (OB).

Hourly demand profiles for space heating, domestic hot water and space cooling, were generated with the Python-based tool BAGEL (Maccarini et al., 2021), which enables an automatic creation of building energy models starting from pre-defined geometries and basic input parameters (e.g. U-values, internal gains, ventilation rates). The energy models developed in BAGEL use a resistance-capacitance method to describe the thermo-physical behavior of buildings, as specified in the ISO 13790 standard (International Standard Organization 2008). Since the urban area is still under development, only little information was available about the characteristics of the buildings. Therefore, most of the input parameters for the models were assumed based on Danish Building Regulation and authors' assumptions. These parameters are shown in Table 1. Note that the three residential building typologies (TH, MFH and BA) only differ in terms of geometry and boundary conditions (e.g., terraced houses have some adiabatic walls).

Buildings were equipped with floor heating systems with supply water temperature of about 35°C. Cooling for office buildings was delivered by chilled beam units with supply water temperature of about 20°C (Maccarini et al., 2020). Cooling demand in residential buildings was not considered. Domestic how water was provided at 60°C.

Tab. 1: Input parameters for typical building typologies

	Residential (TH, MFH, BA)	**Office (OB)**
Total floor area	85,000 m^2	50,000 m^2
U-value (walls/roof/floor/windows)	0.3/0.2/0.2/1.1 W/m^{2}K	0.3/0.2/0.2/1.1 W/m^{2}K
Internal heat gains	5 W/m^2 (weekly schedule)	25 W/m^2 (weekly schedule)
Window-to-wall ratio	0.25	0.4
Domestic hot water load	4 W/m^2 (constant profile)	1.5 W/m^2 (constant profile)
Air change per hour	0.4 h^{-1}	1.25 h^{-1}
Heating set-point	20°C	21°C
Cooling set-point	-	24°C

2.2 District network energy models

The schematic layout of the 5GDHC system is illustrated in the Figure 1. The plant consists of a heat exchanger connected to an industrial facility, which provides wastewater at 15°C. Prosumer substations consist of three components (see Fig. 1b): decentralized heat pump for space heating, decentralized heat pump for domestic how water, and heat exchanger for direct cooling (in office buildings). A temperature difference of 4 K was assumed between supply and return pipelines. Pipes were dimensions assuming a pressure drop per pipe length of 250 Pa/m.

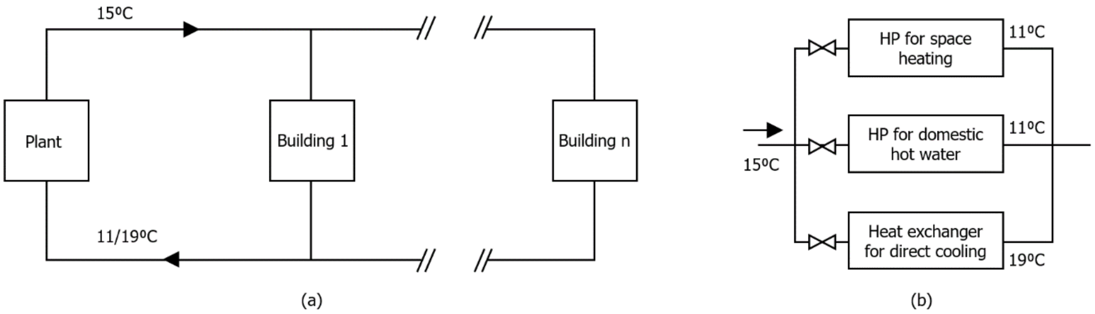

Fig. 1: Schematic of the 5GDHC network (a). Schematic of the prosumer substation (b).

To evaluate the energy performance of the 5GDHC system, a comparative study was conducted in respect to a traditional DH network, which operates with supply water temperature of 80°C. Figure 2 shows the schematic layout of the traditional DH system. Substations consists of two components: heat exchanger for space heating and heat exchanger for domestic hot water. Cooling is provided by stand-alone air-based chillers.

To describe the thermal and hydraulic dynamics of the network simulation models of both system configurations were developed using the open-source, equation-based and object-oriented Modelica language (Mattsson et al., 1998). As demonstrated by previous works (Wetter et al. 2019, Saelens et al., 2019), Modelica represents a useful tool for the modeling and simulation of district heating and cooling networks. Basic models such as pipes, valves, heat exchangers and heat pumps were retrieved from the Modelica Buildings library (Wetter et al., 2014), while more complex models, such as substations and ground heat losses were developed in-house during the project. To reduce modeling efforts and computational time, the buildings were aggregated in five clusters. Table 2 illustrates the distance between each cluster in the network.

Tab. 2: Distance between clusters

Pipe segment	**Distance [m]**
Plant – Cluster A	170
Cluster A – Cluster B	190
Cluster B- Cluster C	180
Cluster C- Cluster D	220
Cluster D – Cluster E	170
Total	930

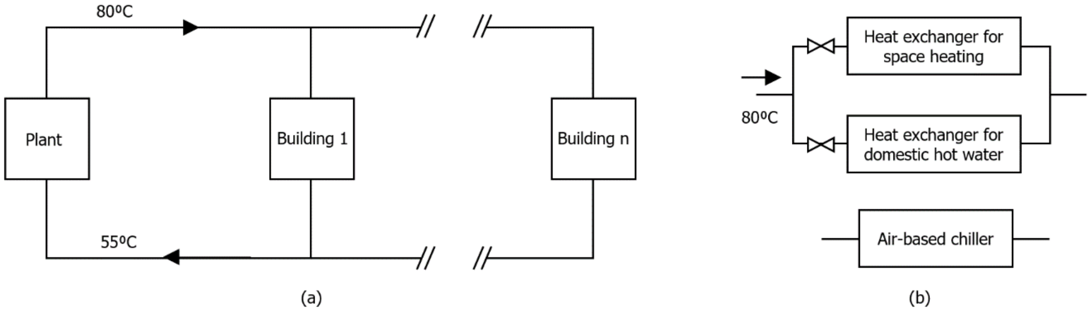

Fig. 2: Schematic of the traditional DH network (a). Schematic of the substation (b).

2.3 Component models

This section describes the physical assumptions made for the main component models. Heat pumps were modelled using an idealized internal control that can track the set-point of the water temperature leaving the condenser. The COP of the heat pump model is calculated as:

$$COP = \eta \frac{T_{con}}{T_{con}-T_{eva}} \qquad \text{(eq. 1)}$$

Where T_{con} [K] is the condenser temperature, T_{eva} [K] is the evaporator temperature, and η [-] is the Carnot effectiveness, which was assumed equal to 0.4. Air-based chillers in office buildings were modelled with a similar approach.

The plant was modeled differently for the two system configurations. In the 5GDHC system, the plant was represented by an unlimited source of thermal energy at 15°C, which can deliver a constant water temperature of 15°C in the network at any time. Such energy source can be, for example, a lake, ground water or waste heat/cold from industries. In the traditional DH system, the plant was represented by an ideal heat source, which can raise the temperature in the network from 55°C to 80°C using an amount of thermal power equal to:

$$\dot{Q} = \dot{m} c_p \left(T_{sup} - T_{ret} \right) \qquad \text{(eq. 2)}$$

Where $\dot{m}$ [kg/s] is the water mass flow rate, c_p [J/kg K]is the specific heat capacity, T_{sup} [K] is the supply water temperature, and T_{ret} [K] is the return water temperature.

The pipes were modelled in such as way that the flow resistance is calculated using a fixed flow coefficient, which is computed based on a pre-defined pressure drop at design flow rate. For off-design conditions, the model is capable of calculating the flow friction as a function of the flow rate. Pipes were insulated in the traditional DH system configuration, while they were uninsulated in the 5GDHC system configuration.

The ground surrounding the pipes was set to a pre-calculated value, according to a formula as a function of the time of the year and the depth below the ground surface, which was assumed to be 1 m.

Circulation pumps were modelled by assuming that that the required mass flow rate can be provided at any time by overcoming the pressure drop in the hydraulic circuit. The electric power consumption is determined as a function of the hydraulic and motor efficiency as:

$$P_{ele} = \frac{\dot{V} \Delta P}{\eta_{hyd} \eta_{mot}} \qquad \text{(eq. 3)}$$

Where $\dot{V}$ [m^3/s] is the water volumetric flow rate, ΔP [Pa] is the pressure drop, η_{hyd} [-] is the hydraulic efficiency and η_{mot} [-] is the motor efficiency. A constant value of 0.7 was assumed for both the motor efficiency and the hydraulic efficiency.

3. Results and discussion

Figure 3 shows the water temperature entering the substation of Cluster E, which is the farthest substation from the plant. This is the substation where the water temperature is most affected by heat exchange with the ground. Results show that the water temperature in the 5GDHC varies between approximately 5°C in winter and 17°C in summer. This means that, in winter, the water in the circuit rejects heat to the ground, while in summer it absorbs heat. The value of the water temperature entering the substation in summer is particularly critical as it should be sufficiently low for direct cooling (i.e., via heat exchanger). In this specific case, since buildings are equipped with high-temperature cooling systems (about 20°C), a maximum temperature of 17°C may represent a suitable value.

Figure 4 illustrates the water flow rate circulating in the network for both system configurations. For the 5GDHC system, the water flow rate ranges between 10 kg/s and 110 kg/s. For the traditional DH system, the water flow rate is between 1.5 kg/s and 20 kg/s. The larger values obtained for the 5GDHC system are mainly due to the smaller temperature difference between the supply and return pipe, which is 4 K. In comparison, the traditional DH system has a temperature difference of 25 K. It can be also noticed that, in summer, the traditional DH system circulates a small, constant water flow rate, which is required for domestic hot water. Conversely, the 5GDHC system operates large water flow rates, as it provides not only domestic hot water, but also cooling to buildings.

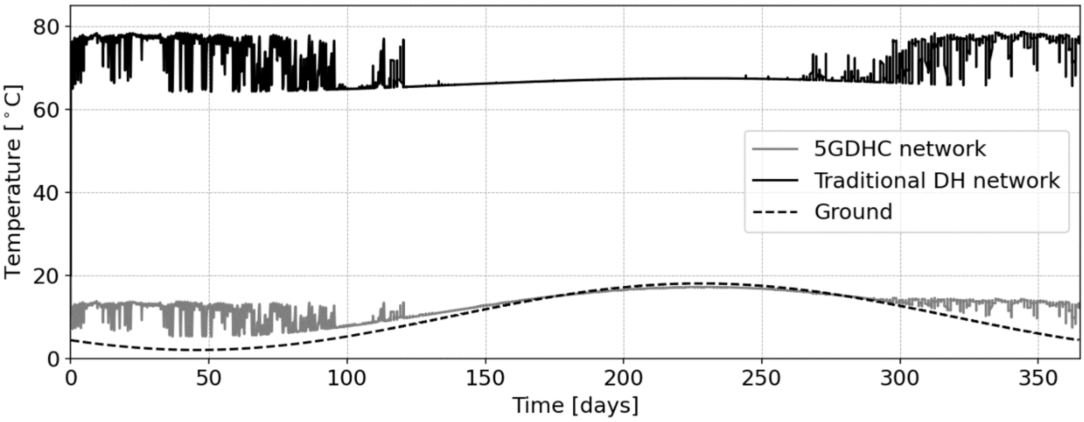

Figure 3: Water temperature entering the substation of Cluster E in comparison to ground temperature

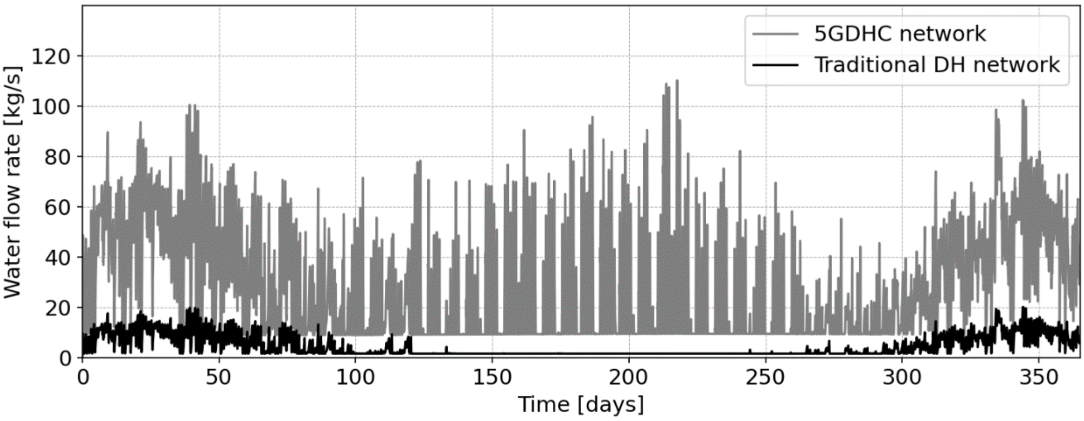

Figure 4: Water flow rates circulating in the network

Figure 5 shows the annual primary energy use of the 5GDHC system in comparison to the traditional DH system. Primary energy factors of 0.8 and 2.5 were used, respectively, for district heat and electricity [6]. Simulation results show that primary energy savings of about 41% can be achieved for the case study considered in this work. This is mainly due to the ability of decentralized heat pumps to adapt the temperature of heat distribution to different uses. This represents a significant advantage, as each machine operates at the best possible ideal COP. In comparison, traditional DH systems are constrained by the worst user in term of heat distribution temperatures. In addition, the 5GDHC network can deliver cooling without any energy input (except for circulation of water).

4. Conclusions

The present work carried out an early-stage feasibility study of an ambient-temperature DHC system located in Denmark. To evaluate the energy performance of the ambient-temperature DHC system, a comparative study was conducted in respect to a traditional DH network. Dynamic energy simulation models were developed using Modelica. Results show that the evaluation of the water temperatures in the 5GDHC network is critical, especially when substations are equipped with compressor-less cooling. Furthermore, due to the small temperature difference between supply and return pipes, higher water flow rates are needed with respect to a traditional DH network. To reduce pressure losses, pipes with large diameters are typically installed. In terms of primary energy use, savings of about 41% can be achieved in comparison to a traditional DH network. This is mainly due the ability of decentralized heat pumps to adapt the temperature of heat distribution to different uses.

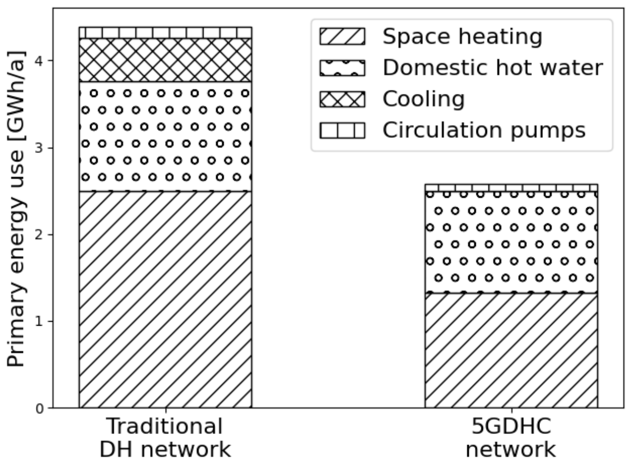

Fig. 5: Primary energy use comparison between traditional DH network and ambient-temperature DHC network

5. Acknowledgments

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