THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Gothenburg District Cooling System

– An evaluation of the system performance based on operational data

MARIA JANGSTEN

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

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MARIA JANGSTEN

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Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

The global energy demand for providing cooling in buildings is expected to increase the next decades, along with a rapid growth in the number of air conditioners and chillers. A more energy efficient, economical and environmentally viable solution to this increased cooling demand, is district cooling. In Sweden, this technology has been developed since the mid-1990's and currently delivers about 1 TWh of cooling annually, to 40 cities.

Common issues with district cooling are mainly related to the temperatures. First, a low temperature difference between the supply and return water, called low delta-T, persist despite extensive efforts by previous research to provide solutions. Second, low conventional supply and return temperatures remain, potentially as a result of limited knowledge about the temperatures used in the connected buildings. Previous research on the low delta-T has primarily focused on district cooling systems without heat exchangers separating the connected buildings from the distribution system.

The purpose of this thesis was therefore to investigate issues with low delta-T in a district cooling system with heat exchanger separation and to explore potentials of using higher temperatures, by increasing the knowledge about the connected buildings. The investigation was based on analyses of operational data from both primary and secondary sides of the heat exchangers in 37 of the connected buildings in Gothenburg district cooling system. This system is designed for a delta-T of 10 °C and chilled water supply temperatures of 8 °C in the connected buildings.

The delta-T in Gothenburg district cooling system varies between 6-8 °C, and the results showed that the main causes to this low delta-T were the following: a low temperature approach between the supply streams of the heat exchanger; operation in the saturation zone on the primary side of the heat exchanger; and low return temperatures from cooling coils and fan coil units in the connected building chilled water systems. The results also demonstrated that 75% of the recorded chilled water supply temperatures were higher than 8 °C when the outdoor temperature was 28 °C. If high temperature district cooling was used, more than 50% of the annual district cooling generation would be supplied by free cooling from the river.

Keywords: district cooling, low delta-T, building chilled water systems, energy transfer station, high temperature district cooling

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Thank you!

Maria Jangsten
Gothenburg, March 2020

Appended Publications

Paper I

Jangsten, M., Lindholm T., Dalenbäck J-O. (2019). *Analysis of Operational Data from a District Cooling System and its Connected Buildings.*

Paper under review in peer reviewed journal.

Contribution: As the first author, Maria Jangsten designed and conducted the study as well as authored the paper. Torbjörn Lindholm and Jan-Olof Dalenbäck have provided guidance, comments and feedback on the study and the writing process.

Paper II

Jangsten, M., Filipsson, P., Lindholm T., Dalenbäck J-O. (2020). *High Temperature District Cooling: Challenges and Possibilities Based on an Existing District Cooling System and its Connected Buildings.*

Paper published in special issue of Energy – the International Journal.

Contribution: As the first author, Maria Jangsten designed the study, conducted the analysis and authored the paper. Peter Filipsson contributed with results and analysis of section 3.2 as well as input to the article. Torbjörn Lindholm and Jan-Olof Dalenbäck have provided guidance, comments and feedback on the study and the writing process.

The following publication is also authored by Maria Jangsten but not included in the Licentiate Thesis:

Jangsten, M., Lindholm T., Dalenbäck J-O. (2019). *Time to Question the Low Temperatures in District Cooling Systems*.

Published in Euroheat and Power Magazine III-IV/2019, 42-45.

Table of Contents

List of Abbreviations

AHU	Air Handling Unit
BMS	Building Management System
CHW	Chilled Water
COP	Coefficient of Performance
DC	District Cooling
DCS	District Cooling System
ETS	Energy Transfer Station
FCU	Fan Coil Unit
FDD	Fault Detection and Diagnosis
HTC	High Temperature Cooling
HTDC	High Temperature District Cooling
HVAC	Heating, Ventilating, and Air Conditioning
SFDD	Sensor Fault Detection and Diagnosis

Nomenclature

$t_{DC,\ supply,\ distr.}$	District Cooling Supply Temperature from Production Plant
$t_{DC,\ return,\ distr.}$	District Cooling Return Temperature to Production Plant
$t_{DC,\ supply}$	District Cooling Supply Temperature on Primary Side of Heat Exchanger in Energy Transfer Station
$t_{DC,\ return}$	District Cooling Return Temperature on Primary Side of Heat Exchanger in Energy Transfer Station
$t_{CHW,\ supply}$	Building Chilled Water Supply Temperature on Secondary Side of Heat Exchanger
$t_{CHW,\ return}$	Building Chilled Water Return Temperature on Secondary Side of Heat Exchanger
Δt_{DCS}	Temperature Difference of District Cooling System Supply and Return Temperatures at Production Plant
Δt_{DC}	Temperature Difference of District Cooling Supply and Return Temperatures on Primary Side of Heat Exchanger
Δt_{CHW}	Temperature Difference of Building Chilled Water System on Secondary Side of Heat Exchanger
Δt_1	Temperature Approach between Supply Sides of the Heat Exchanger
Δt_2	Temperature Approach between Return Sides of the Heat Exchanger
Δt_{out}	Outdoor Temperature
Δt_{river}	River Temperature
$\dot{V}$	District Cooling Water Flow Rate
$\dot{Q}$	Cooling Power

Chapter 1: Introduction

The introduction will provide some general information and a future outlook about the topic in this thesis, both from a global and a Swedish perspective. With this as a foundation, the research gap and problem formulation will be introduced and explained after which the aim and research questions will be defined. Lastly, delimitations and limitations of the study will be identified, and the structure of the thesis outlined.

1.1 Global Development

Buildings account for more than 55% of the total electricity usage globally, of which 65% is supplied by fossil fuels (IEA, 2019). To achieve a reduction in carbon dioxide emissions and mitigate climate change, the building sector must become more energy efficient and employ more low-carbon technologies. However, one of the fastest growing energy end-use sectors in buildings is space cooling due to the increasing electricity demand for equipment such as air conditioners and chillers. Today space cooling accounts for 18.5% of the global electricity usage, but is expected to increase to 37% by 2050 if not addressed (IEA, 2018). A technology that has the potential to reduce the electricity demand to provide cooling for buildings is district cooling (DC). Instead of building individual chillers, air conditioners and heat pumps, chilled water (CHW) is generated in a central cooling plant and distributed by large pumps and underground pipes to the connected buildings (Olama, 2017).

To achieve carbon dioxide emission reductions for the building sector, the transformation to a renewable and sustainable energy system is essential. To support this transformation, a concept called Smart Energy Systems has been developed. It is based on a holistic approach by integrating sectors such as electricity, heating, cooling, industry, buildings and transportation, since they cannot be designed and operated without influencing one another. By integrating these sectors, more affordable and optimal solutions can be identified to aid the transformation of the current energy system into at future renewable based and sustainable energy system (Lund et al., 2017).

District cooling is an important component of a future smart energy system since renewable energy can be integrated by the use of natural cooling sources such as the sea, lakes and rivers (see section 2.1.1 for details and more information). This reduces the primary energy need for chilled water generation in chillers. District cooling systems (DCS) can also successfully incorporate thermal energy storage, both daily and seasonally (Al-Noaimi et al., 2019; Näslund, 2000), which increases the flexibility in terms of chilled water production matching the demand with fluctuating electricity prices (Inayat & Raza, 2019). In areas where the district cooling system is integrated with the district heating system, or has access to waste heat, synergies arise from using heat to produce chilled water by absorption chillers (S. Werner, 2017b). District cooling is therefore a crucial component to avoid both the increased need for electricity to provide cooling in buildings, but also to contribute to the transformation into a future sustainable energy system based on renewable energy (Dominković et al., 2017; Lund, Østergaard, et al., 2018). Similarly, as claimed by Inayat & Raza (2019), district cooling is “undoubtedly the future energy solution and the environmental solution” to provide cooling in buildings.

1.2 Swedish Perspective

District cooling from a Swedish perspective is to a large extent linked to district heating. This is because district heating is a well-established and mature technology with large market shares which owners, mainly municipalities, developed most of the district cooling systems (S. Werner, 2017a; Westin, 1998). Compared to district heating, district cooling is very small and today there is a total of 36 companies delivering approximately 1.0 TWh of cooling annually to 40 Swedish cities (Johannesson, 2019). The highest delivery was almost 1.2 TWh in 2018, because the summer that year was extremely warm and sunny compared to normal. The average temperatures were 1-3 °C above normal in the north, and 2-4 °C above normal in the south (SMHI, 2018). The delivered district heating the same year was equal to about 50 TWh (Burstein, n.d.).

The principal drivers behind the district cooling development in Sweden was the CFC refrigerant ban and a growing need for space cooling in Swedish buildings. This space cooling demand has emerged as a result of designing for low heat losses which has led to a larger cooling demand in the summer (S. Werner, 2017a). As can be seen in Figure 1, the district cooling deliveries and the length of DC piping have gradually increased since the mid-90's until today. Over the next 10 years, DC in Sweden is expected to grow by 50% (Dalin, 2019).

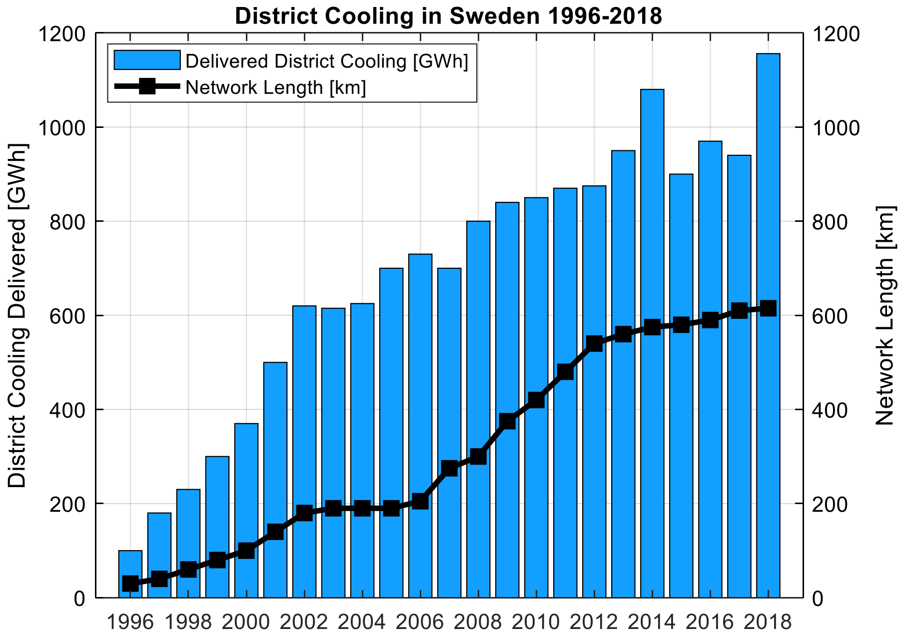

Figure 1: Deliveries of district cooling in Sweden 1996-2018 in GWh along with total installed network lengths in km. Reproduced from "Fjärrkyla" by Johannesson (2019).

In Figure 2, the DC production mix of the 24 largest DC providers in Sweden can be seen. The most common technology is heat pumps, representing 47% of the district cooling generated, and the second largest cooling source is free cooling (Abrahamsson & Nilsson, 2013). As a result of available excess district heating during the summer months, synergies between district heating and cooling arise from having absorption chillers produce chilled water during the months with low heat demands, accounting for 11% of the Swedish DC production (Abrahamsson & Nilsson, 2013; S. Werner, 2017a).

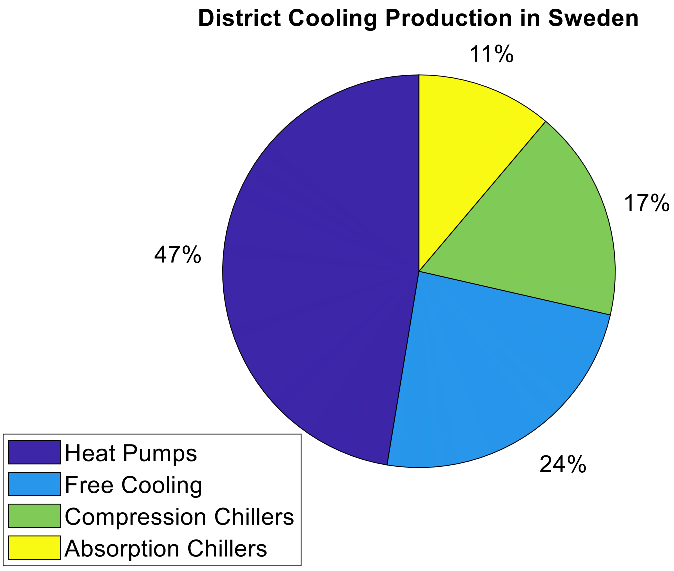

Figure 2: Share of DC production technology in Sweden (figured modified from Abrahamsson & Nilsson, (2013)).

The largest district cooling system in Sweden is located in Stockholm. It has a total installed capacity of 270 MW and constitutes 57% of the total Swedish district cooling market. The system comprises 250 km of piping and is mainly supplied by heat pumps and free cooling from the Baltic Sea. The second largest district cooling system is located in Gothenburg, with a total installed capacity of 70 MW and 30 km of piping. Instead of heat pumps, Gothenburg DC system is mainly supplied by absorption chillers running on waste heat. Free cooling from the river is also used, primarily in the winter. In 2018, Stockholm district cooling system delivered 420 GWh of cooling compared to around 100 GWh by Gothenburg DCS (Abrahamsson & Nilsson, 2013; Städje, n.d.; Stockholm Exergi, 2018). The work in this thesis is based on data from the district cooling system in Gothenburg.

Barriers for further development of district cooling systems in Sweden were investigated by Palm & Gustafsson (2018), where the most critical parameter was the lack of knowledge of district cooling among the real estate owners and their tenants. This is a challenge that needs to be addressed in order for district cooling to maintain a competitive position to meet the increasing Swedish cooling demand (Sernhed et al., 2018).

1.3 Problem Formulation

The supply and return temperatures of district cooling systems have traditionally been, and are still, designed to be in the range of 4-8 °C supply and 13-16 °C return (IDEA, 2008). For the district cooling system to be cost efficient with regard to pumping, a temperature difference of 9-12 °C is optimal (Olama, 2017). However, previous research has shown that the system design temperature difference rarely is maintained over time, causing the district cooling system to suffer from the “low delta-T syndrome.” A low delta-T increases the energy usage since it causes additional chillers to operate and the distribution pumps to deliver a higher flow rate to satisfy the same cooling load (IDEA, 2008). Delta-T is a central concept in this thesis and will recurrently be referred to as low or high.

Many studies have established solutions to resolve the low delta-T syndrome (Fiorino, 1996), however, these studies have primarily focused on DCS with direct building connections or with heat exchanger separation primarily for static pressure relief in high rise buildings (Gao et al., 2012). All district cooling systems in Sweden, as well as the one in Gothenburg, have indirect connections with heat exchangers separating the distribution system from the connected buildings. For such district cooling systems, there is a need to evaluate the causes and solutions to the low delta-T, since they may be different from DCS with direct connections. To do so, both sides of the heat exchanger need to be analyzed since it previously has been established that “the solution to common delta-T problems requires looking beyond the energy transfer station (ETS) into the building systems” (IDEA, 2008). For DCS with heat exchanger separation, such investigations become more complicated since the ownership of the systems on either side of the heat exchanger is separate. The district cooling provider usually has little information about the chilled water (CHW) system in the connected building. For that reason, there is a need to increase the knowledge about the connected buildings systems and their temperature requirements.

Previous research on Swedish district cooling systems and the connected buildings have focused on recommendations on how the ETS should be designed and how the connected buildings should be controlled to achieve a more efficient usage of the district cooling. Källman et al. (2004) aimed to achieve an increased return temperature in the district cooling system by simulating three different heating, ventilating and air conditioning (HVAC) systems in an office building. The results showed that it was possible to achieve return temperatures higher than 16 °C on the primary side of the heat exchanger and 18 °C on the secondary side. Moreover, the results showed that return temperature requirements on the primary side should be a function of the building’s chilled water return temperature.

Werner & Jonsson (2012) investigated measures to increase delta-T in two commercial buildings by simulations and measurements. It was shown that by restricting the maximum cooling power, delta-T could be increased. In a study by Fredriksen et al. (2016), it was demonstrated based on calculations that limiting the flow in the building chilled water system was an efficient method to increase the secondary return temperature compared to using outdoor temperature compensated supply temperature setpoints on the secondary side. These previous studies show that there are several suggestions and potential improvements that can be applied to buildings and energy transfer stations connected to DCS to ensure high temperatures. However, these studies were either based on theoretical evaluations or approached from either side of the heat exchanger in the ETS. For that reason, an assessment of the actual operation of both sides of the heat exchanger in an existing district cooling system is needed.

A vast amount of research has been conducted focusing on the role of district heating in smart energy systems (Lund, Duic, et al., 2018; Lund, Østergaard, et al., 2018; Lund et al., 2014), but district cooling has received less attention in this context. For DCS supplied by natural cold sources with temperature variations during the year, it is possible to increase the share of renewable energy by increasing the use of free cooling (Fredriksen et al., 2016). However, this share is limited by the conventional low DC temperatures of 4-8 °C supply and 13-16 °C return. At the same time, the technological development of high temperature cooling (HTC) systems in buildings is advancing, utilizing chilled water temperatures of 16 °C and up (Jiang et al., 2015). Building owners that implement HTC systems may choose other cooling sources than district cooling, for example, direct coupling to the ground for free cooling (Filipsson et al., 2020). Therefore, there is a need to explore higher temperatures in the district cooling system as well.

1.4 Aim of Licentiate Thesis

The aim of this licentiate thesis is to investigate causes to the low delta-T between the supply and return water for the Gothenburg district cooling system, by increasing the knowledge about the connected building energy transfer stations and chilled water systems. The aim is also to explore higher temperatures in the district cooling system to increase the share of free cooling of the annual district cooling generation.

1.4.1 Research Questions

Based on the above, there are two main problems with the existing temperatures in district cooling systems:

1. Low delta-T between supply and return temperature.

2. Low supply and return temperatures.

Even though these two problems are interrelated, they affect the district cooling system differently and are in this thesis investigated by different approaches. Problem number 1 has a direct impact on the energy efficiency and operating cost of the district cooling system and is approached by increasing the knowledge about the customers ETS and building CHW systems. Problem number 2 is of a more general nature for district cooling systems connected to natural cold sources with temperatures varying depending on the ambient temperature. In this thesis, problem 2 is approached by theoretically exploring the impact on the district cooling generation by different temperature levels with the increased knowledge about the customers' systems as a foundation. Based on this, the following research questions are posed for the two problems stated:

RQ 1a) What are the causes to low delta-T in an existing district cooling system with heat exchanger separation?

RQ 1b) How can low delta-T in an existing district cooling system with heat exchanger separation be resolved?

RQ 2) What are the potentials for higher temperatures in an existing district cooling system based on the temperature requirements of the connected buildings?

These three research questions are treated in each of the appended papers where problem 1 and research questions 1a and b are investigated in Paper I. In Paper II, the focus is on problem 2 and with the goal to explore research question 2.

1.4.2 Delimitations and Limitations

The context for this thesis is given in its entirety in Chapter 2, however, low delta-T and the temperatures in district cooling systems are closely linked to other aspects of the topic district cooling. For this reason, the following aspects have been omitted in this thesis:

Cooling load predictions and calculations is an important aspect in regard to the operation and planning of district cooling systems, especially as a profitability measure and input to modelling of district cooling systems. However, different types of cooling loads in buildings, cooling load aggregations and methods of estimating and calculating cooling loads are not part of this licentiate thesis and have not been investigated.

Whether or not the district cooling system is the most optimal cooing provider for the buildings in Gothenburg, compared to building individual chillers, heat pumps or other solutions, is another delimitation of this thesis. Neither will other means of providing cooling or reducing the cooling demands in the connected buildings be explored.

Another aspect of district cooling that has been excluded from this thesis is different hydraulic configurations of district cooling systems, such as pressure head profiles of the piping network, pumping schemes and distribution layouts. This is because the aim of this thesis is to explore the low delta-T in regard to the energy transfer stations and the connected buildings, and not with respect to the hydraulics of the distribution system. Also excluded from this thesis is the effect of thermal energy storage integration, replacement of chillers in the chilled water production plants or the integration of new cooling technologies.

Limitations of the thesis that are outside the control of the researcher and constitute potential weaknesses in the study, include the nature of the data which the study is based upon. The data is operational as measured by permanently installed equipment and testing of data reliability and validity has been limited. Potential erroneous measurements could remain among the data which could negatively impact the results. However, such erroneous measurements have been judged to have a minor impact on the conclusions drawn (see section 3.4.2 for more details).

1.4.3 Structure of the Thesis

This licentiate thesis is structured as per the following: in Chapter 2 the frame of reference is provided, including a background to district cooling and building chilled water systems. Also provided in Chapter 2 is a literature review which serves as a foundation to the issues investigated in the appended papers. In Chapter 3, an elaboration of the research methodology is provided with a justification and explanation of the chosen research methods. Furthermore, the district cooling system in Gothenburg is described in Chapter 3, since this system represents the applied object of the studies in the two appended papers. The results and discussion are combined in Chapter 4 and in Chapter 5 the conclusion as well as answers to the research questions are provided. Lastly, in Chapter 6, future research is considered.

Chapter 2: Frame of Reference

The frame of reference serves as the foundation of this thesis by alternating between providing background to the topic and reviewing previous work related to the research questions. First, information about district cooling and its components are presented as applied generally. Secondly, related work on district cooling temperatures and the low delta-T syndrome are presented from the perspective of district cooling systems. Lastly, information about the connected buildings HVAC systems along with related work on the low delta-T syndrome and high temperature development is provided.

2.1 District Cooling

District Cooling is a technology where chilled water is generated centrally in large chiller plants and is distributed to connected buildings by underground pipes. A district cooling system consists of three main components: production plant, distribution system and connected building chilled water systems. The buildings are connected by means of plate frame heat exchangers in the energy transfer station, see Figure 3 (Olama, 2017; Skagestad & Mildenstein, 2002). District cooling systems can be supplied by natural cooling sources, absorption chillers running on waste heat and mechanical compression chillers with electricity as input (Frederiksen & Werner, 2014). District cooling is common in the United States, especially at university campuses, healthcare centers and airports. More recently it has also grown extensively in the Middle East, Asia and Europe (Tredinnick & Phetteplace, 2016).

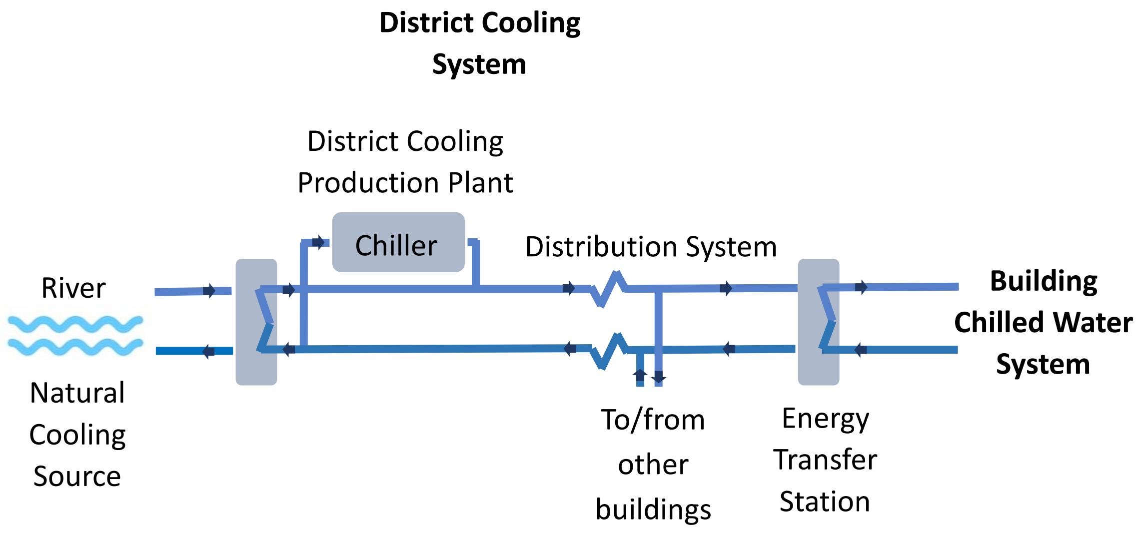

Figure 3: Schematic of a district cooling system with its main components.

DC is cost efficient in appropriate applications (Rezaie & Rosen, 2012), such as in cities where the cooling demand is aggregated by the large number of buildings. Also, different types of buildings make the accumulated cooling demand diverse and the production more efficient (IDEA, 2008). It has been shown that district cooling can contribute to reducing the need for fossil fuels to provide cooling in buildings (Rezaie & Rosen, 2012). DC also generates several benefits for both building owners and the city. The benefits for building owners include an eliminated need for individual chillers and heat rejection units in each building, making more rentable space available. Furthermore, the need for operation and maintenance of chillers is reduced which enables them to focus on the core business (Frederiksen & Werner, 2014). The benefits for the city include an alleviation of noise pollution (Calderoni et al., 2019) and heat island effects caused by the heat rejection units. Moreover, fewer individual chillers reduce the usage of refrigerants, which supports the Montreal Protocol and Kigali Amendment. The aggregated need for electricity for chillers is also reduced since large chillers have the potential of achieving higher efficiencies than smaller units used in buildings (ASHRAE, 2013).

District cooling has higher capital investments and operating costs compared to district heating and may not always be the most cost optimal option to provide buildings with cooling. If the DC chillers have the same efficiency as individual cooling systems, DCS is more energy consuming (Gang et al., 2017). Nevertheless, DC has the potential to achieve higher operating efficiencies compared to in-building chiller systems, as a result of the concentration effect of diverse cooling demands and the possibility of integrating natural cold sources (Jing et al., 2017; Shimoda et al., 2008).

The number of district cooling systems around the world is unknown, however, at least 150 systems are estimated to be in operation. The annual cold delivery from these DCS is approximately 83 TWh, where 67% is delivered in the Middle East, 27% in the US and the remainder in Japan and the EU (S. Werner, 2017b). In Europe, the cold deliveries by DCS were around 3.5 TWh in 2018, out of which roughly 30% were delivered by Swedish DC systems, 30% in France and 40% in the remaining European countries with DCS (Dalin, 2019).

2.1.1 Free Cooling

District cooling can make use of available local natural cold sources by integrating them into the district cooling system, also referred to as free cooling. Natural cold sources are, for example rivers, lakes and the sea (Frederiksen & Werner, 2014; Skagestad & Mildenstein, 2002). When the natural cold source used is the sea, it is also called sea water air conditioning (SWAC), divided into either shallow or deep SWAC. The difference between the two is the economically viable water temperature profile. Deep SWAC has access to sea water temperatures around 5 °C irrespective of ambient outdoor temperature. DCS with deep SWAC can therefore utilize free cooling all year round without the need for additional chillers. Shallow SWAC utilizes cold sources with temperatures that vary with the ambient temperature. For such DCS, free cooling is utilized 100% when the sea water temperature at the intake point is 5 °C. The remaining part of the year the sea water can be used as a heat sink for the chillers' condensers (Hunt et al., 2019).

Examples of DCS integrated with natural cold sources include the DCS in Stockholm, Sweden, which uses cold water from the Baltic sea. The DCS in Paris, France, uses the river Seine for 100% free cooling when the is water temperature is 8 °C or less, and the remaining part of the year as a heat sink for the condensers. In Toronto, Canada, deep lake water from 83 m below the surface is used for free cooling independent of the outdoor air temperature (Calderoni et al., 2019). Similarly in Ithaca, United States, lake water is pumped from the depth of 73 m and used for free cooling all year round (Zogg et al., 2008).

Deep or shallow SWAC is crucial for the integration of renewable energy sources in DCS (Gang et al., 2016; Inayat & Raza, 2019), where success factors are available seawater temperatures of the geographical location and the urban environment (Zhen et al., 2007). For DCS with shallow SWAC the share of free cooling is determined based on the supply and return temperatures of the district cooling system. If the primary return temperature is increased, the share of free cooling can be increased accordingly (Fredriksen et al., 2016).

2.1.2 Energy Transfer Station

The thermal energy transfer between the DC distribution system and the connected building takes place in the energy transfer station (also called substation). There is both indirect and direct ETS and the choice of connection type is typically determined based on the district cooling system being a public utility or user owned (ASHRAE, 2013; IDEA, 2008; Olama, 2017). If the DCS is user owned the building chilled water systems can be directly connected since the need for a contractual separation is unnecessary. However, if the DCS is publicly owned, with separate ownership of the connected buildings, the ETS connection has to be indirect by means of plate frame heat exchangers, see Figure 4. The indirect connection also serves as a safety measure in case of leakages (IDEA, 2008; Tredinnick & Phetteplace, 2016).

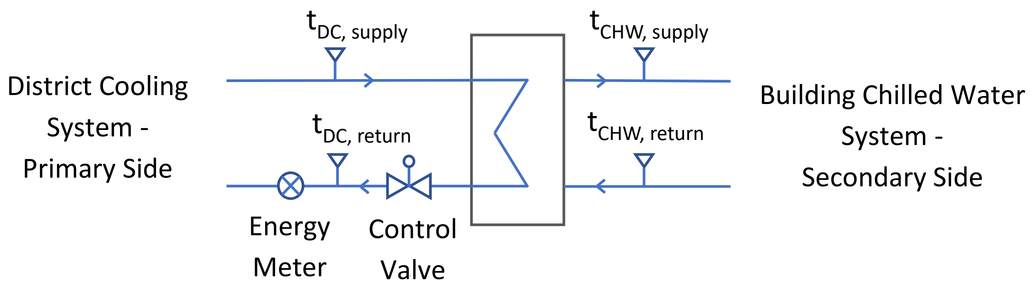

Figure 4: Outline of energy transfer station in district cooling system with indirect building connections by plate frame heat exchangers. Also shown are the general locations of the measurement equipment with energy meter and control valve located on the primary side and temperature sensors located on both sides of the heat exchanger.

In DCS with indirect ETS connections, the district cooling system distribution side of the ETS is referred to as the primary side or the DC side of the heat exchanger. The connected building chilled water system is also called the secondary side of the heat exchanger or the CHW side of the system. Both terms for referring to either side of the heat exchanger are used in this thesis.

Although the heat exchanger is needed in DCS with separate building ownership, it also creates a barrier between the primary and secondary sides with regard to information and data transfer. Even if the DC provider may own part or all of the ETS equipment, it is common that the DC provider has no access to the building chilled water systems' data, nor that the building owners have access to the data measured by the DC provider (for example, see temperature sensor locations on either side of the heat exchanger in Figure 4).

2.2 District Cooling System Temperatures

Conventional district cooling systems are designed with supply temperatures between 4-7 °C. This temperature is dictated by the connected cooling loads and limited by the performance of the DC plant and the distribution system. The cost effectiveness of a district cooling system is heavily dependent on the temperature difference between the supply and return, referred to as delta-T. A delta-T as high as possible is desired since it leads to smaller pipe sizes and lower pumping costs. Typically, delta-T's of 9-12 °C generate lower economical capital expenditure and lower pumping costs, but it is not uncommon that systems have been designed for lower delta-T's such as 7 °C. Based on an optimal delta-T of 9-12 °C, the resulting design return temperature should be 13-19 °C. However, the DC return temperature is limited by the return temperatures from the energy transfer stations, which in turn are affected by the return temperature in the connected building chilled water systems. Design return temperatures are for this reason difficult to ensure and maintain (IDEA, 2008; Olama, 2017).

For Swedish district cooling systems, general guidelines suggest design temperatures of 4-10 °C supply and 14-20 °C return, with 6 °C as the supply benchmark temperature and 16 °C as the return benchmark. Based on this, the recommended temperatures in the building CHW systems should be 6-14 °C supply and 16-20 °C return, with 8 °C as the supply benchmark and 18 °C as the return benchmark temperature. The building CHW systems benchmark temperatures are recommended for cooling coils in all-air HVAC systems. For air-water and all-water systems, such as chilled beams and fan coil units (FCU), supply and return temperatures of 14/17 °C are suggested (Energiföretagen Sverige, 2019).

According to Skagestad & Mildenstein (2002), it is common that DCS vary the chilled water supply temperature based on the outside ambient temperature. This operation strategy allows an increased chilled water supply temperature as the system cooling demand decreases. However, the supply temperature always has to be sufficiently low to achieve the desired dehumidification of the supply air in the connected buildings, even for lower outside ambient dry bulb temperatures. As stated by Calderoni et al. (2019), there is a greater level of freedom in designing the building systems which dictate the associated DC supply and return temperatures when developing new buildings and districts. For existing district cooling systems, there are limited possibilities to affect the supply temperature, especially regarding the required supply temperatures in the connected buildings. However, this is something that is going to be challenged in this thesis.

2.2.1 Systems with Direct Connections

A widespread problem in district cooling systems is failing to achieve the design delta-T between the DC supply and return water (Olama, 2017). This is called the "low delta-T syndrome" and causes an excessive water flow rate in the distribution system in order to satisfy the cooling demand. This causes additional chillers to be started, resulting in an increased need for pump and chiller electricity, ultimately increasing the costs and wasting energy (IDEA, 2008).

The low delta-T syndrome has been extensively researched in the past decades for district cooling systems with direct building connections, meaning there is no heat exchanger between DC distribution system and the connected buildings chilled water systems. Fiorino (1996), (1999) and (2002) explained twenty-five different ways to eliminate the low delta-T, ranging from component selection criteria in the building chilled water systems to configurations of the distribution system. Kirsner (1997) and Waltz (2000) emphasized the need for variable flow in the distribution system and the building CHW system to respond to low delta-T operation. However, B. Rishel & Avery (2000) pointed out that valves used for constant flow usually are not compatible with the variable flow systems' pressure differentials, leading to leakage flows and causing a low delta-T.

Typical causes of the low delta-T syndrome are the use of 3-way valves (Griffith, 1987; Hartman, 2001; Luther, 2002; Taylor, 2002) as well as an improper selection of cooling coils, control valves, setpoints and controls, such as not closing the shut off valves when the air handling unit's (AHU) fans shut off (Taylor, 2002). Moreover, oversized valves, undersized actuators (Luther, 2002) along with valve and actuator combinations unable to operate at system pressures (Griffith, 1987), are additional potential causes of the low delta-T syndrome in chilled water systems. G. Wang et al. (2006) emphasized the need of using 2-way control valves in the connected building to avoid a low delta-T during part load conditions and that bypass connections between the chilled water supply and return in the building CHW systems need to be eliminated.

The low delta-T syndrome is avoided by proper design and component selection, operation and maintenance (Lizardos, 1994; Taylor, 2002). For example, the DC distribution pipes have to be optimally sized, and the design chilled and condenser water temperatures have to be properly chosen (Taylor, 2011), something which could create problems with low delta-T when expanding an existing DCS. A proposed solution to the low delta-T is to install a check-valve in the bypass line between the chillers and the DC distribution system (Kirsner, 1998; Taylor, 2002). This solution has been experimentally tested and simulated, yielding energy savings in the DC system of 7-9% (Ma & Wang, 2011; S. Wang et al., 2010). Also, as opposed to a check valve, a differential bypass valve between the chiller loop and the connected cooling loads has been evaluated together with a sensor fault detection and diagnosis (SFDD) method applied to the return water temperature sensor in the chiller loop. The SFDD method was able to detect faults such as drift and precision degradation and could also be used to find relationships between sensor reading datasets thorough data clustering (Luo et al., 2019).

Several case studies or retrofit assessments on how to resolve the low delta-T in entire district cooling systems have been carried out on a variety of DCS with direct building connections. To find effective solutions to resolve the low delta-T, an overview of the system is necessary (Griffith, 1987). It is equally important to review the original chilled water design when determining the causes to low delta-T and proposing retrofit solutions, so that the cause of the problem can be resolved instead of simply treating the symptoms (Luther, 2002). Some of the proposed solutions from retrofit assessments of DCS included conversion from constant to variable flow in the distribution system and building chilled water system, elimination of throttling valves through the chillers, change of control logic of chiller operation, replacement of undersized pipes in the distribution loop, correction of unintentional short circuits, replacement of cooling coil control valves with calibrated two-way valves and reduction of the DC supply temperature to 5.5 °C (Hattemer, 1996; Hyman & Little, 2004; Kirsner, 1995; Kreutzmann, 2002; Reed & Davis, 2009; Taylor, 2006).

Sun & Liu (2009) performed a case study in which a hydraulic simulation was carried out based on a survey and measurements of the DCS. It was determined that the distribution loop delta-T was considerably lower than the design value, especially during part load conditions. The proposed solutions to the low delta-T included different end-user and central chiller plant retrofits as well as control system optimizations. Another DCS case study combined with simulations showed that having a higher temperature difference on the secondary side, compared to the primary side, lead to average monthly energy savings of 5-7% compared to DCS with equal temperature differences in both distribution system and the connected buildings' systems (Lee et al., 2012).

2.2.2 Systems with Heat Exchanger Separation

Previous studies on the low delta-T syndrome in DCS with heat exchanger separation have also been conducted. The DCS application of these studies has been a high-rise building where the primary purpose of the heat exchangers is to reduce the high static pressure. For this type of DCS, Gao et al. (2012) developed a fault detection and diagnosis (FDD) method for the low delta-T by detecting flow in the bypass line between the chiller loop and distribution system to the heat exchangers. It was shown that the low delta-T was caused by a too low setpoint of the outlet water after the heat exchangers. This led to a significant increase in chilled water pumping on the primary side of the heat exchangers which caused a low delta-T. The low delta-T increased when the setpoint on the secondary side of the heat exchangers was set to be reasonably higher in relation to the temperature on the primary side.

Later on, Gao et al. (2016) developed a control scheme to handle the low delta-T in the same high rise DCS. The control strategy limited the flow rate in the by-pass between the chiller loop and the distribution system to the heat exchangers, as well as it reset the supply temperature setpoint after the heat exchangers to follow the variations of the supply temperature before the heat exchangers. For the same high-rise DCS, Gao, Wang, Gang, et al. (2016) also developed a model-based method for practical implementation. The method was based on operational data of the DCS to evaluate low delta-T operation when the energy consumption of the chilled water pumps increased. The model was capable to predict normal energy use by the chilled water pumps and the system water flow rate if no low delta-T syndrome occurred by considering the load ratio of individual AHUs in the building chilled water system.

These studies show that issues related to low delta-T in DCS with heat exchangers separating the distribution system from the connected buildings become more complex to identify. Despite the multitude of proposed solutions and methods to resolve the low delta-T in district cooling systems the issue still prevails, something which may be closely related to the fact that no universal solution can be applied to all systems (Coad, 1998; Fiorino, 2002; B. J. Rishel, 1998). In the design phase of a district cooling system it is crucial to identify the types of loads to be served in the connected buildings. Also, the cooling loads need to be designed to achieve the return temperatures required by the district cooling system's production plant. This is something often overlooked, especially in the early establishment phase of a district cooling system where customers are recruited by disposing of an old chiller for which the building chilled water system has been designed for. For this reason, it is essential each DCS has connection standards for the buildings and their chilled water systems (Coad, 1998). Moreover, for the customers to invest in equipment that optimizes and improves the performance of their chilled water systems, incentivized DC chilled water rates are needed (Moe, 2005).

2.3 Building Chilled Water Systems

In commercial buildings, the need to provide cooling arises from the requirements of thermal comfort and indoor air quality such as defined by the European Standard EN 16798-3:2017 (CEN, 2017) and ASHRAE Standard 55 (ASHRAE, 2010). It is the task of the building's HVAC system to monitor and regulate the indoor environment and ensure that the requirements are fulfilled by suppling or removing heat and moisture (sensible and latent loads) as well as removing pollutants generated by internal loads and the occupants of the building.

When it comes to providing space cooling, the HVAC system can be divided into four types: all-air systems, water-air systems (commonly referred to as air-water in the US), all-water systems and unitary refrigerant-based systems (not included among the buildings studied in this licentiate thesis) (McQuiston et al., 2005; Nilsson, 2003). The HVAC systems in the buildings included in this thesis are grouped according to Figure 5. All-air systems include air handling units with 100% outdoor air and cooling coils, water-air systems are composed of active chilled beams supplied with chilled water and primary air from the ventilation system and all-water systems are composed of fan coil units supplied with chilled water, but no primary air.

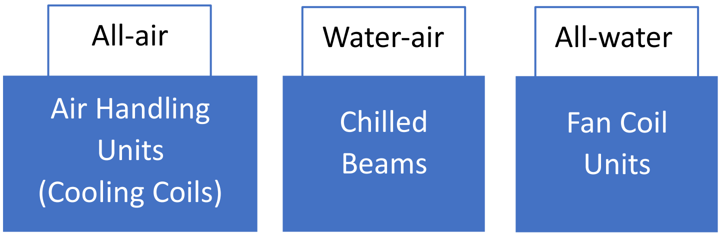

Figure 5: Classification and type of building HVAC system among the buildings studied in this thesis.

In all-air systems, the indoor sensible and latent loads are removed together through cooling and dehumidification by the cooling coils. In order for dehumidification to occur, the chilled water temperature needs to be lower than the indoor air dew point temperature (Liu et al., 2013) and commonly used temperatures are therefore 6-7 °C. In water-air systems with chilled beams, the cooling process takes place without dehumidification and a supply water temperature above the dew point temperature of the air is required. Fan coil units can be equipped with a condensation removal system, which allows the supply water temperature to be less than the dew point temperature (Nilsson, 2003).

2.3.1 Faults & Low delta-T

Similar to previous studies on low delta-T in district cooling systems, there are many previous studies on the low delta-T that have instead focused on the components of the building chilled water systems, such as cooling coils and fan coil units along with different strategies to overcome the low delta-T. For example, equipping cooling coils in AHUs with pressure independent valves coupled with a delta-T management strategy can double the cooling coils' delta-T and increase the load-to-flow ratio (Henze et al., 2013).

Thuillard et al. (2014) investigated possibilities of mitigating delta-T degradation by first establishing the flow rate saturation zone for which the delta-T decreased due to an unnecessarily high flow rate without providing additional cooling capacity. The low delta-T was then mitigated with three different control strategies for individual cooling coils: limit of chilled water flow, limit of delta-T, or a combination of both. It was shown that the most effective strategy to avoid entering the saturation zone was by a combination of both flow and delta-T limitations.

Another flow limiting strategy was tested by Hartman (2001), where the flow through a cooling coil was controlled with a simultaneous monitoring of the return temperature. This was done because low delta-T can arise from overflow in individual cooling coils due to constantly changing pressure differentials. Similarly, Gao et al. (2011) developed a flow-limiting technique ensuring the water flow in the AHUs cooling coils not to exceed that of the chiller loop in the DC distribution system. Z. Zhang et al., (2012) simulated delta-T profiles with various waterside and airside conditions for cooling coils with different geometric configurations. The simulations showed that cooling coils exhibit a complex behavior which could be an explanation to why it is difficult to draw conclusions about the changing coil delta-T with changing cooling load. The flow limiting strategy to improve delta-T has also been tested on FCUs, where control valves were able to successfully limit the flow and improve delta-T, compared to using magnetic valves (Song et al., 2019).

Faults are common in the operation of HVAC systems and are many times the reason to low delta-T in the building chilled water system, which consequentially could be transferred to the district cooling system. Identifying and resolving such faults are something several previous studies have investigated and proposed solutions for. Valenzuela del Río et al. (2016) developed a machine learning algorithm to detect abnormalities in a building CHW system by clustering chilled water data to classify it as normal or abnormal. Zhang et al. (2015) categorized different techniques to analyze data from building CHW systems supplied by district cooling, with the gol to identify better operational settings or operational faults to address. Gao, Wang, Shan, et al. (2016) developed a system level fault detection and diagnosis method to detect and diagnose the low delta-T syndrome in an HVAC system due to performance degradations of the AHUs and the heat exchangers.

Focusing on the impact of cooling coils in HVAC systems, Yan et al. (2018) developed a fault detection and diagnosis method to identify possible causes of the low delta-T issue. It was based on a simplified cooling coil model to analyze the impact of operating parameters. The load distribution characteristic (also called coupling effect) between the different cooling coils was shown to be a critical factor influencing the chilled water system delta-T. These results serve as an explanation as to why the chilled water system delta-T always is lower than the delta-T of individual cooling coils, especially during part load operation. Chang et al. (2014) investigated the coupling effect of a chilled water system with fan coil units. This study also showed the delta-T was reduced during part load when a high coupling factor between the FCUs was present. The low delta-T occurred because of the chilled water being redirected to the end terminals with open valves, from the end terminals with closed valves.

These previous studies show that problems with low delta-T and faults in HVAC systems can be resolved by different operating strategies. However, in order to know what operation strategy to implement it is crucial to first establish the causes of low delta-T and how the faults in building chilled water systems affect the primary side of the district cooling system.

2.3.2 High Temperature Cooling Systems in Buildings

High temperature cooling systems are a modified cooling technology that can improve the efficiency of the cooling process. This technology has rapidly advanced in the past decade through research and evaluation of proposed methodologies and applications (Jiang et al., 2015; Li et al., 2014; Schmidt, 2009). In HTC systems, the sensible and latent cooling loads are decoupled and individually controlled by temperature and humidity independent control (Liu et al., 2013). A high temperature water-based cooling system such as radiant panels, handles the sensible cooling load. This system supplies chilled water temperatures of approximately 16 °C and up, compared to conventional temperatures of 6-8 °C. The dehumidification is managed by a separate ventilation system (Liu et al., 2013; Saber et al., 2016).

Iyengar et al. (2013) performed laboratory tests on an HTC system with a decentralized ventilation and sensible radiant cooling in Singapore. The HTC system was able to successfully remove the sensible loads and dehumidify the incoming outdoor air. Saber et al. (2014) tested a radiant cooling system coupled with a decentralized dedicated outdoor air system in a laboratory located in a tropical climate. Chilled water supply temperatures of 8-14 °C were used for the ventilation system and 17-19 °C for the radiant panels. It was shown that the ratio of sensible to latent cooling loads was approximately 0.5 and that the sensible heat ratio increased to 0.6 in the afternoon, where 30% of the sensible cooling load was handled by the supply air units and the remainder by the radiant panels.

High temperature cooling systems have been installed in various commercial properties (T. Zhang et al., 2014) and previous studies have evaluated their operation. Zhao et al. (2011) evaluated the operation of an HTC system in an office building in Shenzhen, China. The latent loads were removed by a liquid desiccant outdoor air handling unit driven by heat pumps, and chilled water temperatures of 17.5 °C were supplied to dry fan coil units and ceiling panels to handle the sensible loads. The HTC system was able to achieve significant energy-savings compared to a conventional HVAC system, at the same time as a comfortable indoor environment was provided despite hot and humid outdoor conditions.

In a study by Lun Zhang et al. (2015), a radiant floor cooling system coupled with displacement ventilation was compared with a conventional jet ventilation system for two different airport terminals. The radiant cooling system was supplied by 16-20 °C chilled water and the ventilation system comprised a liquid desiccant outdoor air handling unit. The results showed that the HVAC energy utilization was 34% less in the HTC system compared to the conventional system. This was made possible by reducing the losses from mixing of hot and cold fluids, and by removing the heat gain from solar radiation directly.

Filipsson et al. (2020) evaluated the operation of an HTC system in a Swedish office building along with the indoor air temperatures. The HTC system consisted of self-regulating active chilled beams supplied by a chilled water temperature of 20 °C, and air handling units for dehumidification supplied by 17 °C chilled water. It was demonstrated that the HTC system could provide the building with enough cooling without exceeding desired indoor air temperature levels during the record warm summer of 2018. These previous studies on HTC systems demonstrate that although conventional low temperatures may be required for latent loads, cooling of indoor spaces can comfortably be achieved by higher temperatures as well.

High temperature cooling systems in buildings enable usage of new types of cooling sources, such as coupling to the ground for free cooling (Filipsson et al., 2020), utilization of cooling towers for free cooling and more efficient low temperature lift chillers (Liu et al., 2013; Saber et al., 2016; Seshadri et al., 2019). For example, a chilled water temperature of 16 °C reduces the temperature difference between the refrigerant's condensing and evaporating temperatures in the chiller, which increases the coefficient of performance (COP) around 50%, compared to conventional chillers supplying 7 °C chilled water (T. Zhang et al., 2014). Also, it has been shown that the COP and cooling capacity of a mechanical vapor chiller can improve about 3.5% for each 1 °C of increased chilled water temperature (Thu et al., 2017).

With the technological development of HTC systems in buildings advancing, it is important DC utility owners support this development with incentives for the customers. This is to avoid foregoing any new customers or experiencing a withdrawal of existing customers that choose HTC systems for their buildings. Moreover, if a majority of the DC customers implements HTC systems in their buildings, supplying a low conventional DC temperature of 6 °C may become redundant and inhibit a larger share of natural free cooling to be used.

Chapter 3: Research Methodology

In this chapter, an elaboration of the research methodology is provided with departure in the worldview guiding the researcher. This establishes the foundation for the research strategy chosen, which successively serves as a justification for the chosen research and data collection methods, in conjunction with background information about the applied district cooling system used in the study. Lastly, the data analysis method is explained in detail.

3.1 Theoretical Framework

Research is the systematic process of establishing knowledge that does not yet exist within a field, thereby expanding the prevailing knowledge base with a novel contribution (Deb et al., 2019). This systematic process involves a set of methods or tools to reach the end goal of establishing new knowledge. The research methods should not be confused with methodology, which is the theoretical and philosophical assumptions behind the methods and that which is being investigated. The methodology provides the foundation to the choices made in the research process since it influences the researcher's ideas on what methods to use. It involves the philosophy of science grounded in questions concerning epistemology and ontology, where ontological questions concern the study of things that exist in the world and epistemological questions are about what constitutes knowledge (Ahmed et al., 2016; Chalmers, 1999).

Answers to epistemological and ontological questions are found within a paradigm, which is a belief system or worldview that guides the researcher (Ahmed et al., 2016). Examples of paradigms are idealism, realism and pragmatism which contain different ontological beliefs about the study of things that exist in the world. Idealism and realism are two opposing positions, whereas pragmatism is an ontological neutral position (Yu & Strobel, 2011). Pragmatism allows the researcher to focus on the problem and adopt any approach to understand it (Creswell & Creswell, 2018). The research in this thesis is conducted within the field of applied engineering where a problem (low delta-T and low temperatures), encountered in the operation of an engineered system (the district cooling system) is being studied. For this reason, pragmatism is the worldview guiding this research process.

The intended audience of the research also shapes the choice of the research design (Creswell & Creswell, 2018). The primary intended audience for this thesis is utility companies, such as Göteborg Energi AB, who own and operate district cooling systems. The vision for this thesis is therefore to bring some practical value and applicability for utility companies to further improve the operation of their district cooling systems. Also, the scientific community, conducting research on district cooling systems and smart energy systems, is also an intended audience of this thesis.

3.2 Research Strategy

The research strategy is chosen based on the above theoretical framework, but also according to the nature of the problem (Creswell & Creswell, 2018). Based on previously established knowledge of the problems investigated in this thesis, both sides of the system (the district cooling system and the connected buildings) need to be investigated. The problems (as described in section 1.3) are related to the operation of both the district cooling system and the connected building. The strategy to investigate the problem is therefore chosen based on the type of data available from the system, which is empirical operational data, based on measurements of reality.

Different methods of reasoning to build or test theory are undertaken depending on the nature of the research and the data it is based upon. Such methods include induction, deduction and abduction. Abductive reasoning is a combination of deduction and induction (Ahmed et al., 2016), where deductive reasoning is used when a hypothesis is tested. In inductive reasoning, the point of departure is observations made or facts from which theories are derived from detecting patterns (Creswell & Creswell, 2018). As already mentioned, empirical data, based on measurements from the reality, is used in this research. Given this type of data, inductive reasoning is therefore the chosen research approach to first systematically investigate the data and then build a theory upon it.

With this research approach, the research activities can be categorized as exploratory, descriptive and explanatory. Exploratory research refers to the stage in which data about a certain phenomenon is collected with the output being possible associations between variables. Descriptive research involves describing patterns based on the exploratory phase, with the goal of developing empirical generalizations. Explanatory research involves the development and testing of explicit theory based on the empirical generalizations (Peecher & Solomon, 2001). The research activity is closely linked to the type of research question posed. Therefore, based on the research questions in section 1.4.1, the research approach of this thesis is a combination of exploratory and descriptive research activities to attempt to provide answers to them. In Paper I, the focus is on the descriptive stage of the research, whereas the focus of Paper II lies in the exploratory phase.

3.3 Gothenburg District Cooling System

District cooling in Gothenburg, Sweden (57.7089° N, 11.9746° E) was established in 1993 by installing distributed cooling islands throughout the city. In 2002, the cooling islands were connected by underground pipelines into a network which today is about 30 km long. The district cooling system is currently composed of two separate networks, which can be seen in Figure 6, along with two remaining cooling islands (not shown). The larger of the two networks has an installed capacity of 54.7 MW and supplies the central downtown area of Gothenburg towards the south. The smaller network supplies the commercial area of Lindholmen on Hisingen with a total installed capacity of 15.6 MW. The work with connecting the two systems with a pipeline underneath the river will be completed in 2021 and is part of a 15-year plan of doubling the total installed capacity, based on a projected increase of the cooling demand in the city.

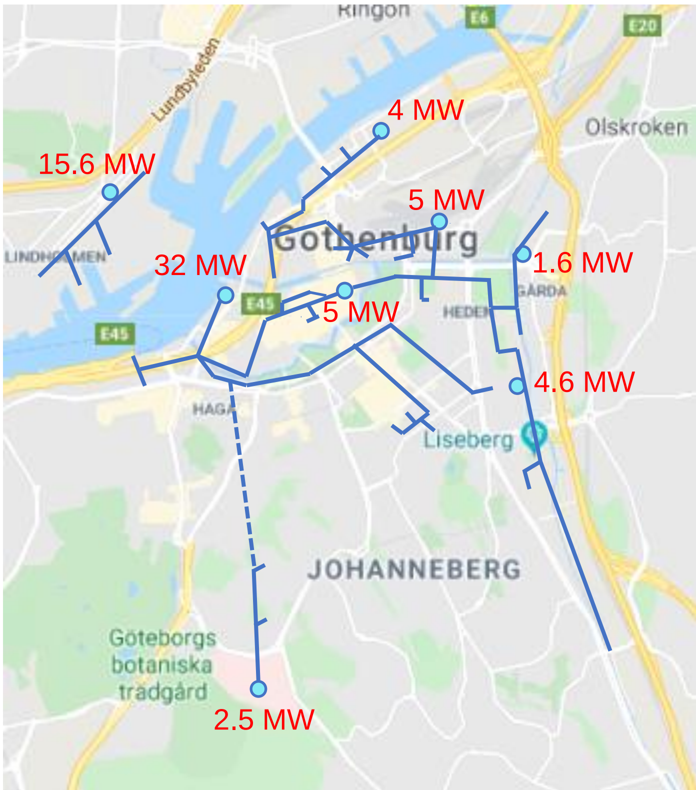

Figure 6: Map of Gothenburg district cooling system with approximate locations of pipelines and chilled water production units.

In the base load plant in the larger system, free cooling is available via heat exchangers between the river and the district cooling system. Free cooling is utilized 100% when the temperature of the river is ≤ 5 °C, which occurs from December to April. When the river temperature is > 5 °C, it pre-cools the returning DC water prior to entering the compressor chillers. The chilled water production mix, when the river temperature is more than 5 °C, consists of absorption chillers utilizing district heating and electric compression chillers. The annual chilled water production is based on approximately 47% absorption chillers, 31% compression chillers and 22% free cooling. Compared to the Swedish national DC production mix, the share of absorption chillers in Gothenburg DCS is significantly higher, which is a result of abundant waste heat in the district heating system in the summer.

The cooling demand of the connected buildings is to a large extent dependent on the outdoor temperature and varies between different years depending on the outdoor air conditions. In Figure 7, the aggregated annual cooling demand of the connected energy transfer stations in Gothenburg DCS can be seen for the year of 2018. The data is based on hourly average values, with a maximum hourly demand of 56.6 MW.

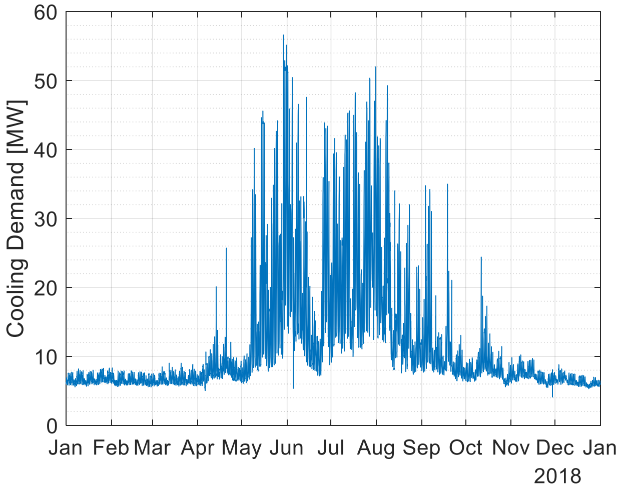

Figure 7: Cooling demand of 2018 based on all connected energy transfer stations connected to Gothenburg district cooling system. The data is based on hourly average values.

Both the large and the small district cooling system are designed for supply and return temperatures of 6 and 16 °C from May to October (Göteborg Energi AB, n.d.). In Figure 8, the supply and return temperatures to and from the base load production plants of both systems can be seen from April to October of 2018. The supply temperatures deviate slightly from the design temperature, whereas the return temperatures never reach the design level of 16 °C and instead are approximately 12 °C from May in the larger system and 14 °C in the small system, with 24-hour fluctuations depending on day- and nighttime operation.

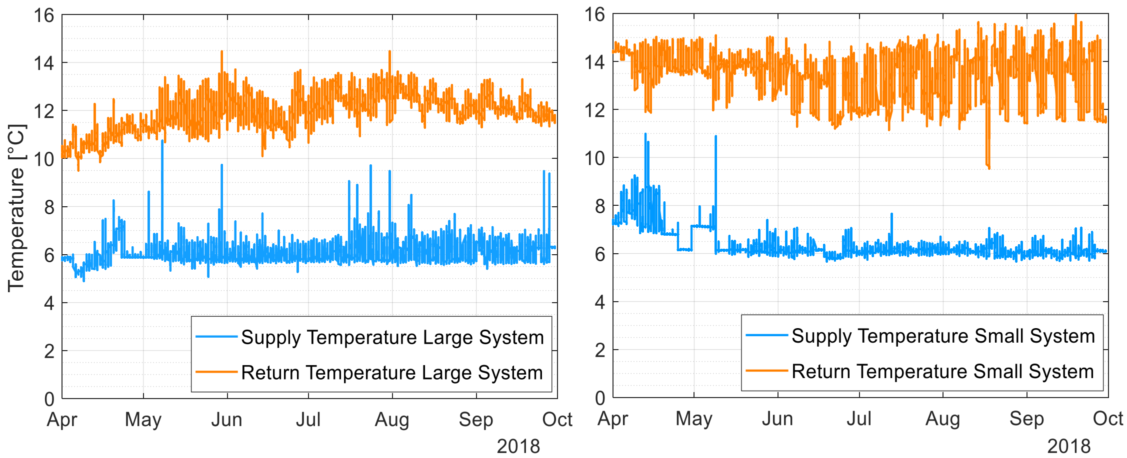

Figure 8: Left: Supply and return temperatures of the large district cooling system and Right: the small district cooling system. The temperatures are measured at the base load production plants during the months of April to October of 2018.

There are approximately 160 buildings connected to both district cooling systems. All buildings are commercial and the type of business in the buildings range from offices, retail, restaurants, education facilities, cultural and recreational activities as well as hotels and hospitals. In this licentiate thesis, 37 of these buildings, belonging to seven of the largest property owners in Gothenburg, are included from which data has been individually collected. Almost all buildings, with the exception of a couple of older ones, have one connection point to the DCS which is in the energy transfer station, typically located in the basement of the building. The ETS is owned and maintained by the property owner, although the utility provider owns and maintains the energy meter on the primary side.

3.4 Data Collection Method

As explained above, the research strategy has been developed based on empirical data from both the district cooling system and some of its connected buildings. Since the district cooling system and the buildings are owned and managed by different entities, the data availability and accessibility of the connected buildings was unknown in the initial design phases of the research strategy. However, the data availability of the district cooling system was known. The data collection method was therefore initiated by exploring the accessibility and availability of the potential data from the connected buildings. This was done by examining the connected buildings to the district cooling system and determining the most appropriate ones, primarily based on property owner. Property owners with four or more buildings connected to the district cooling systems were selected and contacted, and depending on interest, availability and the possibility of cooperating in the study, the buildings were selected.

The subsequent step in the data collection method was to obtain operational data from the buildings which owners had agreed to cooperate. Based on this method, the buildings included in this thesis have been selected, as opposed to conducting a random sampling. Ultimately, seven different property owners agreed to cooperate in this study and a total of 37 buildings were selected based on available and accessible data.

3.4.1 Data Availability

The data were collected from the databases of the district cooling provider and the property owners building management systems (BMS), see Figure 9 for location of temperature sensors and measurement equipment. The district cooling production plant data was obtained for the years of 2017-2018 and the data from the building energy transfer stations was collected from April-September of 2018.

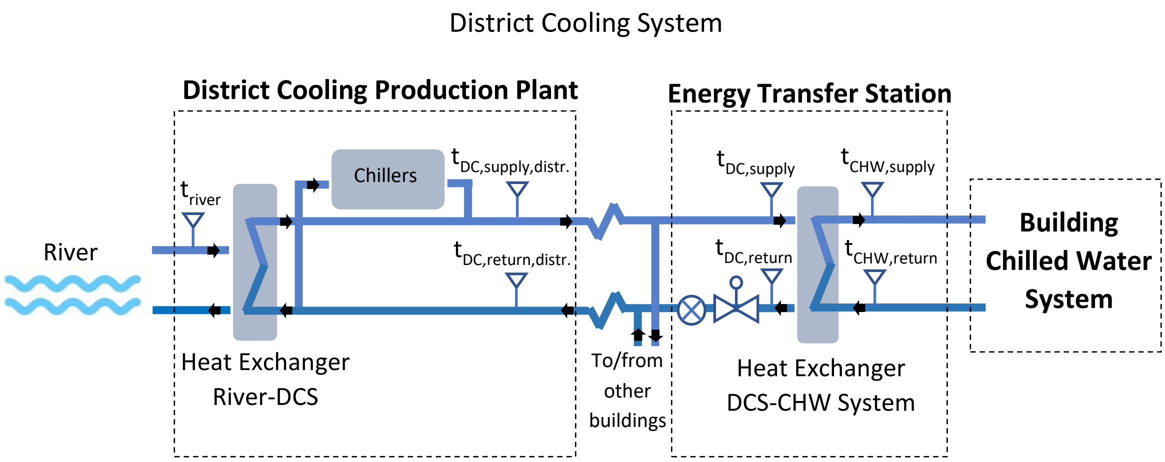

Figure 9: An outline of the district cooling system with production plant, energy transfer station and connected building chilled water systems. Each part of the system, marked with a dashed line, represents a section that has been investigated in this thesis for which data has been collected and analyzed.

The building ETS data were collected both from the district cooling provider, the primary side, and from the property owners BMS, the secondary side. The data type is automatic hourly meter readings as measured by permanently installed equipment. In Table 1, details of the measurements and equipment of the district cooling production plant can be found. In Table 2 and Table 3 information about the data from the building ETS is listed, collected both from the district cooling provider's database and the connected buildings' BMS.

Table 1: Data measured by permanently installed equipment in the district cooling plant and stored in the database of the district cooling provider.

Data Variables from District Cooling Production Plant	Unit	Measurement Reading Interval	Measurement Device
Generated cooling power from production plant, $\dot{Q}$	MW	1/h, hourly average	Energy Meter Integrator
Supply temperature, $t_{DC\ supply,\ distr.}$	°C	1/h, instantaneous	Thermowell RTD temperature sensor
Return temperature, $t_{DC\ return,\ distr.}$	°C	1/h, instantaneous	Thermowell RTD temperature sensor
River temperature, t_{river}	°C	1/h, instantaneous	Thermowell RTD temperature sensor

Table 2: Data collected from the district cooling side of the heat exchangers in the energy transfer station, as measured by permanently installed equipment and stored in the database of the district cooling provider.

Data Variables from Primary Side of Energy Transfer Station	Unit	Measurement Reading Interval	Measurement Device
Cooling power, $\dot{Q}$	kWh/h	1/h, hourly average	Energy meter integrator
Chilled water flow rate, $\dot{V}$	m^3/h	1/h, hourly average	Ultrasonic flow sensor
Supply temperature, $t_{DC,\ supply}$	°C	1/h, instantaneous	Thermowell RTD temperature sensor
Return temperature, $t_{DC,\ return}$	°C	1/h, instantaneous	Thermowell RTD temperature sensor
Delta-T between supply and return, Δt_{DC}	°C	1/h, instantaneous	Energy meter integrator

Table 3: Data collected from the building chilled water systems, as measured by permanently installed equipment, stored by each building management system.

Data Variables from Building Management Systems (BMS)	Unit	Measurement Equipment
Control valve signal	%	2-way pressure balanced globe valve
Outdoor temperature, t_{out}	°C	RTD temperature sensor
Supply temperature, $t_{CHW,\ supply}$	°C	Thermowell RTD temperature sensor
Return temperature, $t_{CHW,\ return}$[1]	°C	Thermowell RTD temperature sensor
Supply temperature subsystems (cooling coils, FCUs, chilled beams)[1]	°C	Thermowell RTD temperature sensor
Return temperature subsystems (cooling coils, FCUs, chilled beams)[1]	°C	Thermowell RTD temperature sensor

[1]Not available in all buildings investigated.

3.4.2 Data Uncertainty

Any misrepresentative data, indicating that the building chilled water system is turned off or that the building's cooling demand almost is zero has been removed. This included removal of data points when the chilled water flow rate was less than the lowest interval of the flow meter as well as data measurements for when the signal from the control valve actuator was zero.

Some of the downloaded data was corrupt or missing, for example, due to loss of connection between measurement equipment and storing software. The data were recorded during 2017 and 2018 with summer conditions that differed significantly. The summer of 2018 was much warmer than normal, with a total of 25 days with outdoor temperatures > 25 °C and a maximum recorded outdoor temperature of 34.1 °C. The summer of 2017 had a maximum temperature of 26.3 °C and only nine days with outdoor temperatures > 25 °C (SMHI, n.d.).

The energy meter in each energy transfer station is based on European Standards EN 1434 and has an accuracy of ±0.5%, typical for district cooling applications (Tredinnick & Phetteplace, 2016). The temperature sensors are based on standard EN 60751 and have accuracies of ±0.4% and a resolution of 0.01 °C. For a temperature difference of 10 °C, the standard allows deviations of the energy meter up to ±0.8% and ±1.4% for the temperature sensors. The maximum tolerance for the water flow is 5%, but according to Swedish standards, flow meters are allowed a higher tolerance in operation. Measured water flow rate data less than the lower operating range, q_i, for each flow meter was removed during the data preprocessing step.

The uncertainty of the energy meter is also related to the resolution of the integrator, which either is high (decimals) or low (integers in increments of 10 or 100 kW). For energy transfer stations with a low-resolution integrator, the cooling power was instead calculated based on measured temperature difference and water flow rate. Potential sources of error for the temperature measurements originate from the fact that the sensors are paired and not individually calibrated with respect to the absolute temperature.

Although there is a wide variety of measurement equipment manufacturers among the studied buildings, all water temperatures have been measured by RTD temperature sensors, immersed in the pipes with accuracies of ±0.3-0.4 °C. The outdoor temperature sensors have an accuracy of ±0.3 °C. However, the main source of error for the outdoor temperature is the location of the sensor.

3.5 Data Analysis Method

Many previous studies of DC temperatures, and specifically the low delta-T, have been approached by deductive reasoning. For example, in papers developing fault detection and diagnosis strategies to overcome the low delta-T syndrome, a hypothesis on what is causing the low delta-T has been investigated. The low delta-T has also been explored based on theoretical inductive reasoning, however, generally, little time has been spent on exploratory data analysis (C. Zhang et al., 2018). As described in section 3.2, induction is the chosen method of reasoning in this thesis to build theory from the data. Moreover, with the goal of this thesis being of practical application, exploratory data analysis (Tukey, 1977) combined with data visualization (Sahay, 2017) and domain knowledge, were chosen as the data analysis method. Data visualization has previously been used in a study by Valenzuela del Río et al. (2016), where the visualization of operational data provided general trends and an initial identification of abnormalities of the building CHW data. Also, in a study by Thuillard et al. (2014), visualization was used to investigate the saturation zone of the chilled water data.

The visualization and analysis of the data have been combined with domain knowledge (also referred to as tacit knowledge) of the chilled water systems. The tacit knowledge was mainly incorporated by means of workshops where both utility provider and building owner provided input based on their experiences and knowledge to the visualization of the chilled water data and the patterns identified. Based on this tacit knowledge, the exploratory data analysis has been inductively analyzed to describe the patterns identified with the aim of developing empirical generalizations.

3.5.1 Data Visualization

According to Linyu Zhang et al. (2015), an effective way of visualizing measured building chilled water data is to utilize multivariate visualization with different data variables plotted against each other. By using this method, it has previously been established that important variables for analyzing the operation of building CHW systems are chilled water flow rate, cooling power and outdoor temperature (Valenzuela del Río et al., 2016). Based on this, but also limited to the available data as summarized in Table 1, Table 2 and Table 3, the chilled water data has in this thesis been visualized accordingly:

1) **Performance of primary side of energy transfer station**:
   The variables cooling power $\dot{Q}$, primary delta-T Δt_{DC}, and chilled water flow rate $\dot{V}$, are measured by the DC provider and available from the primary side of each ETS (see Table 2). These variables have therefore been selected to analyze the performance of the ETS from the primary side based on the method utilized by Thuillard et al. (2014), with cooling power and chilled water flow rate being normalized. The purpose with this graph is twofold: 1) to determine the performance of the ETS by identifying the trend of delta-T with an increasing chilled water flow rate and 2) find the best performance point of the ETS and identify the saturation zone. The capacity of the heat exchanger in the ETS is a non-linear function of the flow rate due to the impact of delta-T and is related to the chilled water flow being constant or variable on either or both sides of the heat exchanger. For a variable flow on both sides of the heat exchanger, delta-T slightly decreases for an increased flow (Skagestad & Mildenstein, 2002). For a certain chilled water flow rate, the cooling power transferred across the heat exchanges reaches a maximum. However, the amount of chilled water required to increase the cooling power from 90% to 100% could be disproportionately large. In the study by Thuillard et al. (2014), a reference point at 85% normalized cooling power was used. To find the best performance point of the energy transfer stations in this study, a normalized cooling power of 90% has been selected. The highest delta-T for this cooling power was identified and the corresponding flow rate. This point is referred to as the best performance point, where an increase beyond 90% of the normalized cooling power can be considered only a marginal increase. Any chilled water flow beyond the best performance point does not contribute to an increased cooling power, but instead typically leads to a deteriorated delta-T and is therefore called the saturation zone (Thuillard et al., 2014), see area marked with a dashed line in Figure 10.

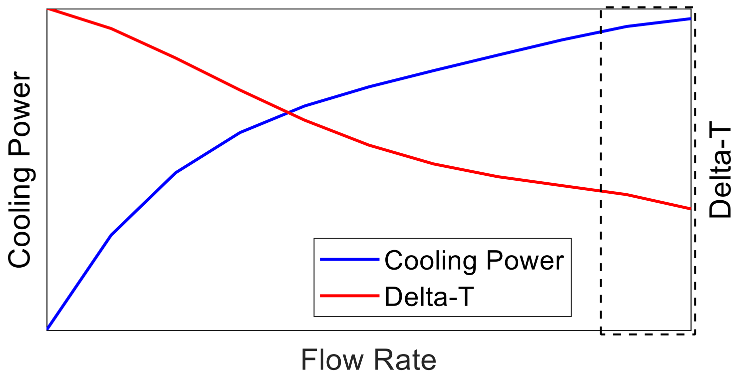

Figure 10: Illustration of saturation zone (area marked with dashed lines) for an increased cooling power, increased chilled water flow and with decreasing delta-T.

2) Comparison of primary and secondary sides of the energy transfer station:
In order to find the causes to a low delta-T on the primary side, it is crucial to analyze the temperatures on both sides of the heat exchanger in relation to an independent variable. According to the available data in Table 2 and Table 3, the independent variable could be cooling power, chilled water flow rate, control valve signal or outdoor temperature. As per the results of Valenzuela del Río et al. (2016), the outdoor temperature was identified as an important variable when determining the functioning of chilled water systems. It affects the cooling power of the buildings, although there are more variables influencing this as well, such as solar radiation and occupancy. However, using the outdoor temperature as the independent variable also enables a comparison between the different buildings and was therefore chosen as the independent variable for the visualization.

3) Buildings chilled water temperatures:
Box plots is an easy way to summarize large sets of data to display the most frequently occurring patterns (Tukey, 1977). For this reason, the information about the buildings chilled water supply and return temperatures have been visualized by means of boxplots for different outdoor temperatures.

4) District cooling generation from free cooling and chillers:
The data from the district cooling plant as described in Table 1, has been visualized annually for different supply and return temperature levels. The purpose of this is to explore the effects different temperature levels would have on the amount of free cooling as a share of the annual district cooling generation.

3.5.2 Heat Exchanger Temperatures

In order to analyze the visualized data from the energy transfer station, four different temperature differences need to be defined. According to Figure 11, (showing the temperature sensor locations in the ETS) there is one delta-T on either side of the heat exchanger, Δt_{DC} and Δt_{CHW}, as well as there is a temperature difference between the supply sides, Δt_1, and the return sides, Δt_2, of the heat exchanger.

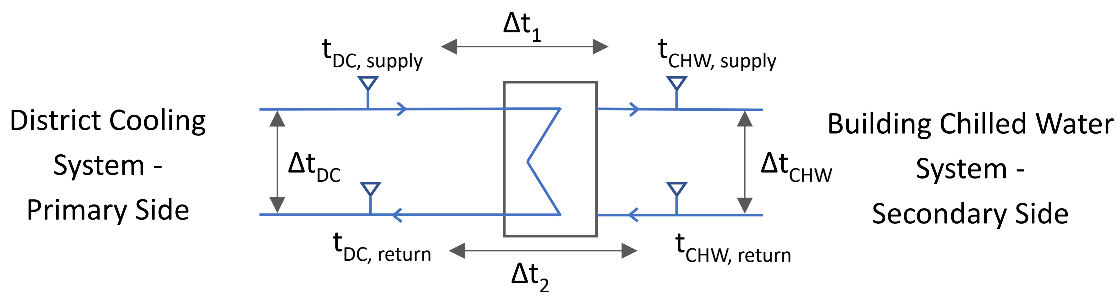

Figure 11: Temperature differences in the energy transfer station, separating the district cooling distribution system from the building chilled water system.

The temperature differences on either side of the heat exchanger are defined as:

$$\Delta t_{DC} = t_{DC,return} - t_{DC,supply} \tag{1}$$

$$\Delta t_{CHW} = t_{CHW,return} - t_{CHW,supply} \tag{2}$$

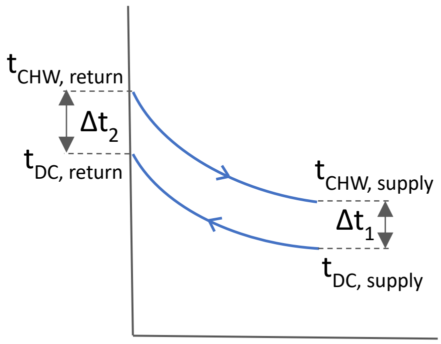

Figure 12: Temperature diagram for a counterflow heat exchanger.

The temperature differences between the supply and return sides of the heat exchanger, also called the temperature approaches across the heat exchanger, illustrated in Figure 12, are defined as:

$$\Delta t_1 = t_{CHW,supply} - t_{DC,supply} \tag{3}$$

$$\Delta t_2 = t_{CHW,return} - t_{DC,return} \tag{4}$$

The general design guidelines for DC connected building CHW systems suggest $t_{CHW, supply}$= 7-8 °C and $t_{CHW, return}$= 18 °C. Although the temperature approaches, Δt_1 and Δt_2, in a plate frame heat exchanger can be as low as 1 °C between single-phase streams (Thulukkanam, 2013), 1-2 °C is typically utilized for district cooling applications (Energiföretagen Sverige, 2019). With $t_{CHW, return}$ of 18 °C and Δt_2 = 2 °C, $t_{DC, return}$ of 16 °C is attainable according to Eq. (4).

Chapter 4: Results and Discussion

In this chapter, the results are presented combined with a discussion. They have been divided into three sections as marked in Figure 9, focusing on different parts of the district cooling system and its connected buildings as well as following the order of the appended papers. Section 4.1 includes the results pertaining to the data from the Energy Transfer Stations (paper I). In section 4.2 the results of the Building Chilled Water Systems are presented (paper I and II). Lastly, in section 4.3, the results from the District Cooling Production Plant are presented (paper II), exploring how the DC production is affected by higher temperatures in the district cooling system.

4.1 Energy Transfer Stations

The results from the energy transfer station of the 37 buildings studied include data from both the DC provider (primary side) and the building owners' BMS (secondary side). First, the primary data are shown, followed by a comparison of data from both primary and secondary sides. Only a few examples of some selected buildings are shown to illustrate the trends observed. A categorization based on building type was not possible since each building was unique with regard to building characteristics, business type, cooling demands, type of HVAC system, end terminals and HVAC system operation strategy.

4.1.1 Primary Side of Heat Exchanger

As described in section 3.5.1, the performance of the primary side of the heat exchanger has been analyzed by identifying different delta-T trends, the "best performance point" and the following saturation zone for each of the studied buildings energy transfer stations. The different delta-T trends across the chilled water flow rate range, with associated cooling power can be categorized into the following, with examples illustrated in Figure 13a-d:

a) Delta-T decreasing with increasing chilled water flow rate and cooling power (Building 8).
b) Delta-T mainly constant with chilled water flow rate and cooling power (Building 28).
c) Delta-T increasing (or slightly increasing) with increasing chilled water flow rate and cooling power (Building 23).
d) Others: none of the above trends observed (Building 17).

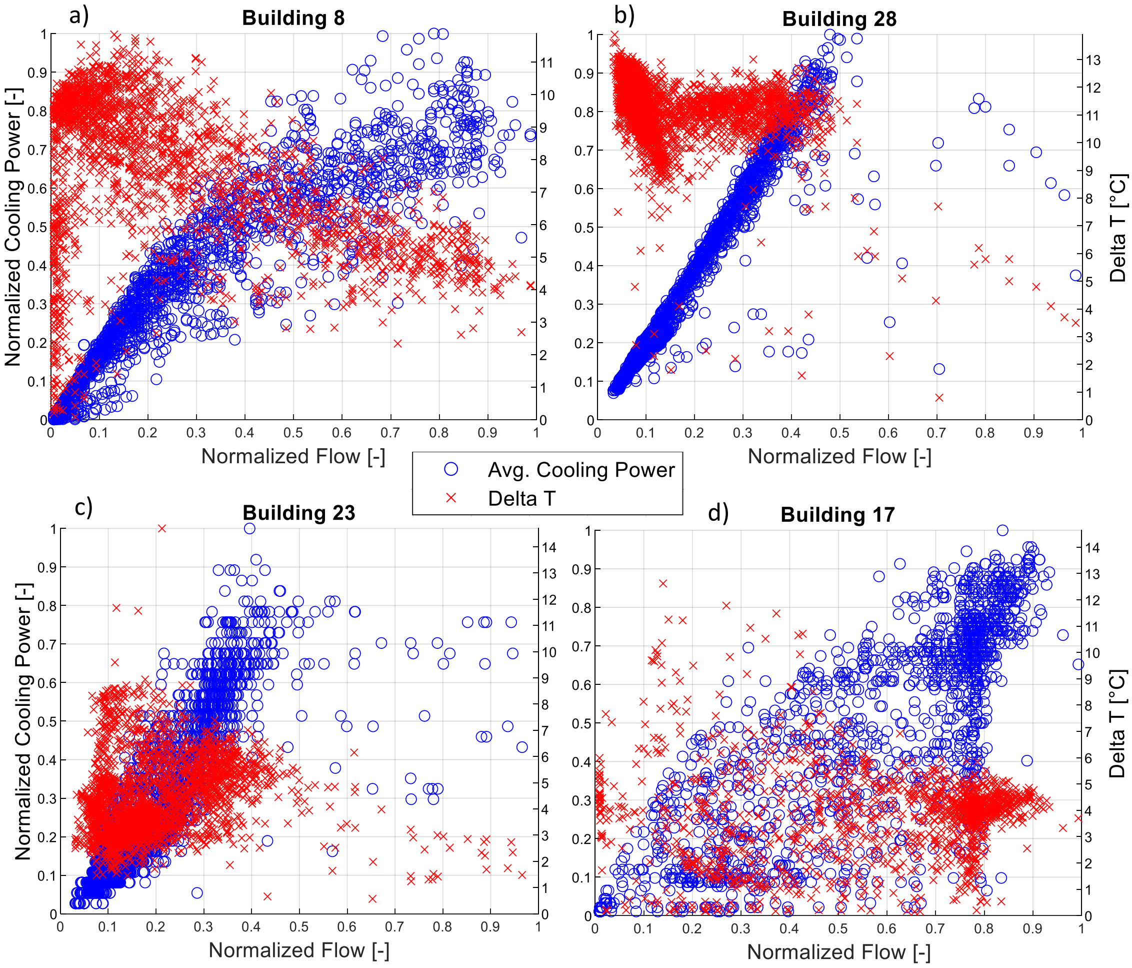

Figure 13: Performance of the primary side of the energy transfer station indicating different delta-T trends with increasing chilled water flow rate and cooling power: categories a)-d).

The worst performing ETS were found in categories c) and d) with mainly low primary delta-T's. The best performing ETS, with the highest primary delta-T's, were found in category b). In Figure 14, the share of each delta-T category among the studied buildings can be seen, with category a), a decreasing delta-T for an increased chilled water flow rate and cooling power, being the most common.

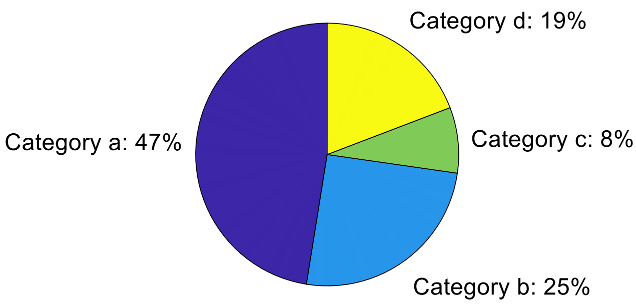

Figure 14: Share of each delta-T category among the studied buildings' energy transfer stations.

As explained in section 3.5.1, an increased chilled water flow rate that does not contribute to an increased cooling power, but instead leads to a deteriorated delta-T is called the saturation zone. This saturation zone can be seen in Figure 13a-d for flow rates beyond 90% or more of the cooling power, and it was also observed in almost all the studied buildings. The point for which the normalized cooling power is 90% or more, immediately prior to entering the saturation zone is the "best performance point." For each building ETS in Figure 13a-d, this point corresponds to a normalized flow rate of 0.62, 0.71, 0.41 and 0.63, along with a Δt_{DC} of 8.1, 11.5, 3.5 and 6.9 °C. What this means is that an increase in flow rate beyond the best performance point does not lead to a significant increase in cooling power, but instead causes Δt_{DC} to decrease below its maximum. This zone may be related to a low temperature approach between the supply sides, if the primary supply temperature for example increases during some hours without the secondary supply temperature following. A graphical representation of the best performance point of the studied buildings can be seen in Figure 15.

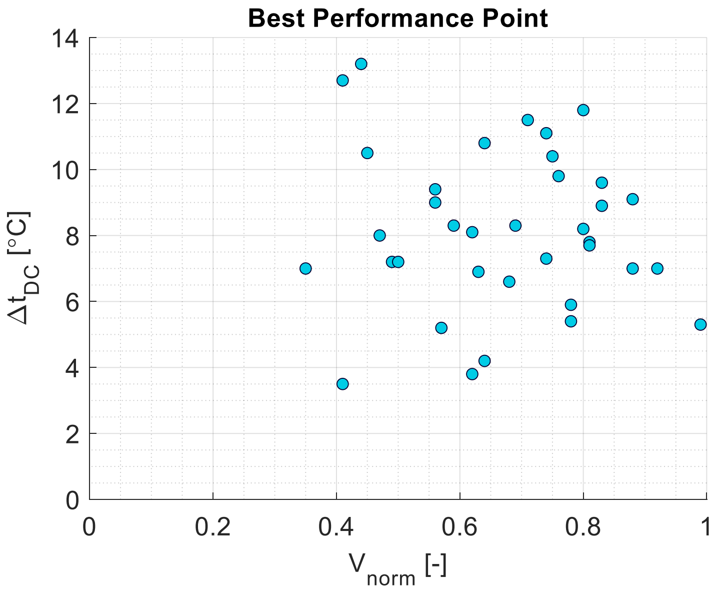

Figure 15: Best performance point of the studied buildings' energy transfer stations. Each point represents a delivered cooling power of 90% or more of measured maximum. Some buildings were omitted due to unrealistic temperature measurements and energy integrators with a too low resolution.

According to Figure 15, it is evident that a majority of the buildings can utilize a chilled water flow rate lower than the measured maximum to deliver a cooling power of 90% or more. For this reason, flow restrictions may be suitable to implement in the ETS to avoid operation in the saturation zone with an excessive water flow rate being utilized at the expense of a deteriorated delta-T.

4.1.2 Primary and Secondary Sides of the Heat Exchanger

As described above, a comparison between the temperature levels of both sides of the heat exchanger is presented in this section. The comparison makes it possible to investigate the causes of low delta-T on the primary side, since knowledge about the temperatures on the secondary side is needed in order to do so. For example, in Figure 16a, the primary delta-T (Δt_{DC}) starts to decrease for t_{out} > 19 °C. In contrast, the secondary delta-T (Δt_{CHW}) in Figure 16b starts to slightly increase for the same outdoor temperature. The reason for the low primary return temperature can be further investigated by calculating the temperature approaches, Δt_1 and Δt_2, as described in section 3.5.2. For $t_{out} \geq 25$ °C, the average Δt_1 is 0.5 °C with a corresponding average Δt_2 of 7 °C. This shows that a low temperature approach between the supply sides of the heat exchanger causes a large temperature approach between the return sides and consequently a low delta-T on the primary side. A potential reason to this could be that the $t_{CHW,\ supply}$ setpoint is too low in relation to the $t_{DC,\ supply}$. This then results in a $\Delta t_1 \leq 2$ °C and consequently causes a low Δt_{DC} due to an increased primary chilled water flow rate, as correspondingly shown by Gao et al. (2012). To resolve the issue with low primary delta-T in such ETS', Δt_1 needs to be increased by ensuring the setpoint of the secondary supply temperature is kept at a minimum of +2 °C above the primary supply temperature at all times, as recommended by the DC design guidelines (Energiföretagen Sverige, 2019).

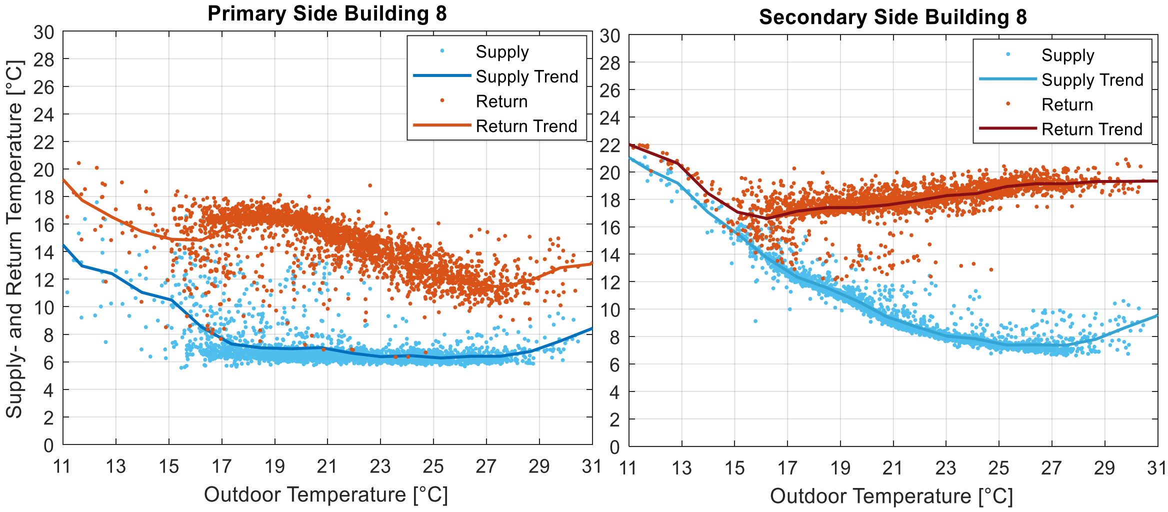

Figure 16: Supply and return temperatures shown as a function of outdoor temperature for Building 8. Left (a): Primary side chilled water data as measured by the DC provider. Right (b): Secondary side chilled water data as measured by the BMS.

In Figure 17b, the building CHW system delta-T, Δt_{CHW}, is very low for all outdoor temperatures, in contrast to Figure 16b. However, Δt_{DC} on the primary side of the heat exchanger does not deteriorate with an increasing outdoor temperature, but remains fairly constant between 6-9 °C. This could be explained by the low temperature approach between the return streams on both sides of the heat exchanger, Δt_2, which is an average of 0.6 °C for $t_{out} \geq 25$ °C. Simultaneously, the temperature approach between the supply streams, Δt_1, is 3.6 °C for $t_{out} \geq 25$ °C, much larger than the DC design guidelines of 1-2 °C (Energiföretagen Sverige, 2019). Therefore, a large Δt_1 allows for a $\Delta t_2 \leq 2$ °C, which in turn enables the highest possible $t_{DC,\ return}$ for this ETS. However, the primary return temperature in building 3 is lower than 16 °C, and to resolve the low Δt_{DC} issue a higher $t_{CHW,\ return}$ needs to be achieved by upgrading the CHW system.

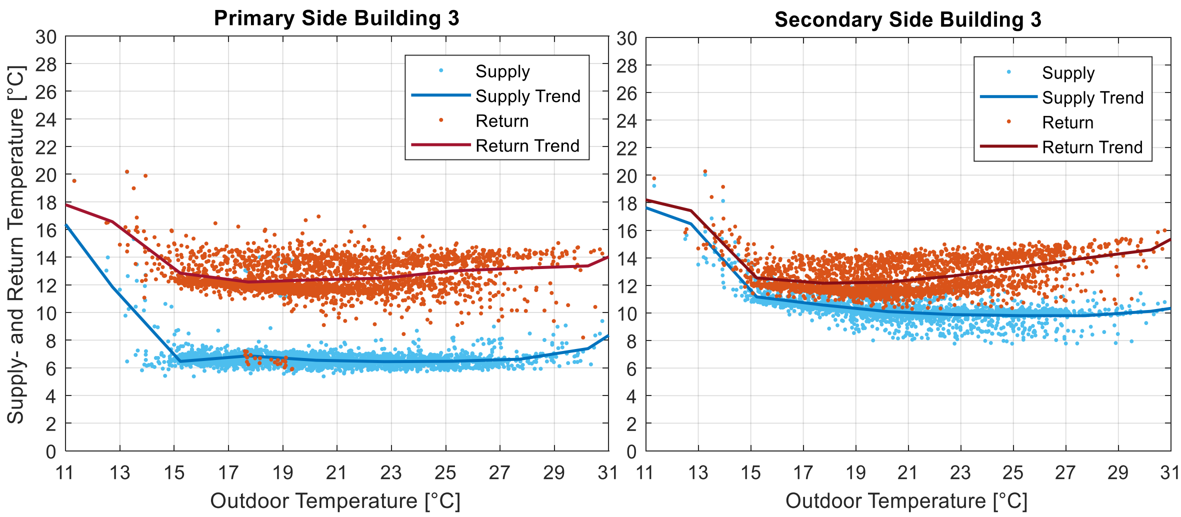

Figure 17: Supply and return temperatures shown as a function of outdoor temperature for Building 3. Left (a): Primary side chilled water data as measured by the DC provider. Right (b): Secondary side chilled water data as measured by the BMS.

In Figure 18, temperature approach, Δt_2 can be seen as a function of temperature approach Δt_1 for 26 of the investigated buildings' energy transfer stations. The temperature approaches are average values for $t_{out} \geq 25$ °C.

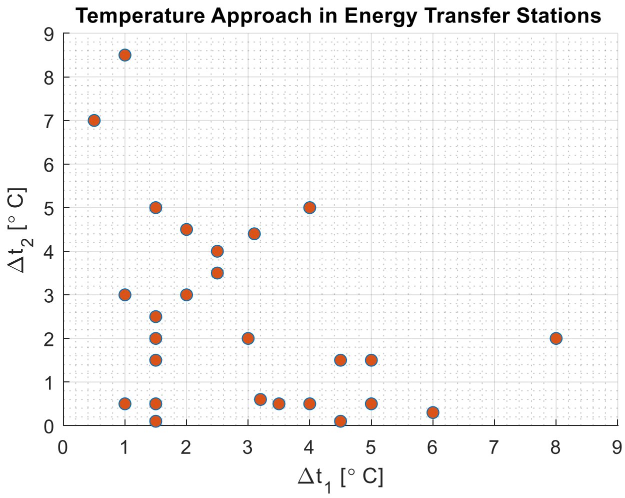

Figure 18: Temperature approach between supply streams of the heat exchanger, Δt_2, as a function of temperature approach between the return streams, Δt_1, for 26 of the investigated buildings' energy transfer stations.

According to Figure 18, six buildings had an average $\Delta t_1 \geq 2$ °C, but also an average $\Delta t_2 > 2$ °C. These six buildings also have primary return temperatures of 15 °C or less for $t_{out} \geq 25$ °C. For these six buildings, a large Δt_1 is insufficient to achieve high primary return temperatures. Potential reasons could be fouled heat exchangers which require a higher Δt_1 to achieve a lower Δt_2, or that the building CHW system needs to be upgraded through revised control strategies, balancing of the system and potentially replacing components.

Nine of the buildings in Figure 18 had an average $\Delta t_1 > 2$ °C which was associated with an average $\Delta t_2 \leq 2$ °C. The primary return temperatures for these buildings were between 13 and 17.5 °C which correspond to the highest possible $t_{DC,\ return}$ for these ETS'. The remaining buildings in Figure 18 had an average $\Delta t_1 < 2$ °C, out of which five buildings had a corresponding average $\Delta t_2 \leq 2$ °C and five had a $\Delta t_2 > 2$ °C. All these buildings had primary return temperatures of 14 °C or less. However, three of the buildings with $\Delta t_2 > 2$ °C had average building CHW return temperatures of 17.5 °C or more which were not transferred to the primary side, potentially due to Δt_1 being less than 2 °C.

Based on the above analysis, it is crucial to evaluate the temperature approaches of the heat exchanger to determine its performance and to evaluate potential causes to the low delta-T. For some ETS', the recommended temperature approach of 2 °C is inadequate to avoid a low primary delta-T. For such ETS, a more in-depth evaluation of the heat exchanger as well as the building's chilled water system needs to be done. For ETS' where the primary return temperature is reduced as a result of a $\Delta t_1 < 2$ °C, an adjustment of the secondary supply temperature setpoint may be a sufficient solution to resolve the low primary delta-T issue.

It is also evident that the connection standards for the ETS and incentives for the DC customers, as pointed out by Coad (1998) and Moe (2005), have not been enforced or implemented for the connected buildings in Gothenburg district cooling system. On the contrary, this was not a suitable option to attract customers in the early development stages of the DCS in Gothenburg, where the progress was dependent on the number of new customers choosing district cooling instead of their own chillers.

4.2 Building Chilled Water Systems

In Figure 19, the supply (CHWS) and return (CHWR) temperatures of the studied buildings' chilled water systems are presented by means of boxplots. The temperatures have been measured on the secondary side of the heat exchanger in the ETS. The median value is represented by the middle line, the upper and lower limits of the box correspond to the upper and lower quartiles, and the dashed lines mark the maximum and minimum observations with the outliers (blue and red crosses) located below or above, extending more than 1.5 times the interquartile range away from the upper and lower quartiles.

As previously mentioned, the design guidelines recommend 8 °C for the CHW supply temperature. However, as can be seen in the left diagram in Figure 19, this value is found in the lower quartile for outdoor temperature categories 14 to 30 °C. This means that 75% of the recorded CHWS temperature values are higher than 8 °C. The lowest median CHW supply temperature occurs for t_{out}=28 °C and is equal to 9.3 °C. For the same outdoor temperature, 25% of the CHW supply temperatures are 11 °C or higher (corresponding to the upper quartile). This indicates that some building CHW systems use supply temperatures greater than 8 °C for summer outdoor conditions.

Another observation from Figure 19 is that the median CHW supply temperature decreases as the outdoor temperature increases, from approximately 13 °C to 9 °C from the lowest to the highest outdoor temperature category. This indicates that many CHW supply temperatures are outdoor temperature compensated, as described by Skagestad & Mildenstein, (2002), which was also confirmed by the information about the building CHW systems' operation. It was found that the CHW supply temperature was controlled in different ways depending on cooling demand and the type of business in the building as well as occupancy, end terminals and building management system. In general, three methods of regulating the CHW supply setpoint were found among the studied buildings: 1) constant,

2) outdoor temperature compensated and 3) calculated based on the building's cooling demand.

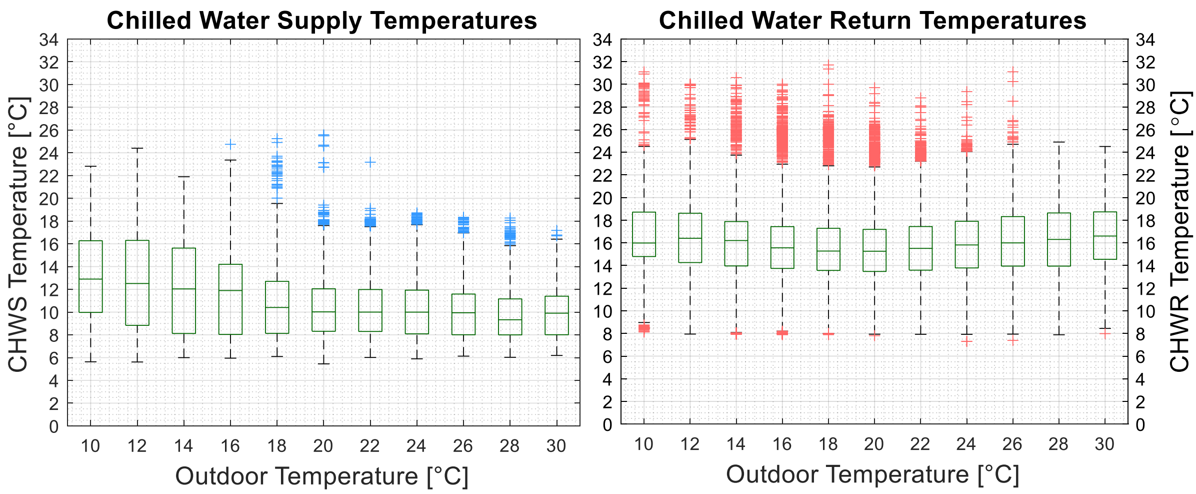

Figure 19: Boxplot of the building chilled water supply and return temperatures for 11 outdoor temperature categories. Each temperature category contains different numbers of data points due to different operating conditions among the buildings, where each data point is an hourly measurement recorded during April to September of 2018. Left: chilled water supply (CHWS) temperatures. Right: chilled water return (CHWR) temperatures.

For the CHW return temperatures in the right diagram in Figure 19, a larger spread among the values for all outdoor temperature categories can be observed, compared to the CHW supply temperatures. Moreover, with the design guidelines recommending the CHW return temperatures to be 18 °C, the upper quartile value is between 17.5-18.5 °C for all temperature categories, meaning that 75% of the CHWR temperatures are lower than the design guidelines. This indicates three potential scenarios: 1) the CHW systems have not originally been designed for district cooling; 2) the design guidelines have been disregarded; or 3) the operation of the CHW system needs to be revised and upgraded.

In Figure 20, a compilation is shown of the majority of the building chilled water systems' composition, with subsystems, end terminals and associated temperature ranges. The temperature ranges were based on average temperatures, when the outdoor temperature was ≥25 °C, for buildings with individual monitoring and data available for the subsystems. The CHW systems were typically composed of a combination of an all-air system with a water-air or an all-water system, with chilled beams or fan coil units as end terminals. A combination of all three types was also frequent. The cooling coils were located either inside the air handling unit (AHU) or in the supply air duct. Of the 37 buildings, three buildings had CHW systems with only cooling coils for AHUs and two buildings had CHW systems composed of only FCUs and/or chilled beams.

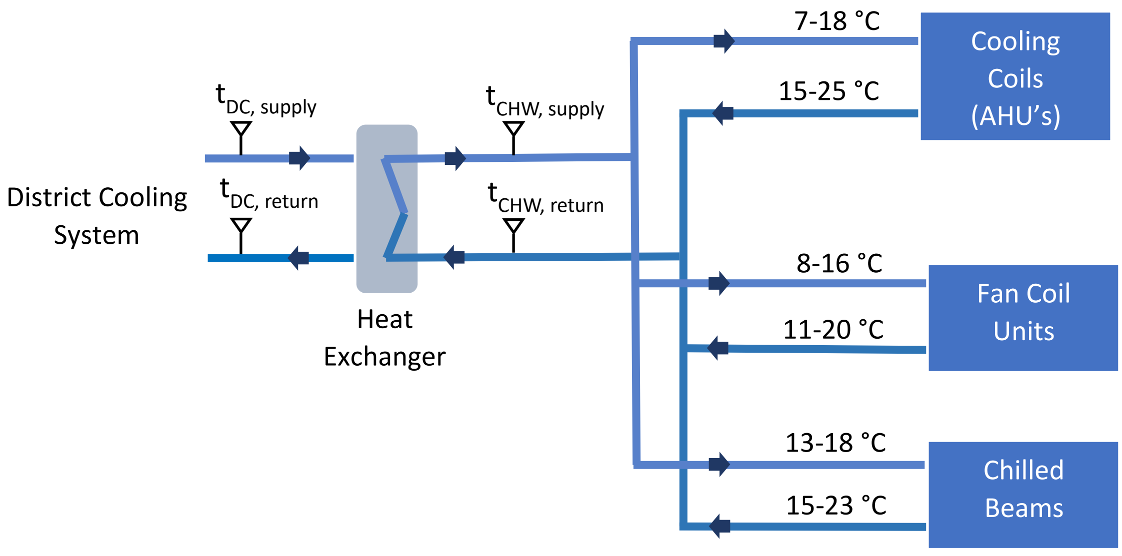

Figure 20: Typical composition of building chilled water systems connected to the district cooling system with subsystems and associated supply and return temperature ranges. The ranges are based on average temperatures for each subsystem with available data, as observed when the outdoor temperature is 25 °C or more.

The required chilled water temperatures in a building's chilled water system is decided by the type of end terminal installed. According to Figure 20, the supply temperature range was relatively large for the cooling coils. However, only eight buildings, with a total of 17 different subsystems, had individual monitoring with data available for the cooling coil temperatures. Out of these, only 11 subsystems measured the return temperature as well. The temperature ranges shown are for this reason based on only a few of the 37 buildings included in the study. For the remaining buildings without individual monitoring for the AHUs, the cooling coil supply temperature was the chilled water temperature as measured directly at the outlet of the heat exchanger ($t_{CHW,\ supply}$ in Figure 20).

Similar to the cooling coils, only six buildings with a total of 11 subsystems had separate monitoring of the FCUs. Some of the FCU subsystems had low supply temperatures, which was also commonly observed for the AHU cooling coils. However, some of the FCU subsystems had higher supply and return temperatures which likewise was observed for some of the cooling coils, but typical for the chilled beam subsystems.

Individual data available for the chilled beam subsystems were more common, at least for the supply temperature since this is regulated based on the dew point temperature of the air. 19 buildings had data available for a total of 28 systems, out of which 19 had data available for the return temperature as well. For chilled beams, temperatures higher are obvious due to dew point regulation, yet, some fan coil unit systems and cooling coils also used such high temperatures. Despite the chilled beam subsystems using high temperatures, the accumulated return temperature of the building chilled water system ($t_{CHW,\ return}$ in Figure 19 left and Figure 20) was not significantly affected by the chilled beam subsystem. Instead the return temperatures from the AHU cooling coils influenced the accumulated return temperature of the CHW system. This is because the share of the chilled beam subsystem is smaller than the subsystem supplying cooling coils in the AHUs. Therefore, the advantage of the chilled beam system's higher supply and return temperatures is diminished in conjunction with the other subsystems of the building CHW system.

Based on the buildings' CHW subsystem temperatures encountered in Figure 20, it is evident that low conventional supply temperatures of 7-8 °C are needed for some cooling coils and FCU subsystems. However, significantly higher temperatures are used as well for all three types of subsystems. Common for all three types of subsystems is that both supply and return temperature ranges are large, compared to the range recommended by the design guidelines (Energiföretagen Sverige, 2019), as well as there is substantial overlap between the three subsystems temperature ranges.

4.3 District Cooling Production Plant

In this section, the results based on data from the district cooling plant are presented. In section 4.3.1, the DC cooling production is based on the actual DC supply and return temperatures from 2017 and 2018 and in section 4.3.2, the DC cooling production is based on new proposed higher temperatures.

4.3.1 Free Cooling with Present Temperatures

In the upper diagram of Figure 21, the actual supply and return temperatures as measured in the district cooling system in 2018, along with the river temperature and cooling generated, result in an annual production mix as seen in the lower diagram. The green area represents the annual cooling production by free cooling from the river, equal to 22.4%. The grey area represents the cooling produced by the chillers. Based on data from 2017, the share of free cooling was 28.1%.

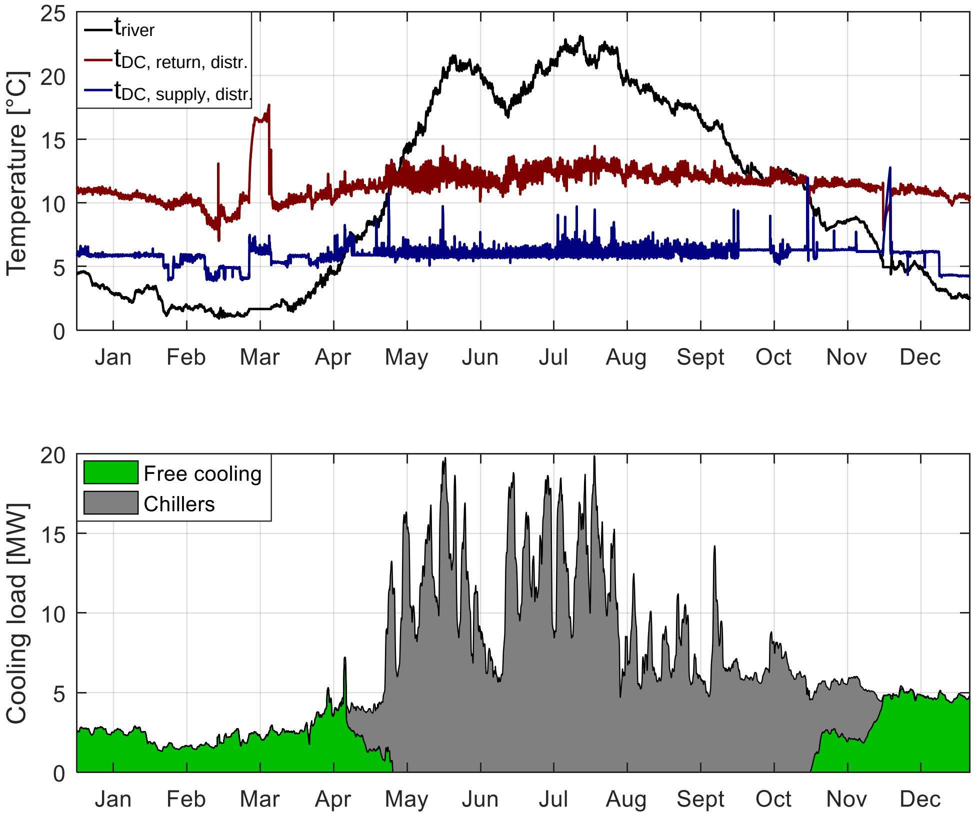

Figure 21: Upper: Actual district cooling system supply and return temperatures and river temperature of 2018. Lower: Cooling power generated by the base load plant, shown as average daily values based on the temperatures from the upper diagram, separated into free cooling and chiller generated cooling (absorption and/or compressor chillers).

If the low delta-T in the district cooling system was resolved, and a return temperature of 16 °C would be maintained throughout the year, the share of free cooling (based on actual river temperature and cooling generated) would be 28.1% for 2018 and 34.2% in 2017.

4.3.2 Potential Free Cooling with Higher Temperatures

Based on the results from section 4.2 and the reviewed literature in section 2.3.2, high temperature district cooling (HTDC) with supply temperatures of 12-14 °C and return temperatures of 20-22 °C are proposed. These increased temperature levels complement the temperature reduction in district heating systems (Lund et al., 2014) and the development of district cooling systems as part of a future smart energy system by allowing for the integration of more renewable energy (Lund et al., 2017). If a supply temperature of 12 °C and a return temperature of 20 °C were used in the district cooling system, the share of free cooling would be equal to 43.5%, see Figure 22 (based on actual river temperatures and cooling generated in 2018). The share based on river temperatures and cooling generated in 2017 would be equal to 54.5%, equal to almost a doubling of free cooling for each year.

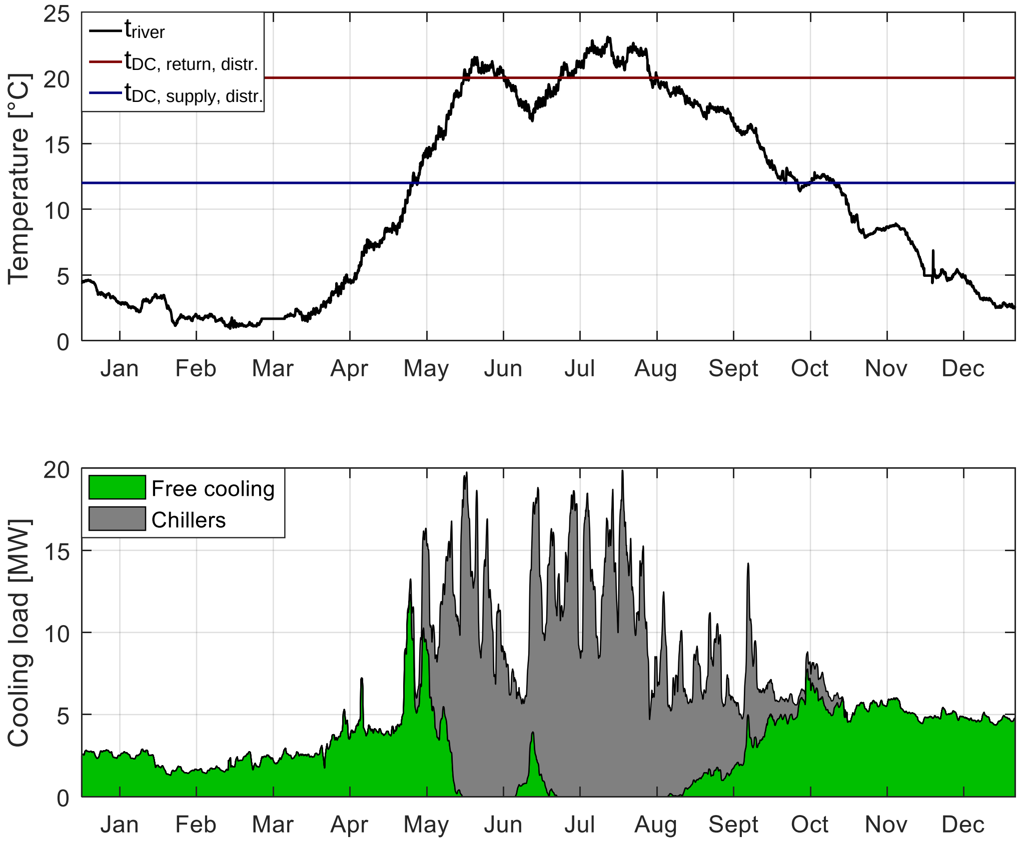

Figure 22: Upper: Theoretical high supply and return temperatures of the district cooling system and actual river temperature for the year of 2018. Lower: Cooling power generated by the base load plant, shown as average daily values based on the temperatures from the upper diagram, separated into free cooling and chiller generated cooling (absorption and/or compressor chillers).

One of the intentions with smart energy systems is to deliver heating and cooling to more energy efficient buildings (Lund, Østergaard, et al., 2018). The purpose of high temperature district cooling is therefore to adapt to the modified cooling demands in buildings where high temperature cooling systems are implemented. Another main feature of smart energy systems is the integration of renewable energy sources (Lund, Østergaard, et al., 2018). This is enabled by high temperature district cooling since it increases the utilization of natural free cooling.

In many of the connected buildings, the supply temperature setpoint is outdoor temperature compensated, which means that the supply temperature is higher when the outdoor temperature is lower. This opens up for possibilities of utilizing higher temperatures in the district cooling system during parts of the year, especially during the transition period from free cooling to chillers and vice versa, occurring during spring and fall. During this period, the river is too warm for 100% free cooling, at the same time as there is a heating demand, which prohibits the use of absorption chillers for district cooling generation.

Chapter 5: Conclusions

The aim of this thesis was to investigate causes to the low delta-T in Gothenburg district cooling system by increasing the knowledge about the connected building energy transfer stations and chilled water systems. The investigation was done by collecting and analyzing data from both sides of the heat exchanger in the energy transfer stations of 37 buildings connected to the district cooling system. Guiding the research process was three research questions, where question 1a) was stated as follows:

RQ 1a) What are the causes to low delta-T in an existing district cooling system with heat exchanger separation?

The results showed that the low delta-T in an existing district cooling system with heat exchanger separation is caused by:

- *Limited use of connection standards for the energy transfer stations and building chilled water systems.*
  The early development of the district cooling system was dependent on the number of customers connecting to the district cooling system. For that reason, the building's compatibility with district cooling was often disregarded.

- *A low temperature approach between the supply streams of the heat exchanger.*
  For example, secondary chilled water setpoints that violated the required temperature approach between the supply sides of the heat exchanger, caused the primary return temperature to decrease. In many energy transfer stations, the higher the temperature approach between the supply sides, the lower the temperature approach between the return sides. If the temperature approach between the supply sides was too low (less than 2 °C), high secondary return temperatures that existed on the secondary side were not being transferred to the primary side.

- *Operation in the saturation zone on the primary side of the heat exchanger.*
  The saturation zone occurs at the expense of a low delta-T since the cooling power decreases for an increased chilled water flow rate. This increased chilled water flow rate therefore caused a low delta-T.

- *Low return temperatures from cooling coils and fan coil units in connected building chilled water systems.*
  Many of the studied building chilled water systems exhibited low return temperatures that also caused a low return temperature on the primary side. By investigating the temperatures in the building chilled water subsystems, it was evident that the subsystems with the lowest return temperatures were cooling coils in air handling units as well as fan coil unit systems.

- *Secondary supply temperatures that are non-optimized based on the building's prevailing cooling demand and/or in conjunction with secondary setpoints that are non-outdoor temperature compensated.*

Many of studied buildings had supply temperatures that were outdoor temperature compensated. In the absence of this, some low primary delta-T could therefore be due to secondary supply temperatures that are unnecessarily low for the building's prevailing cooling demand. This caused low return temperatures on both sides of the heat exchanger and a low delta-T.

Research question 1b) was the following:

RQ 1b) How can low delta-T in an existing district cooling system with heat exchanger separation be resolved?

The analysis indicated that the low delta-T in an existing district cooling system with heat exchanger separation can be resolved by considering the following recommendations:

- *Consistent use of connection standards for the energy transfer stations and building chilled water systems.*
  The continued development of the district cooling system needs to take the building's compatibility with district cooling into consideration during the design phase.

- *Evaluate the temperature approaches of the heat exchanger in the energy transfer stations and adjust if necessary and possible.*
  Two different scenarios for this solution have been identified:
  For energy transfer stations where the primary return temperature is reduced as a result of a temperature approach less than 2 °C between the supply sides, ensuring that the secondary supply temperature setpoint is appropriately higher than the primary supply temperature, may be a sufficient solution to resolve the low delta-T.
  For energy transfer stations with adequate temperature approaches, but nevertheless a low delta-T, a more in-depth evaluation of the heat exchanger, the building chilled water system and the building's actual cooling demand need to be done to resolve the low delta-T, potentially optimizing the secondary supply temperature based on different cooling demands and/or outdoor temperatures.

- *Restrict the flow on the primary side of the heat exchanger to limit operation in the saturation zone.*

- *Ensure that there are economic incentives for the customers to actively work with increasing the temperatures in their building chilled water systems.*

The aim of this thesis was also to explore higher temperatures in the district cooling system to increase the share of free cooling of the annual district cooling generation, with the following research question guiding the process:

RQ 2) What are the potentials for higher temperatures in an existing district cooling system based on the temperature requirements of the connected buildings?

This research question was explored based on the results from the increased knowledge of the connected building chilled water systems and by analyzing data from the district cooling production plant. The results showed that the potentials for higher temperatures in an existing district cooling system are the following:

- *Increasing the building chilled water supply temperature with 1-2 °C.*
  When the outdoor temperature was 28 °C, the lowest median building supply temperature was 9.3 °C. For the same outdoor temperature, 25% of the building supply temperatures were 11 °C or higher. This indicates that higher temperatures than the recommended design guidelines of 8 °C to a large extent are used, which opens up for possibilities to use higher temperatures in the district cooling system as well (provided that the temperature would be sufficient for all connected buildings).

- *The use of outdoor temperature compensated supply temperatures in the connected building chilled water systems.*
  This enables possibilities, based on the same principle, for higher supply and return temperatures in the district cooling system as well. This could be attractive for parts of the year, for example during the transition period from free cooling to chiller generated cooling.

- *Addressing building return temperatures that are lower than 18 °C.*
  75% of the building chilled water return temperatures were lower than the design guideline's recommended temperature of 18 °C. Although some cooling coils in AHUs and fan coil unit systems had low return temperatures, it was also shown that these subsystems have the potential to be designed and/or operated with higher temperatures as well.

- *Utilizing district cooling supply and return temperatures of 12 and 20 °C would almost double the share of free cooling of the annual cooling generation, in comparison to the actual temperature levels.*
  Higher district cooling temperatures, and in particular high supply temperatures, may not be feasible in certain climates and for all district cooling systems and buildings. However, as shown in this thesis, it is important to reconsider the use of conventional low district cooling temperatures and, if possible, pursue higher temperatures in existing district cooling systems, with higher return temperatures as a minimum effort.

Chapter 6: Future Research

One of the most significant outcomes of this research project is that the problems and possible improvements have been presented and discussed during workshops between Göteborg Energi and their customers. This has fostered a joint interest in improving both sides of the district cooling system. Göteborg Energi now has the intention to install more sensors in the district cooling system (part of a general digitalization plan). The sensors are intended to be used for supervision and with time, to diagnose and improve the performance in cooperation with the customers. Göteborg Energi also has the intention to invest in consultants that will support their customers to improve their systems. Both these efforts will enhance the conditions for future research.

Although some causes to the low delta-T syndrome in a district cooling system with heat exchangers have been identified, the issues remain. Therefore, strategies on how to resolve them need to be implemented to systematically work on eliminating the low delta-Ts. This thesis provides a foundation for the continuation with the work to resolve the low delta-T syndrome. There are several areas in which the presented results can be applied and extended, for example it could be of value to test and evaluate the solutions identified. Such solutions include flow restrictions on the primary side and adjustments of secondary chilled water supply temperature setpoints. If carried out, the tests should also comprise proper follow-up and documentation to confirm the intended improvements.

In this study, 37 of the connected buildings were analyzed, but approximately 120 remain. Therefore, it could be beneficial to develop an energy transfer station diagnosis method to quickly audit the performance of the remaining buildings. Also, for the customers to actively work with increasing the temperatures of their chilled water systems, they need incentives to do so. Göteborg Energi has already initiated the process of replacing old contracts and tariffs with new ones and for further development on this, the presented results can be of use. Furthermore, proper follow-up is essential to achieve the intended improvements for Göteborg Energi and their customers.

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