THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

District Cooling – Towards Improved Substation Performance

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Abstract

The global cooling demand in buildings is rapidly increasing and to supply this demand, district cooling is one solution. However, many district cooling systems suffer from low delta-Ts (receiving low return temperatures from the buildings connected to the system). The low delta-Ts cause an increased water flow rate, congested distribution networks, require more chiller to operate and reduce the amount of free cooling possible to use. Ultimately, the costs increase, and energy is being wasted. The problem with low delta-Ts has previously mainly been investigated in district cooling systems without heat exchangers in the substation separating the system and the buildings. The purpose of this thesis is therefore to contribute with such knowledge with the aim to develop a systematic approach on how to evaluate and improve the performance of district cooling substations with heat exchangers, to achieve high delta-Ts.

The work was done by analyzing data from both sides of the heat exchanger of approximately 40 substations of buildings connected to an actual district cooling system. The results show a majority of the investigated substations perform poorly. The reasons to this are many but some examples include incompatibility with the district cooling system and limited or lacking follow-up and optimizations of the buildings' systems and substations. Low delta-Ts, high overflows and flow in the saturation zone are primary side performance indicators, developed and tested to evaluate the substation's performance. The performance indicators showed improvements can be done to almost all investigated substations. Three additional performance indicators were developed including data from the secondary side. These showed further reasons to poor substation performance can be explained by the heat exchanger's temperature approaches. Moreover, high primary flow rates in relation to the secondary flow rates were also shown to cause low delta-Ts. Two control strategies were identified as potential solutions to resolve some low delta-Ts. These control strategies were field tested in four buildings and shown to successfully increase delta-T and eliminate the flow in the saturation zone.

To achieve improved performance, it is recommended to employ a systematic method to follow up the substations on a regular basis. This can be done by using the developed performance indicators together with a ranking system as support for decision-making on which substations to address first. Moreover, a systematic follow-up method can be used for collaboration between the utility company and the customers, or it can be used by the property owners as part of their optimization work. Lastly, incentives for improved substation efficiency can be strengthened by adding a temperature component to the price model.

Keywords: district cooling, substation, energy transfer station, low delta-T, heat exchanger, high temperature district cooling, HVAC, control strategy, operational data

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Maria Jangsten
Gothenburg, September 2022

Appended Publications

This thesis is based on the following appended publications:

Paper I — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2020). Analysis of operational data from a district cooling system and its connected buildings. *Energy,* vol 203, 117844.

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. *Energy*, vol 199, 117407.

Paper III — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2022). District cooling substation design and control to achieve high return temperatures. *Energy,* vol 251, 123913.

Paper IV — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2022). A performance assessment method for district cooling substations based on operational data. *Science and Technology for the Built Environment*. In press.

Paper V — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2021). Field test of active night cooling supplied by district cooling in three commercial buildings. *Cold Climate HVAC & Energy Conference 2021*. Tallinn, Estonia.

Paper VI — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2022). District Cooling – assessment of price models supporting the efficiency. [Paper presentation]. *International Conference on Evolving Cities 2022.* Southampton, United Kingdom.

Contribution: As the first author of all papers, Maria Jangsten has conducted the studies including methodology, analysis, and original draft writing. Co-supervisor Torbjörn Lindholm and main supervisor and examiner Jan-Olof Dalenbäck have supported with supervision, editing and feedback as part of the studies and the writing process. Co-author Peter Filipsson contributed with results, feedback and editing as part of Paper II.

The following publications are also authored by Maria Jangsten but not included in the thesis:

Publication I — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2019). Time to Question the Low Temperatures in District Cooling Systems. Euroheat and Power Magazine III-IV/2019, 42-45.

Publication II — Jangsten, M. (2020) *Gothenburg District Cooling System – An evaluation of the system performance based on operational data* [Licentiate thesis]. Chalmers University of Technology.

Publication III — Jangsten, M., Lindholm, T., Dalenbäck, J-O. (2022). Bättre fjärrkylasystem med enkla åtgärder. Energi & Miljö 93 (5) 42-45.

List of abbreviations

AHU	Air Handling Unit
BMS	Building Management System
CHW	Chilled Water
DC	District Cooling
DCS	District Cooling System
DH	District Heating
FCU	Fan Coil Unit
FDD	Fault Detection and Diagnosis
HTC	High Temperature Cooling
HTDC	High Temperature District Cooling
HX	Heat Exchanger
HVAC	Heating, Ventilating, and Air Conditioning
PI	Performance Indicator
PIs	Performance Indicators
RTD	Resistance Temperature Detector
SCADA	Supervisory Control and Data Acquisition
SVR	Support Vector Regression

Nomenclature

$\dot{Q}$	Cooling power [kW]
$\dot{V}$	Volumetric flow rate [m^3/h]
t	Temperature [°C]
Δt	Temperature difference [°C]
C	Heat capacity rate [W/°C]
$c_{p,water}$	Specific heat capacity of water [kJ/(kg·°C)]
ρ_{water}	Density of water [kg/m^3]
A	Coefficients of support vectors
b	Coefficient determining the position of the separating hyperplane

Subscripts

DC	District cooling, substation primary side
DC, supply	Supply stream to heat exchanger: primary inlet cold side of heat exchanger
DC, supply, prod	Supply from DC production plant to DC system
DC, return	Return stream from heat exchanger: primary outlet cold side of heat exchanger
CHW	Chilled water, substation secondary side
CHW, supply	Supply stream to building: secondary outlet warm side of heat exchanger
CHW, return	Return stream from building: secondary inlet warm side of heat exchanger
max	Maximum
corresponding	Corresponding flow for maximum cooling power
out	Outdoor

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1

Introduction

Carbon neutrality by the year 2050 – a worldwide adopted mission; possible, or simply the platitude[1] of this century? Despite a global consensus on the criticality of meeting this goal, with less than thirty years to go many sectors are concerningly off track. One such sector is buildings, and the efforts to reduce energy intensity and shift to renewable technologies need to increase. For example, in 2030, the energy use per square meter must be reduced with 35% compared to 2021 (IEA 2022). Contrariwise, the energy use for comfort cooling in buildings is projected to triple by the year 2050 compared to 2016, resulting in comfort cooling being the fastest growing energy end-use in buildings globally. To supply this increased cooling demand, the number of individual cooling units and associated equipment such as chillers, air conditioners, heat pumps, fans and dehumidifiers will increase from a total of 3.9 billion units to 9.2 billion units by 2050, to supply both residential and commercial cooling demands (IEA 2018). To limit the increased energy use by these units, more stringent energy performance standards for air conditioners have for example been suggested (IEA 2021). However, a potentially energy efficient cooling supply technology which has received little attention in this context is district cooling (DC). In a district cooling system (DCS), chilled water is efficiently generated in central production plants and distributed by a network of underground pipes to the buildings. DC thereby removes the need for building individual cooling equipment and utilizes the economy of scale such as aggregation of the connected buildings' cooling demands and other synergies on a city level (Frederiksen and Werner 2014). Other advantages from utilizing DCS instead of individual cooling units include reduced use of refrigerants as well as decreased heat island effects and less noise pollution in cities.

1.1 Future Role of District Cooling

For the building sector to achieve carbon neutrality by 2050, 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

[1] Platitude = remark or statement, especially one with a moral content, that has been used too often to be interesting or thoughtful.

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 to the district cooling system by using natural cooling sources such as the sea, lakes, and rivers (Østergaard et al. 2022). This reduces the primary energy need for chilled water generation in chillers. Moreover, if thermal energy storages, either daily and seasonally (Al-Noaimi, Khir, and Haouari 2019; Näslund 2000), are integrated to the DCS, the chilled water production can be optimized with respect to fluctuating electricity prices and increase the flexibility (Inayat and 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 important to avoid an 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 (Østergaard et al. 2022; Dominković et al. 2017; Lund et al. 2018). As claimed by Inayat & Raza (2019), district cooling operated with renewable energy is “undoubtedly the future energy solution and the environmental solution” to provide cooling in buildings.

1.2 Swedish Perspective

District cooling in Sweden was established in the 1990’s and has since grown to about 530 km of piping, delivering around 1.0 TWh of cooling annually. The largest share, 35% of the district cooling, is delivered to offices and commercial premises. Around 15% is supplied to public facilities, 17% to industries, 3% to multifamily residential buildings, with the remainder being unspecified (Johannesson 2019; Energiföretagen Sverige 2022). District cooling is to a large extent linked to district heating (DH). This is because district heating is a well-established and mature technology with large market shares, delivering about 50 TWh of heat annually (Burstein 2022). Compared to DH, the DC market is small and today there is a total of 37 companies delivering district cooling to 40 Swedish cities (Johannesson 2019). The highest delivery was almost 1.2 TWh in 2018, because the summer was extremely warm and sunny compared to normal. The average temperatures in Sweden were 1-3 °C above normal in the north, and 2-4 °C above normal in the south (SMHI 2018).

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 buildings for low heat losses which has led to larger cooling demands in the summer (S. Werner 2017a). The owners of the DH systems, often municipalities, have also developed the district cooling systems (S. Werner 2017a; Westin 1998). By the year 2030, DC in Sweden is expected to grow by 50% compared to 2019 (Devcco 2019).

The distribution of chilled water production according to technology in Swedish DCS in 2021 was 28% compression chillers, 26% heat pumps and 22% absorption chillers. Free cooling covered 23% of the DC generated in 2021 (Energiföretagen Sverige 2022). In Sweden, the DCS and the buildings connected to the DCS belong to two separate organizations: the utility company, and the property managers. The DCS and the building chilled water (CHW) system are separated with a plate frame heat exchanger in the substation, which in addition to a hydraulic separation also marks the contractual limits of both parties. Such DC systems are called DCS with heat exchanger separation or indirect DCS (Frederiksen and Werner 2014).

1.3 Problem Formulation

The possibility of developing DCS in many Swedish cities was in the early growth phase dependent on the number of contracted customers. Pursuing a high connection rate was the fundamental factor for establishment, and compliance to the design guidelines and ensuring DC-compatible building systems were of less importance. For this reason, buildings with chilled water systems designed for local chillers with low delta-Ts were still connected to the DCS without upgrading for conformity to the DCS design temperatures. After a 20-year initial growth phase, many DCS in Sweden are now planning for a second growth phase (Devcco 2019). However, a prevalent problem in district cooling systems is failing to achieve the design delta-T between the DC supply and return water (Olama 2017). It is called the "low delta-T syndrome" and causes high pumping costs, congested distribution networks and less free cooling possible to use. This in turn causes additional chillers to be started and results in an increased need for pump and chiller electricity, ultimately increasing the costs and wasting energy (IDEA 2008). In the next phase of DCS expansion and development in Sweden, there is a potential to increase the efficiencies of the systems. It has previously been established that knowledge about the performance status of all substations in the DC system is a prerequisite to actively work with improvements of the DC system's delta-T (Walletun and Johnsson 2005). However, there is a lack of a systematic approach on how to evaluate and improve the performance of the substations.

Many studies have been conducted on district heating (DH) systems, which experiences similar issues, but the problem instead is *high* return temperatures (Ntakolia et al. 2021). Although research outcomes on how to increase the efficiency in DH substations to some extent is applicable to DC, no previous studies have been conducted on DC substations specifically. One reason is DC systems have existed for a much shorter period than DH systems, as well as major differences between DC and DH systems are the building systems on the secondary side and the significantly higher delta-Ts in DH systems.

The low return temperatures causing low delta-Ts usually stem from the buildings' chilled water systems. Several studies have established solutions on how 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 have indirect connections with heat exchangers separating the distribution system from the building chilled water system. For such district cooling systems, there is a need to evaluate the causes and solutions to low delta-Ts since they may be different from DCS with direct connections. To do so, both sides of the heat exchanger need to be analyzed (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 system in the building. For that reason, there is a need to increase the knowledge about how the control of the buildings systems influences the DC system along with their temperature requirements.

Previous research on Swedish district cooling systems and the buildings supplied by them have focused on recommendations on how the substation could be designed and how the buildings should be controlled to achieve more efficient use of the district cooling (Källman, Hindersson, and Nord 2004) (Fredriksen et al. 2016). Also, measures to increase delta-T were evaluated in two commercial buildings by simulations (A. Werner and Jonsson 2012). These studies were either based on theoretical evaluations or approached from either side of the heat exchanger in the substation. Therefore, there is a need to evaluate potential improvement measures for existing DC substations, based on actual data and approached from both sides of the heat exchanger. This can contribute with knowledge on what can be improved in an existing DCS as well as recommended for new DCS, to resolve or avoid low delta-Ts.

1.4 Aim of Thesis

Based on the identified problem, the aim of this thesis is to develop a systematic approach on how to evaluate and improve the performance of district cooling substations with heat exchangers to achieve higher delta-Ts.

The objectives of the thesis are threefold:

- to **characterize** how the substations are operating by assessing their performance, including the influence of design, control, and the operation of the buildings' chilled water systems, primarily based on operational data from both sides of the heat exchanger.
- to **develop** performance indicators that can be used to evaluate and improve the substations' performance.
- to **explore** a few potential solutions on what can be done to improve poor substation performance.

1.5 Delimitations and Limitations

The context of this thesis is provided in Chapter 2; however, substation performance and low delta-Ts are closely linked to other aspects of the topic district cooling. For this reason, the following themes constitute delimitations of this thesis:

- Cooling load predictions and calculations are important aspects regarding the operation and planning of district cooling systems, especially as profitability measures 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 thesis and have not been investigated.
- Whether or not the district cooling system is the most optimal cooling source for the buildings in Gothenburg, compared to building individual chillers, heat pumps or other solutions, is another delimitation of this thesis.
- Another aspect of district cooling excluded from this thesis concern the chilled water production plants and the distribution network. For example, production optimization, chiller replacements, integration of new cooling technologies and central thermal energy storages as well as different hydraulic configurations of district cooling systems, pumping schemes and distribution layouts.
- The concept of Smart Energy Systems was briefly introduced in the Introduction, however, no further investigations and analyses with respect to this concept is undertaken as part of this thesis. Instead, the thesis focuses on technical aspects regarding the operation of an existing district cooling system.

Limitations of the thesis are outside the control of the researcher and constitute potential weaknesses, for example the nature of the data which the study is based upon. The majority of the data in this thesis are operational data as measured by permanently installed equipment. This equipment is used as part of the normal operation of the district cooling system and the buildings, either for billing purposes by the utility provider, or for control and monitoring of the buildings' chilled water systems by the property managers. Testing of data reliability and validity has been limited. Potential erroneous measurements could be present among the data which could negatively impact the results. Moreover, merging data from two separate data collection systems with different timestamps and measurement techniques also impact the data reliability.

1.6 Structure of Thesis

This doctoral thesis is structured as follows: 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 research problems investigated in the appended papers. In Chapter 3, the research methodology is presented with a justification and explanation of the research design along with the chosen methods. Furthermore, the district cooling system in Gothenburg and the buildings are described in Chapter 3, since they represent the applied objects of the studies in this thesis. In Chapter 4, the main results of the thesis are summarized, structured to align with the aim. The discussion is presented in Chapter 5, the conclusions in Chapter 6 and lastly, in Chapter 7, future research is considered.

2

Frame of Reference

The frame of reference provides the context of this thesis by presenting background to the topic, relevant theoretical concepts, and a review of previous research.

2.1 District Cooling

In a district cooling system, chilled water is generated centrally in large chiller plants and is distributed to buildings by underground pipes. A district cooling system consists of three main components: production plant, distribution system and substations where the buildings are connected to the DCS, see Figure 1. In the substation, also called energy transfer station, the buildings are connected either directly or indirectly. An indirect connection utilizes a plate frame heat exchangers for hydraulic separation, whereas for direct DCS there are no heat exchangers in the substation (Olama 2017; Skagestad and Mildenstein 2002).

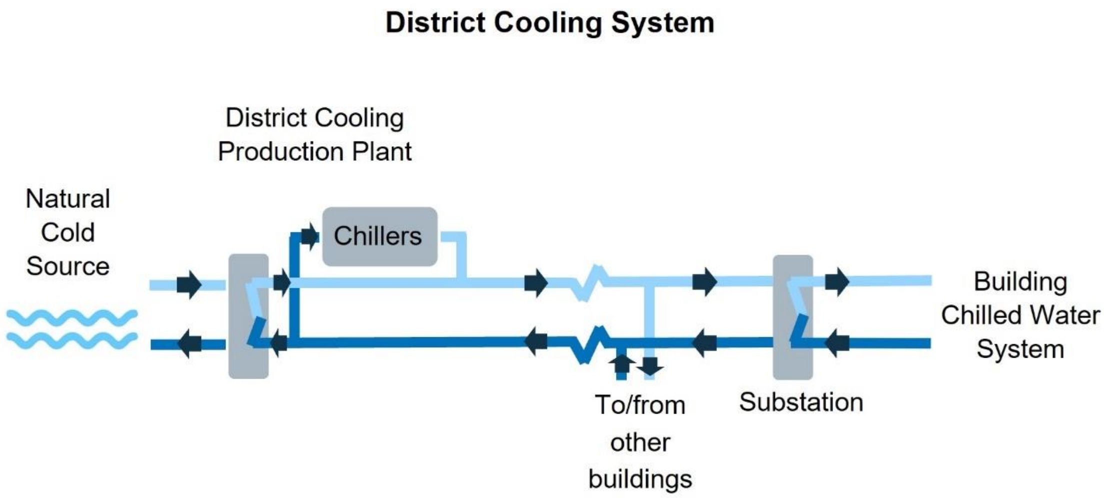

Figure 1: Schematic of a district cooling system with its main components.

District cooling systems can utilize natural cold sources such as rivers, lakes, and the sea. The temperature variations of the cold source determine the annual utilization time for direct free cooling. For cold sources with a temperature between 4-8 °C irrespective of ambient outdoor temperature, free cooling can be supplied to the DCS all year round (Radspieler, Xu, and Haves 2007; Looney and Oney

2007). For cold sources with temperatures varying with the ambient temperature, free cooling can be used 100% when the water temperature at the intake point is 4-8 °C or less (depending on the requirements of the DCS and the buildings). The remaining part of the year the cold source can be used to precool the returning chilled water from the DCS (Jangsten 2020) or as a heat sink for the chillers' condensers (Hunt, Byers, and Sánchez 2019). Other chilled water production methods include absorption chillers running on waste heat and mechanical compression chillers or heat pumps using electricity as input (Frederiksen and Werner 2014).

In cities, DC makes use of the economy of scale because of aggregated cooling demands of the connected buildings. Also, different building types with varying cooling demands make the accumulated cooling demand diverse and the production more efficient (IDEA 2008). District cooling can contribute to a reduced need for electricity to provide cooling in buildings, and thereby reduce the indirect use of fossil fuels (Rezaie and Rosen 2012). DC also generates several benefits for the building owners. These comprise an eliminated need for individual chillers and heat rejection units in each building, including time spent on operation and maintenance of these units. This allows the building owners to focus on the core business as well as more rentable space is made available (Frederiksen and Werner 2014). Moreover, fewer individual chillers reduce the usage of refrigerants, which supports the Montreal Protocol and Kigali Amendment legislated under the EU F-gas Regulation (European Commission 2015). District cooling has high capital investments and operating costs. However, it has the potential to achieve higher operating efficiencies compared to having local chillers in buildings. This is possible because of the concentration effect of diverse cooling demands, the use of natural cold sources (Jing et al. 2017; Shimoda et al. 2008) as well as large chillers typically have higher efficiencies than smaller local units (ASHRAE 2013).

The number of district cooling systems around the world is unknown, but at least 150 systems are estimated to be in operation. The annual cooling energy 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, DC has a very low market share (S. Werner 2016) with cooling deliveries around 3.5 TWh in 2018. Roughly 30% were delivered by Swedish DC systems, 30% in France and 40% in the remaining European countries with DCS (Dalin 2019).

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 difference between the supply and return water temperatures, referred to as delta-T. A delta-T as high as possible is desired since it allows for smaller pipe sizes and lower pumping costs. Typically, delta-Ts of 9-12 °C reduces the capital expenditure and the pumping costs, but it is not uncommon DCS have been designed for delta-Ts as low 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 DCS return temperature is limited by the return temperatures from the substations, which in turn are affected by the return temperatures in the building chilled water systems supplied by the DCS. It is for this reason difficult to ensure and maintain the desired design return temperatures of the DCS (Olama 2017; IDEA 2008). For Swedish district cooling systems, the technical guidelines suggest design temperatures of 4-10 °C supply and 14-20 °C return, with 6 °C as the supply benchmark and 16 °C as the return benchmark temperature (Energiföretagen Sverige 2019). For some DCS, the supply temperature is varied as a function of the outdoor ambient temperature (Skagestad and Mildenstein 2002; Göteborg Energi AB 2021). This operation strategy allows for an increased chilled water supply temperature as the cooling demand decreases.

2.1.1 The Substation

For DCS with heat exchanger separation, substations with a plate frame heat exchanger are used. The heat exchanger constitutes the interface between the DC distribution system (primary side) and the building's chilled water system (secondary side), see Figure 2. In the substation, also referred to as energy transfer station, the energy meter for billing purposes is located along with measurement equipment for control of the building chilled water system. In Sweden, there are technical guidelines for the substation design along with recommended temperature levels for the buildings' CHW systems and the HVAC systems' end terminals. The technical guidelines have been in place since 2004 (Nordengren 2022). Regardless, buildings owners and consultants have autonomy regarding the design and control of the DC substation and the building's CHW system.

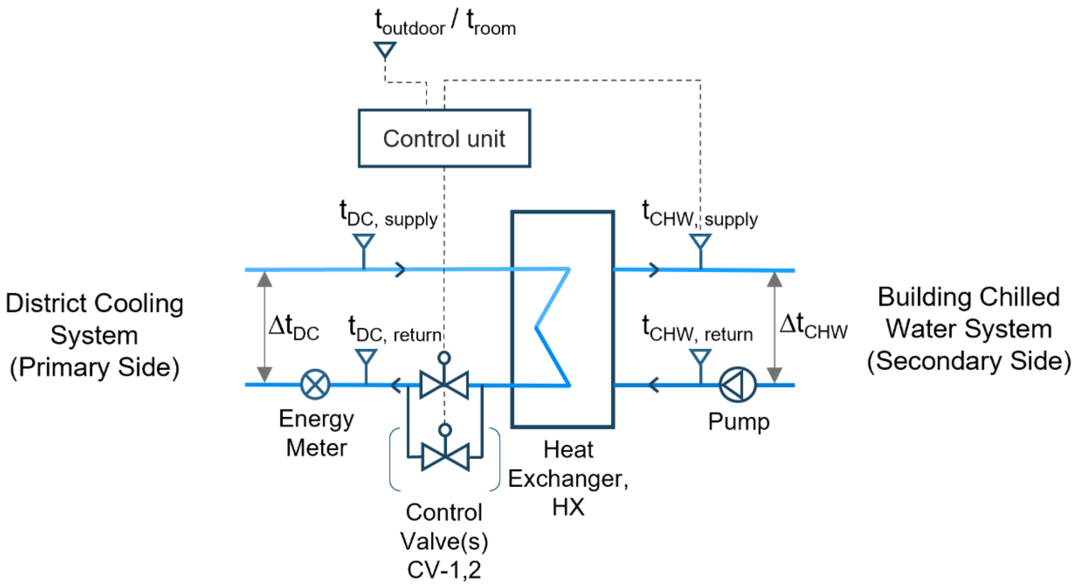

Figure 2: Schematic of the DC substation with equipment and measurement points.

In general, the substation should be controlled according to the following general control strategies, based on the current Swedish technical guidelines (Energiföretagen Sverige 2019):

- The building CHW system pump is demand controlled and starts by a time schedule or when there is a cooling demand in the building. The pump is typically a variable speed pump controlled by a differential pressure regulator in the system, although some systems have constant speed pumps operating on or off.
- The setpoint of the CHW supply temperature should always be higher than the primary supply temperature and automatically adjust accordingly if the primary supply temperature changes.
- The setpoint is achieved by means of opening and closing the motorized control valve(s) which allows the primary water to flow through the heat exchanger. The control valve should be selected according to the design cooling power and have a valve authority of at least 0.5. Larger substations (> 300 kW) should have two control valves in parallel where the second control valve opens if the first one is open 100%.

The Heat Exchanger

The heat exchanger (HX) is the central component in the substations and creates the hydraulic separation between the DC system and the building CHW system. It is typically a symmetrical counterflow plate frame heat exchanger and should conform to the performance specifications according to the AHRI certification programs Liquid to Liquid Heat Exchanger or Liquid to Liquid Brazed and Fusion Bonded Plate Heat Exchangers (Energiföretagen Sverige 2019). Basic theory of plate frame heat exchangers is fundamental to this thesis, where the heat transfer on the primary side of the HX is equal to the heat transfer on the secondary side (Incropera et al. 2007), as expressed by Eqn. 1:

$$\dot{Q}_{DC} = \dot{Q}_{CHW} \tag{1}$$

Each side of Eqn. 1 is equal to:

$$\dot{Q}_{DC} = \dot{Q}_{CHW} = \rho_{water} \cdot c_{p,water} \cdot \dot{V}_{DC} \cdot \Delta t_{DC} = \rho_{water} \cdot c_{p,water} \cdot \dot{V}_{CHW} \cdot \Delta t_{CHW} \tag{2}$$

where $\dot{V}_{DC}$ and $\dot{V}_{CHW}$ are the water flow rates on the primary and secondary sides of the HX, Δt_{DC} is the temperature difference on the primary side equal to $t_{DC,\ return} - t_{DC,\ supply}$ and Δt_{CHW} is the temperature difference on the secondary side equal to $t_{CHW,\ return} - t_{CHW,\ supply}$. The constants $c_{p,water}$ [kJ/(kg·°C)] and ρ_{water} [kg/m^3] are the specific heat capacity and density of water. The temperature dependency of these constants has been disregarded in this thesis. It should be noted that Eqn. 2 is valid when the system is in steady state.

A common method to analyze a plate frame heat exchanger is the temperature effectiveness-NTU method (Frederiksen and Werner 2014; Kandlikar and Shah 1989; Incropera et al. 2007). The temperature effectiveness of the primary side of the heat exchanger, η_{DC}, is the temperature effectiveness of importance from the perspective of achieving the highest possible primary return temperatures. It can be calculated based on Eqns. 3-9:

$$\eta_{DC} = \frac{1 - e^{-NTU(1-R)}}{1 - R \cdot e^{-NTU(1-R)}} \tag{3}$$

where:

$$R = \frac{C_{DC}}{C_{CHW}} = \frac{c_{p,water} \cdot \rho_{water} \cdot \dot{V}_{DC}}{c_{p,water} \cdot \rho_{water} \cdot \dot{V}_{CHW}} = \frac{\dot{V}_{DC}}{\dot{V}_{CHW}} \tag{4}$$

Where C_{DC} and C_{CHW} are the heat capacity rates [W/°C] of the chilled water on the primary (DC) and secondary (CHW) sides of the heat exchanger.

If R=1, then:

$$\eta_{DC} = \frac{NTU}{1 + NTU} \tag{5}$$

$$NTU = \frac{\Delta t_{DC}}{LMTD} \tag{6}$$

$$LMTD = \frac{\Delta t_2 - \Delta t_1}{ln \frac{\Delta t_2}{\Delta t_1}} \tag{7}$$

where:

$$\Delta t_1 = t_{CHW,supply} - t_{DC,supply} \tag{8}$$

$$\Delta t_2 = t_{CHW,return} - t_{DC,return} \tag{9}$$

called supply temperature approach and return temperature approach, see Figure 3 for clarification.

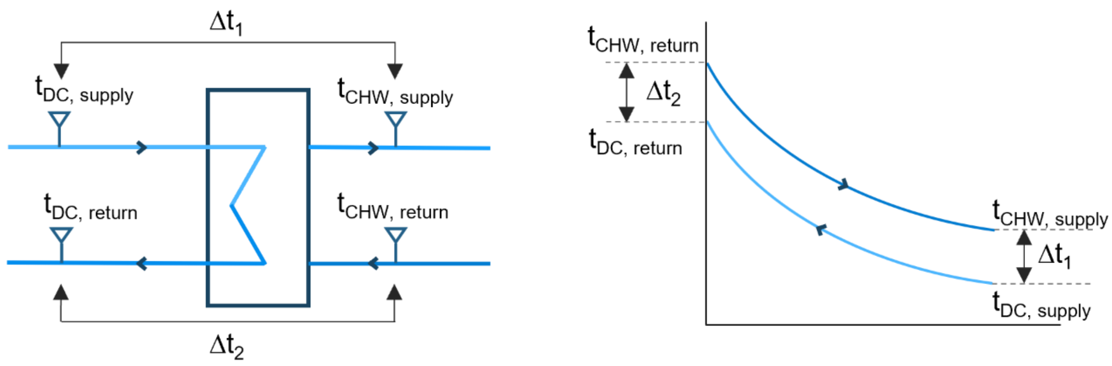

Figure 3: Schematic of temperatures and temperature approaches in a district cooling substation along with temperature diagram for counterflow heat exchanger for district cooling substation applications.

Although the heat exchanger is needed when the DCS and the building ownership are by separate entities, it also creates a barrier between the primary and secondary sides regarding information and data transfer. Even if the DC provider may own part or all of the substation's equipment, it is common the DC provider has no access to the building chilled water systems' data. However, the building manager has the possibility of accessing data from the primary side by connecting with M-bus to the programmable logic controller (PLC) on the primary side by using the "customer access port".

The Control Valve(s)

In the Swedish technical guidelines, the recommended type of control valve is a two-way globe valve, although the valve selection is ultimately the choice of the building owner (Energiföretagen Sverige 2019). The control valve is pressure dependent and has to be properly size considering the differential pressure on the primary side of the substation, since the flow rate through the control valve varies with changes in the cooling demand and the differential pressure of the system (IDEA 2008). The differential pressure of the substation according to the Swedish technical guidelines is 100-600 kPa (Energiföretagen Sverige 2019). Control valves for which the pressure variations can be disregarded are pressure-independent control valves. Such control valves operate to maintain a constant differential pressure across the control surface by varying the size of the passage between the piston and the valve outlet. They can thereby deliver more stable control compared to pressure-dependent valves and help achieving higher delta-Ts (IDEA 2008).

The Energy Meter

The energy meter, located on the primary side of the substation see Figure 2, is provided, owned, and maintained by the utility company. It consists of a flow meter, a pair of temperature sensors and an integrator. It should conform to the Swedish technical guidelines about energy meters for thermal energy (Energiföretagen Sverige 2021).

2.1.2 Price Models

For the DC customers to maintain efficient substations and actively work with resolving low delta-Ts it is important they are provided with sufficient economic incentives. However, pricing DC is oftentimes less transparent than its counterpart DH, and the DC rate structures are diverse. Many previous studies have been conducted on price model evaluations for DH but very few have investigated price models for DC (Olama 2017; Sandoff and Williamsson 2015) and the knowledge about DC pricing has been identified as low (S. Werner 2017a; 2017b) As a minimum, the DC price model should charge based on capacity and consumption, which usually translates to a power and an energy component of the price model. Additional components can be added to encourage efficient buildings and substations. This can for example be done by including a penalty component of the price model which charges for the excess flow due to the actual delta-T being lower than the ideal delta-T (IDEA 2008). In a Swedish context, DC has been developed and is offered by DH companies. Although DC comprises a much smaller share of the utility company's product portfolio compared to DH, it is growing rapidly. To date, no studies on DC price models of Swedish DC companies have been conducted. It is still common the customers' contracts and prices are determined on an individual basis, since the adoption of a standardized price model typically is done when the DCS has reached a certain market size (Devcco 2019).

Of the 37 Swedish utility companies offering DC, four have disclosed their DC price models and price lists online (Göteborg Energi AB 2022; Stockholm Exergi AB 2022; Norrenergi AB 2022; Borås Energi och Miljö 2022). Since DC is part of DH companies, the development of DC price models has typically been done with knowledge and inspiration from DH price models. They should as a minimum consist of three components: 1) a fixed annual price, 2) a fixed capacity price based on measured power and 3) a variable energy price with differentiation for two or three seasons. A possible fourth component and complement to the price model, is a fee based on either the flow, return temperature or the delta-T (Frederiksen and Werner 2014; Rydén et al. 2013). This price model component is what provides the customers with incentives to maintain efficient and well-functioning substations.

The four available Swedish DC price models include different variations of the price components energy and power. Two of the price models also include a flow component and one a bonus/fee-based return temperature component. The flow price components charge based on either the monthly used cubic meters of chilled water (Göteborg Energi AB 2022) or as an average of the three hours with the highest flow rates for each of the months June, July and August (Norrenergi AB 2022). For the price model with a return temperature component, it is calculated as the energy weighted average return temperature from each substation, compared with the network average and is applied only during the months May through September. Customers with a return temperature above the network average receive a bonus of 1 €[2]/(°C·MWh) and customers below the average are charged a fee (Stockholm Exergi AB 2022).

2.2 Building Chilled Water Systems

In commercial buildings, the need for 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). Moreover, process cooling demands may be present in commercial buildings as a result of heat generation from different types of equipment, for example computer servers. It is the task of the building's HVAC system to monitor and regulate the indoor environment and ensure 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.

For the provision of cooling in buildings, 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 thesis) (Nilsson 2003; McQuiston, Parker, and Spitler 2005). The HVAC systems in the buildings investigated in this thesis have been classified as shown in Figure 4. 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

[2] Exchange rate used: 1 SEK = 0.1 €.

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.

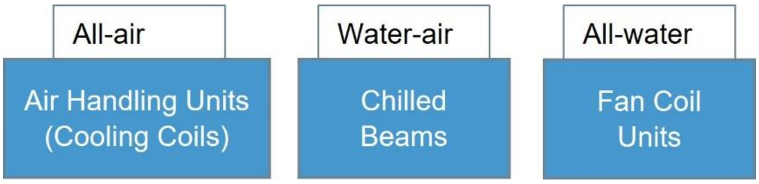

Figure 4: Classification and type of building HVAC system in the buildings part of this thesis.

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 supply temperature needs to be lower than the indoor air dew point temperature (Liu, Jiang, and Zhang 2013) and commonly used supply 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 condensate removal system, which allows the supply water temperature to be lower than the dew point temperature (Nilsson 2003).

Based on the technical guidelines for Swedish DCS, the recommended temperatures in the building CHW systems are 6-14 °C supply and 16-20 °C return, with 8 °C as the supply benchmark and 18 °C as the return benchmark temperature. These benchmark temperatures are recommended for cooling coils in all-air HVAC systems. For water-air 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).

High Temperature Cooling Systems

High temperature cooling (HTC) systems are a modified cooling technology with the possibility to improve the overall cooling efficiency. This technology has rapidly advanced in the past decade through research and evaluation of proposed methodologies and applications (X. Li, Wang, and Shi 2014; Schmidt 2009; Jiang et al. 2015). In HTC systems, the sensible and latent cooling loads are decoupled and individually controlled by temperature and humidity independent control (Liu, Jiang, and Zhang 2013). A high temperature water-based cooling system, such as radiant panels, handles the sensible cooling load with chilled water supply temperatures of approximately 16 °C and up. The dehumidification is managed by a separate ventilation system using conventional supply temperatures of 6-8 °C (Liu, Jiang, and Zhang 2013; Saber, Tham, and Leibundgut 2016). Previous studies on HTC systems demonstrate that although conventional low temperatures may be required for latent loads, sensible cooling of indoor spaces can be achieved by higher temperatures (K. Zhao et al. 2011; Iyengar et al. 2013; Saber et al. 2014; T. Zhang, Liu, and Jiang 2014; L. Zhang et al. 2015; Filipsson et al. 2020). Moreover, in climates of Northern Europe, HTC may be the appropriate solution for more energy efficient provision of cooling for thermal comfort (Filipsson 2020).

2.3 Faults and Low Delta-Ts

The low delta-Ts in district cooling systems are oftentimes the result of faults occurring in the substation and the buildings' chilled water systems. However, faults are not necessarily the only cause and effect for low delta-Ts. This is because many buildings connected to a DCS may not have been designed for the DCS design temperatures. Faults and low delta-Ts have in the context of DCS previously been studied from three general perspectives: 1) DCS without HX separation or HX for pressure relief, 2) buildings' HVAC and CHW systems and 3) for DH systems, the counterpart to DCS. Studies on faults and low delta-Ts in DCS without HX separation are to a large extent overlapped with the studies on HVAC systems, since the difference between the DCS and the HVAC system is less distinct in systems with direct connections.

2.3.1 Low delta-Ts in Direct and High-Rise DCS

For DCS with direct building connections (without heat exchangers in the substation), Fiorino (1996) identified twenty-five ways to eliminate the low delta-T, ranging from component selection criteria in the building CHW systems to configurations of the distribution system. Typical causes of the low delta-T syndrome are the use of 3-way valves (Griffith 1987; Taylor 2002; Hartman 2001; Luther 2002) as well as an improper selection of cooling coils, control valves, setpoints and controls, such as not closing the 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. Gao et al. (2012) showed the low delta-T in an indirect DCS in a high-rise building was caused by a too low setpoint of the outlet water after the heat exchangers. The causes of low delta-Ts presented in these studies are not necessarily the result of faulty operation of the system. The systems may be working as intended and designed for, but instead the causes are results of system deterioration over time, unintended poor design, component selection and improper or inadequate control.

2.3.2 Fault Detection in HVAC and CHW Systems

Many faults causing low delta-Ts in DCS originate in the buildings' HVAC systems. For example, a fault in the ventilation system can be transferred to the CHW side of the HVAC system and ultimately to the primary side of the DC substation, but it can also obscure the cause and effect of the fault (R. Zhang and Hong 2017). Previous studies on fault detection and diagnosis (FDD) in HVAC systems can be separated into system, subsystem (S. Wang, Zhou, and Xiao 2010; Y. Zhao, Wang, and Xiao 2013; Gao et al. 2016; Zhou, Wang, and Ma 2009; Gao, Wang, and Shan 2016; Liang and Du 2007; Luo et al. 2019), and component level (Audivet Durán and Sanjuán 2016; P. Wang, Gao, and Fan 2015; Bruton et al. 2014). Faults can occur at each of these levels and affect the operation of the related subsystems and components (McIntosh 1999). Examples of faults in HVAC systems as identified by Y. Li and O'Neill (2018) are: duct leakage, dampers not working properly, airflow not balanced, improper commissioning, control component failure or degradation, valves not closing properly, cooling coil valve stuck or leaking, heat exchanger faults (scaling, leaking, fouling) and pipe clogging. For example, the fault fouling of cooling coils or other end terminals reduce the overall heat transfer. This causes an increased chilled water flow rate and ultimately a low delta-T, transferred from the building CHW system to the primary side of the DC substation.

Previous studies conducted on faults and low delta-Ts in HVAC systems are usually based on reference models with highly correlated parameters. These models have been shown to work well when the input data is of decent quality and labelled for normal and faulty operation. However, these models need to be validated with operational data before applied in real-world operation (Bode et al. 2020). Moreover, only a few previous studies account for transient conditions and sudden events. This is a major problem for FDD in HVAC systems and makes it difficult to obtain reliable results (G. Li et al. 2021; Mirnaghi Sadat and Haghighat 2020), since faulty operation is challenging to distinguish from transient operation. Other methods to detect faults and resolve low delta-Ts include knowledge and expert rule approaches (Verhelst et al. 2017) which use operational and fault signatures based on operational data from the system (Lee, Yoon, and Won 2022) as well as mixed methods have been suggested (Almobarek, Mendibil, and Alrashdan 2022).

2.3.3 Fault Detection in DH Systems and Substations

In DH systems, low delta-Ts are also a recognized problem, however less detrimental to the system efficiency because of higher design temperature differences. Faults in DH systems have in the past decade been researched under the domain fault detection and diagnosis (FDD) in DH systems and substations. Numerous faults can occur in the DH substation and cause different symptoms such as unsuitable heat load patterns, low average annual temperature difference and poor substation control (Gadd and Werner 2015). According to Swedish utility companies, faults in the DH substations include leakages, malfunctioning control values and actuators as well as faults in the secondary systems. For faults related to the heat exchanger (HX) in the substation, leakage is one of the most common and fouling one of the least common (Månsson, Johansson Kallioniemi, et al. 2019).

2.3.4 Fault Detection Performance Indicators

To identify faults and fault symptoms in DH substations a range of different performance indicators (PIs) have been developed, tested, and evaluated. Gadd and Werner (2014) developed the temperature difference signature as a performance indicator (PI) to identify faults in substations in a Swedish DH system. Zinko et al. (2005) developed an individual substation analysis method and a ranking procedure for DH substations. It included two evaluation methods: 1) the excess flow method based on a reference primary return temperature and 2) the target return temperature. The excess flow is the difference in volume used for the actual measured return temperature and a fictive reference return temperature, selected with respect to all substations to be assessed. The target return temperature is the ideally achievable temperature for a well-performing substation. For DH substations, it is determined by calculating the heat demand of the substation based on a thermodynamic model for either a 1 or 2-stage configuration.

The excess flow method is commonly used among Swedish utility companies to rank substations with poor performance (Månsson et al. 2021). Bergstraesser et al. (2021) used the excess flow method to evaluate faulty substations and identify measures to reduce the DH return temperature in three German DH systems. Månsson et al. (2019) used the PIs primary delta-T, return temperature signature and energy signature together with thresholds to identify the performance of substations in an actual DH system. The energy signature has also been used with neural networks (F. Zhang and Fleyeh 2020), and to construct models of the buildings supplied by DH (Lin et al. 2021). Abghari et al. (2020) linked substation behavior profiles with the PIs substation effectiveness (defined as primary delta-T divided by maximum delta-T) and least temperature difference (defined as the difference between primary and secondary return temperatures, also called return temperature approach). Farouq et al. (2020) used the primary return temperature as a PI to monitor the substation's operational behavior. To identify fouling of the heat exchanger the relation between thermal power and logarithmic mean temperature has been shown to be an effective PI (Guelpa and Verda 2020).

What the previous studies above have in common are the use of PIs to assess the performance of the DH substations and to detect faults. Although the DC system and substation share many similarities with DH, results from studies based on FDD in DH systems and substations may not be directly applicable to DC systems, despite being suggested in previous studies (Zimmerman, Dahlquist, and Kyprianidis 2017; M. Li et al. 2020). For example, cooling demands in buildings are less outdoor temperature dependent than the heating demands and PIs such as temperature signature and energy signature (where the outdoor temperature is one variable) may be less useful for fault detection in DC substations. Moreover, most systems in buildings connected to a DH system are radiator systems, whereas the systems in buildings connected to a DC system usually are more diverse and complex. Also, some of the previous studies have approached FDD in DH substations by diagnosing the symptoms of a fault, for example detecting high primary return temperature faults (Brès et al. 2019). However, since the delta-T between the supply and return water of the DC system is much lower than in DH systems, the return temperature or delta-T alone are insufficient to describe the performance of the DC substation.

Knowledge about the performance status of the substations in a DC system is a prerequisite to actively work with improvements of the DC system's delta-T (Walletun and Johnsson 2005). However, performance assessment methods of the DC substation are lacking. Neither have any previous studies applied performance assessment methods developed for DH substations on DC substations. For DC substations, PIs in addition to those developed for DH substations may be needed to assess the performance and subsequently enable fault detection. Therefore, a method facilitating a quick audit of the DC substation's performance, similar to the individual substation analysis method developed by Zinko et al. (2005) for DH substations, could be a potential solution. Such a method should also have some practical value for utilization by the utility company owning the district cooling system and/or for the DC customers. It has previously been established that increased delta-Ts from the substations can be achieved through good customer relationships (Månsson, Johansson Kallioniemi, et al. 2019; Buffa et al. 2021) and by continuous work of the utility company (Månsson et al. 2021; Zinko et al. 2005; Petersson and Dahlberg-Larsson 2013). A method to quickly determine the performance of the DC substation using performance indicators could therefore enable a systematic substation analysis on a regular basis, aid the customer relationship building and enhance the collaboration if used for follow-up together with the customers.

3

Methodology

In this chapter the research methodology is explained. The point of departure of the research design is the district cooling system in Gothenburg, Sweden, and some of its connected buildings. The research approach, including data collection and analysis methods, have been chosen and adapted based on the practical feasibilities and limitations encountered throughout the research process.

3.1 Research Design

The point of departure of this research is the district cooling system in Gothenburg, Sweden and approximately 40 of the buildings connected to the system, operating under normal conditions. The data collected from these engineered systems are the foundation of this research project. They also represent the practical applicability of the research outcomes. The identified problems of Gothenburg DCS are inefficient operation and low delta-Ts. These constitute practical problems in Gothenburg DCS but are also recognized problems in many DCS nationally and globally. The research problem was approached by collecting data from the district cooling system and some of the buildings connected to the DCS, to describe and characterize the actual situation. Since the data were collected from permanent measurement equipment and during normal operation it is referred to as ”operational data”. The outcomes from the first phase of the research project generated a few potential solutions on how to solve the identified problem. Some of these potential solutions were explored in the second phase of the research project through fields tests and further analysis.

Certain parameters of the research could not be controlled as part of the research design process, including data availability and accessibility. Adaptability has therefore been of importance as part of the research design. In the start-up phase of the research project, collaboration with several building owners was initiated, which has continued throughout the project. Their willingness to collaborate has constituted a key aspect of this research project. In the start-up phase the availability of data from both primary and secondary sides was unknown. As part of developing a research strategy, the data availability and accessibility were investigated. Based on the outcome of the data availability, the research methodology was formed.

The intended audience of the research also shapes the choice of the research design (Creswell and Creswell 2018). The primary intended audience for this thesis is utility companies, such as Göteborg Energi AB, who own and operate district cooling systems, but also the DC customers who own and operate the buildings' CHW systems and substations. The research has been conducted in close collaboration with representatives from the utility company, who on a continuous basis have provided feedback and input to the research process thereby shaping and influencing the research design with expert domain knowledge and insights from practice. Moreover, outcomes of the research project have provided some decision support for the utility company on what actions to take to increase the efficiency of the DCS. Last but not least, the scientific community, conducting research on district cooling systems and smart energy systems, is also an intended audience of this thesis.

The research approach in the first phase of the project included exploring and analyzing operational data to describe the present situation as well as complementing the analysis with field measurements and interviews with consultants. The research approach in the second phase included testing the proposed solutions resulting from the initial phase. These solutions included field tests, evaluation of price models and developing and testing a method for systematic follow-up of the substations' performance.

3.1.1 Literature Study

As part of the research design, the literature study has served as the foundation. The literature study was conducted to incorporate relevant concepts and form the context of the thesis as well as identifying knowledge gaps and evaluating previously applied methods. The literature search was conducted using Scopus, Web of Science as well as the ASHRAE Transactions library. The primary source of literature was scientific papers published in academic journals and conference proceedings. Additionally, research reports from the IEA DHC Annex and other research programs as well as Swedish research organizations and programs such as Energiforsk and Fjärrsyn on DH and DC, have constituted important sources of the research design and theoretical framework. In Figure 5, an overview of central concepts pertaining to each of the appended papers can be found.

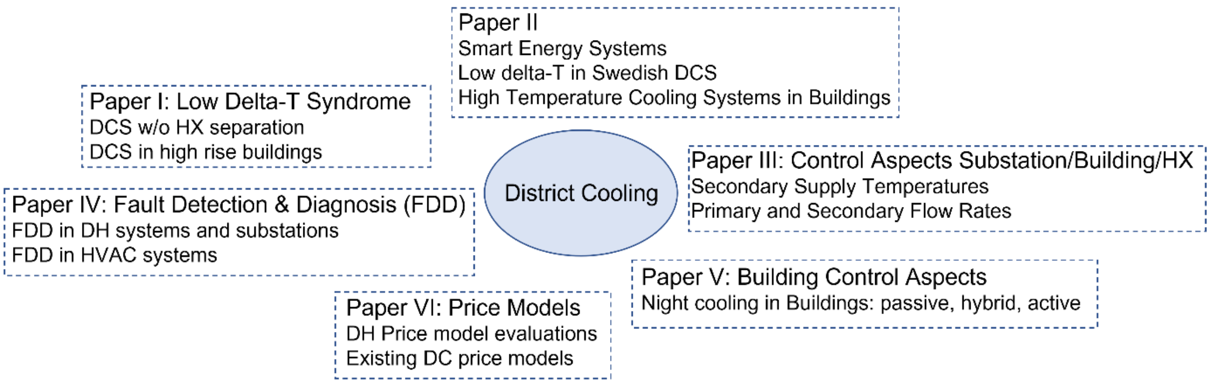

Figure 5: Overview of concepts from the literature studies of each appended paper.

The focus of the literature study in Paper I was on previous research on low delta-Ts in district cooling systems, where the concept "low delta-T syndrome" was identified. Most of the articles were from ASHRAE Transactions. These studies were conducted on DCS without heat exchanger separation as well as smaller DCS where the DC and building owner belonged to the same organization. Moreover, low delta-T studies on a DCS in a high-rise building, where the heat exchangers primarily served to reduce the static pressure, were included. In Paper II the concepts of smart energy systems and high temperature cooling systems in buildings were merged along with incorporating research reports on district cooling from Swedish research institutes. The literature study in Paper III included concepts from previous studies on two control aspects of the substation: the secondary supply temperature and the flow rate relation of the primary and secondary flows. For the secondary supply temperature, studies both from the perspective of the DH substation and the CHW system were reviewed, whereas no previous studies on DC were identified. For the primary and secondary flow rates of the substation, previous studies on both DH and DC were identified along with more detailed studies on plate frame heat exchangers. In Paper IV, the literature study was approached from two perspectives 1) FDD in DH and DH substations and 2) FDD in HVAC systems. No previous studies have been conducted on FDD in DC substations whereby approaching this research domain was done from the two presented perspectives. Paper V was not necessarily related to the temperatures in the DC substation but instead focused on how DC can be used more efficiently by the buildings to reduce their maximum cooling power and how the utility provider could incentivize such actions. The literature study of Paper V investigated the concept of night cooling, including the three aspects passive, hybrid, and active night cooling. Lastly, in Paper VI, price model evaluations were conducted with the aim to provide DC customers with incentives to improve the performance of their substations and increase delta-T. Important concepts were obtained from previous DH price model evaluations along with including five examples of DC pricing from Singapore and Sweden.

3.1.2 Gothenburg District Cooling System

As previously mentioned, the applied object of this research project is the district cooling system in Gothenburg, Sweden, (57.7089° N, 11.9746° E). The district cooling system was established in 1993 by installing distributed cooling islands throughout the city. The locations of the cooling islands were determined based on demand for cooling along with existing provision of district heating in order to utilize district heating in absorption chillers.

In 2002, the cooling islands were connected by underground pipelines into a network which today is almost 40 km long. In 2021, the previously two separate systems on either side of the river, Göta Älv, were connected by a pipeline underneath the river. The district cooling system is owned and operated by the utility company Göteborg Energi AB. The installed capacity in the district cooling systems is about 80 MW, with chiller plants located in different parts of the network, see Figure 6 left. In Figure 6 right, the current system as well as the future vision for district cooling in Gothenburg can be seen.

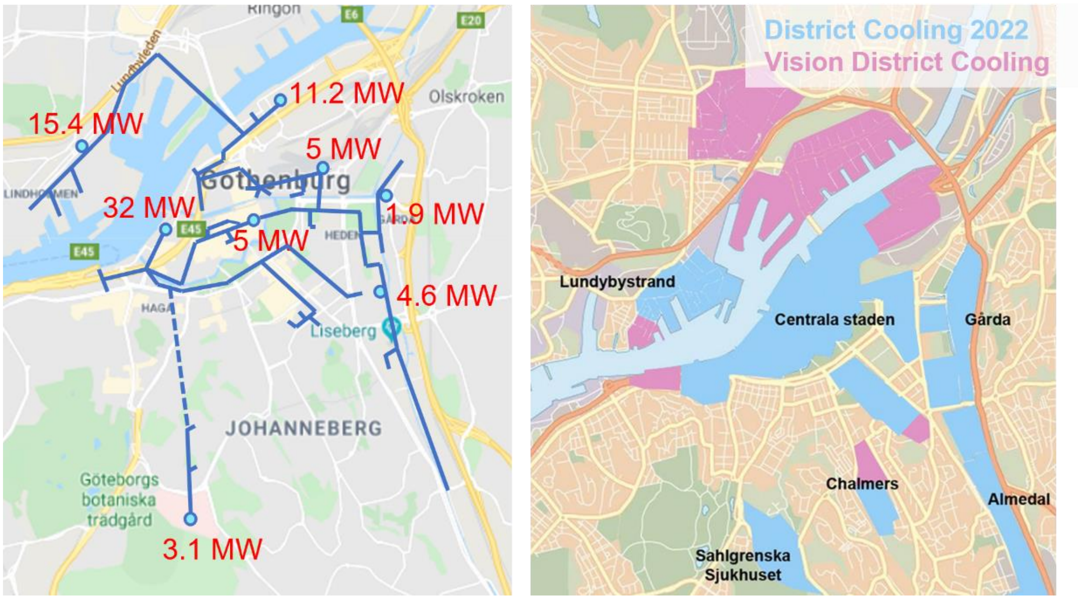

Figure 6: Left: the district cooling system in Gothenburg with production plants, capacities, and an outline of the distribution network. Right: the current district cooling system and the vision of the future district cooling system in Gothenburg.

In the base load plant, Rosenlund, there is 32 MW of installed chiller capacity. In this chiller plant, free cooling is also available from the river via heat exchangers. Free cooling can be used 100% when the river water temperature is ≤ 5 °C, which usually occurs from December to April. When the water temperature is > 5 °C the river 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. The share of free cooling varies on an annual basis with the ambient temperature, the river temperature, and the cooling demands of the buildings. Compared to the Swedish national DC production mix, the share of absorption chillers in Gothenburg DCS is higher, which is a result of abundant waste heat in the district heating system in the summer.

The cooling demand of the buildings is partly dependent on the outdoor temperature and varies between different years depending on the outdoor air conditions. For example, the maximum cooling demand in the DCS was approximately 40 MW for the summer of 2017, whereas 70 MW was reached during the summer of 2018. The difference between the two years was the summer of 2018 being much warmer than average, with temperatures 2-4 °C above normal (SMHI 2018). The district cooling system is growing and the projected cooling demand for the year 2040 is about 160 MW, see Figure 6 right for the expansion plans. This increased cooling demand is largely a result of new buildings in the downtown area of Gothenburg as well as higher demands on thermal comfort in commercial buildings.

According to the latest version of the local technical guidelines for the DC system in Gothenburg, the supply temperature is varied with the outdoor temperature from 6±1 °C for outdoor temperatures ≥25 °C, up to 12±1 °C for outdoor temperatures ≤12 °C (Göteborg Energi AB 2021). The return temperature is required to be ≥16 °C regardless of supply temperature level.

3.1.3 Buildings Connected to the DCS

The buildings connected to the DCS in Gothenburg are all commercial buildings with diverse cooling demands. The business types of the buildings vary from offices with and without retail space and restaurants to healthcare, public service, shopping malls and stores, market halls, hotels, hospitals, museums, and concert halls. In 2021, there was a total of 181 buildings connected to the district cooling system. In Gothenburg DCS, the most common form of substation ownership is by the property owner or property manager. This means, the utility company owns the energy meter and equipment for billing purposes, but the property manager owns the remaining equipment and is responsible for its operation and maintenance.

The buildings are operated by the property owners and in this research project, collaboration with seven different property owners was established. These property owners represent the major property companies in Gothenburg with a large number of buildings supplied by district cooling. The number of buildings initially investigated in this thesis was around 40. This number has varied throughout the appended papers due to numerous reasons, with accessibility and suitability being the principal causes.

The collaboration with the property owners has solely been on a pro bono voluntary basis. To initiate the collaboration, a list with all substations of the DC system was filtered on property companies with the largest number of buildings connected to the DCS. Fifteen companies were inquired for collaboration via the utility company’s key account managers. The inquiry was followed up with an email and/or phone call and if interest and availability were sustained, an initial meeting was held. During the initial meeting, access to the buildings’ SCADA (Supervisory Control and Data Acquisition) systems for remote data collection were arranged for. For buildings from which the data could not be obtained remotely, on-site data collection sessions were scheduled. In total there were nine property owners involved in the initial collaboration, out of which seven have remained active collaboration partners throughout the entire research project.

The data analysis of the first phase of the research project was partly conducted together with the property owners in follow-up meetings and workshops, where the property owners' expert domain knowledge served as input to the analysis. During the field measurements of the secondary flow, the property owners assisted with access and site visits to the substations. Moreover, during the second phase of the research project, when control strategies were field tested in seven different buildings, the property owner ordered programming of the control strategy from their control contractors or changed settings in their buildings' management systems (BMS) to ensure realization of the field tests.

3.2 Data Collection

The studies in the appended papers of this thesis are based on operational data obtained from the data collection systems on both primary and secondary sides of the investigated substations. The data from the primary sides were downloaded from the utility owner's data base with energy meter readings stored for billing purposes. The data from the secondary sides were downloaded from the property owners' SCADA systems, used to monitor and control the cooling operation of the buildings. Complimentary data have also been obtained by field measurements and through interviews with consultants. The conditions for the DCS and the buildings are normal operation, with reservation for unexpected shutdowns or alterations which can be expected as part of normal operation. Buildings known to be undergoing renovations were excluded. The data have been used in all the appended papers of this thesis to investigate different aspects of the substation and the CHW systems in the buildings as well as some effects on the entire district cooling system. In Table 1 an overview of the type of data and data collection system pertaining to each paper can be found.

Table 1: Overview of types of data and data collection systems as included in the appended papers.

Data type	Data collection system	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Operational data	Substation primary side: Energy meter	✓	✓	✓	✓	✓	✓
	Substation secondary side: SCADA system	✓	✓	✓	✓	✓	
	District cooling production plant		✓	✓		✓	
Information about the systems, buildings, and equipment	O&M manuals, equipment specifications, site visits etc.		✓	✓		✓	
Field measurements	Temporary measurement equipment			✓			

3.2.1 Operational Data

The primary data were downloaded during the years 2018-2021, whereas data from the secondary sides were collected based on the objectives of the different appended papers. The data from the secondary side were obtained for the cooling seasons of the years 2018-2021, which lasts approximately from April through September. For the year 2018, data were downloaded from approximately 40 buildings' SCADA systems. For 2021, this number was reduced to 26 due to insufficient data resolution from some of the SCADA-systems, building renovations and other reasons. For 2019 and 2020, data from only a few selected buildings were collected (as used in papers III and V). The cooling demand of the DCS has varied significantly between the four years where factors such as the outdoor temperature in combination with vacation periods and the pandemic Covid-19 have had major influences. In Table 2, details about the collected data can be found.

Table 2: Data collected in the appended papers of this thesis.

No.	Variable	Symbol	Unit	Type of data	Sampling frequency	Data collection system
1	DC-Power	$\dot{Q}_{DC}$	kW	Operational	1/h, hourly average	Energy meter
2	DC-Flow	$\dot{V}_{DC}$	m³/h	Operational	1/h, hourly average	Energy meter
3	DC-Supply Temperature	$t_{DC,\ supply}$	°C	Operational	1/h, instantaneous	Energy meter
4	DC-Return Temperature	$t_{DC,\ return}$	°C	Operational	1/h, instantaneous	Energy meter
5	DC-Delta-T	Δt_{DC}	°C	Calculated	1/h, instantaneous	
6	CHW-Supply Temperature	$t_{CHW,\ supply}$	°C	Operational	1/h, hourly average	Building SCADA system
7	CHW-Return Temperature	$t_{CHW,\ return}$	°C	Operational	1/h, hourly average	Building SCADA system
8	CHW-Delta-T	Δt_{CHW}	°C	Calculated	1/h, hourly average	
9	CHW-Flow	$\dot{V}_{CHW}$	m³/h	Supple-mentary measurement	1/10-min, instantaneous	Temporary field measurement equipment
10	CHW-Control Valve Signal	CV	[%]	Operational	1/h, hourly average	Building SCADA system
11	Indoor air temperature	IAT	°C	Operational	1/h, hourly average	Building SCADA system
12	DCS-Supply Temperature	$t_{DC,\ supply,\ prod}$	°C	Operational	1/h, hourly average	DC operations management system
13	Outdoor Temperature	t_{out}	°C	Operational	1/h, hourly average	DC operations management system and SCADA systems

Field Tests

To test new control strategies not part of the regular CHW operation, three field tests were conducted in seven buildings, as presented in Papers III and V. The control strategies were the following:

- *Active night cooling*. Tested in three buildings during the first half of the summer of 2020, with the second half as reference period. The time schedule control strategy was changed so that the CHW system remained in operation twenty-four hours per day. For the reference period, the time schedule operation was changed back to regular schedules, which means the chilled water systems typically turn off during the nights and weekends, unless the outdoor temperature control component regulates the system to remain in operation. During the active night cooling test, the ventilation time schedules for the three buildings were unchanged.

- *Setpoint minimum limitation*. Tested in one building during the entire summer of 2021, with reference period being the summer of 2020. Also tested in two building during the second half of the summer of 2021, with the first half as reference period. The control strategy was programmed to check that the CHW setpoint, as determined by outdoor temperature compensated curves, was not lower than the minimum limitation value of $t_{DC,\ supply}$ + 2 °C. If so, the CHW setpoint was updated to the minimum limitation value.
- *Primary flow limitation*. Tested in one building during the entire summer of 2021, with reference period being the summer of 2020. The control strategy included a flow limit value and was programmed to read the instantaneous water flow rate from the energy meter. When the water flow exceeds the flow limit value, the control valve starts to close until the water flow is below the limit.

The data collected to evaluate the field tests were operational data as presented in Table 2, as well as field measurements of the secondary flow was conducted during the flow limitation test.

3.2.2 Additional Information

In addition to operational data, information about the buildings, the chilled waters systems, subsystems, and components were obtained as well. This information includes type of control system and operation strategies, information about the installed equipment such as size and operating ranges of the permanent flow meters, control valves, pumps, heat exchangers, and temperature sensors. The information was obtained from the SCADA systems' dashboard of the CHW system, the subsystems, and the end terminals, O&M manuals and equipment specifications, meetings with and inquiries to the building owner's personnel and site visits. However, this information was not available from all investigated buildings. For the substations part of the field measurements, information about pipe material, pipe diameter and insulation thickness were also collected. Information about the energy meter and related equipment were received from personnel at the utility company. Information about the price model was downloaded from the utility company's website and communicated by personnel working with product development.

3.2.3 Field Measurements

To supplement the initial analysis with data not available from the permanent measurement equipment, complementary field measurements were conducted to obtain secondary flow rate data. The flow measurements were carried out in periods of 2-3 weeks in two buildings during the summer of 2019 and in 14 buildings during the summer of 2020. The buildings were selected based on feasibility of correct flow meter installation and availability of the property owners from previous collaborations. Field measurements of the secondary flow were also conducted in the substation where the control strategy flow limitation was tested during the summer of 2021.

The flow meter used was a portable ultrasonic clamp-on flow meter of the type TDS-100F from Ambiductor. For the installation, ten pipe diameters of unobstructed pipe length were required before the flow meter and five pipe diameters after. Moreover, information about the pipe, as described in section 3.2.2, was required input as part of the installation and setup. However, if no information could be retrieved on the pipe, in the substation documentation or by measuring, these parameters had to be estimated. The secondary flow was measured instantaneously with a 10-minute sampling frequency and calculated into hourly averages.

The flow measured by the clamp-on flow meter was verified with the flow measured by the permanent flow meter. This was done by installing the clamp-on flow meter on the primary side of one substation from August 4th to September 15th, 2021. The accuracy of the clamp-on flow meter is reported to be ±1-3%. The clamp-on flow meter measured the flow rate with an error ranging from -3.5 to +3 m^3/h compared to the permanent flow meter. Also, in two of the substations, flow rate fluctuations were observed for flow rates <0.7 m^3/h. In one substation the measured flow was offset with -0.2 m^3/h for the entire measurement period. This suggests there are errors arising from uncertainties due to the clamp-on flow meter installation and the differing sampling frequencies between the permanent and the clamp-on flow meters. Moreover, since measurements during transient conditions produce additional errors (Spitler et al. 2021), uncertainties due to dynamic effects are likely as well. Due to these uncertainties, single flow rate data points may be invalid. However, the trends, as observed from the flow measurements conducted during approximately two weeks per substation, are considered to be valid.

3.2.4 Interviews with Consultants

To support the collected operational data with expert domain knowledge from industry, interviews with seven consultants from six different HVAC consulting companies located in Gothenburg and Stockholm were conducted in 2020. The consultants all currently worked with designing district cooling substations and HVAC systems in buildings. The interviews were conducted in a semi-structured way where interview questions were prepared and followed, but the respondent was free to answer the questions more or less detailed, and a discussion between the interviewer and the respondent was engaged in if feasible. The interview data were not transcribed, but the main outcomes from each interview were extracted along with similarities between the respondents' answers.

3.2.5 Data Uncertainty

The energy meter on the primary side of the substation is of the type Multical 801 (Kamstrup A/S 2015a). It fulfills the European Standard EN 1434 and has an accuracy of $\pm(0.15 + \Delta t_{min}/\Delta t)\%$, where Δt_{min}=2 °C. For example, if the temperature difference is 5 °C, the accuracy is ±(0.15+2/5) = 0.55%. The temperature sensors are of the type Thermowell RTD and fulfill the standard EN 60751, class A, with an accuracy of ±0.1 °C (Göteborg Energi AB 2018). The permanent flow meter accompanying the energy meter is of the type Ultraflow 54 with a tolerance of maximum 5% for the lowest flow of the dynamic range q_i:q_p according to standard EN 1434, where q_i is the lowest flow, q_p is the nominal flow and q_s is the upper flow limit (Kamstrup A/S 2015b). The maximum tolerance for the water flow is 5%, but according to Swedish standards, the flow meters are allowed a higher tolerance in operation.

Although there is a variety of measurement equipment manufacturers among the studied buildings, all water temperatures have been measured by RTD temperature sensors, immersed in the pipes. The temperature sensors are not required to have an accuracy of ±0.2 °C, but this is common in practice. The outdoor temperature sensors typically have an accuracy of ±0.3 °C. However, the main source of error for the outdoor temperature is the location of the sensor which can cause unreasonably high temperature measurements.

In general, the term "data uncertainty" is used for experimental data to define the difference between the true value and the measured valued (Moffat 1988). In this thesis, there are two main types of quantitative data: operational data as measured by permanently installed equipment and data obtained from field measurements with temporary installed equipment. Random errors, which can be reduced as the number of time intervals increases, are considered negligible for the data obtained from the permanently installed equipment. However, for the field measurements, random errors are of concern since only one measurement period of approximately two weeks was conducted per substation. The propagation of errors is also of concern since a systematic error of the temperature sensor propagates as an error in a subsequent temperature difference calculation, which is added in quadrature (Spitler et al. 2021).

Systematic errors arise from poor or absent calibration of temperature and flow sensors, and spatial errors occur due to incorrect sensor positions (Spitler et al. 2021). For the measurement equipment on the primary side, the utility company conducts revisions of the flow meter every five years, and every ten years for the energy meter integrator and the temperature sensors. This involves calibrating the temperature sensors and the flow meter to ensure the measurements are accurate. The measurement equipment on the primary side has high accuracies, low tolerances, low resolutions, and the risk of sensor drifting is minimized by the reoccurring revisions. Therefore, errors due to poor calibration of the temperature sensors and the flow meter is of low concern for the data from the primary side.

The temperature sensors of the energy meter on the primary side are paired, but not calibrated with respect to the absolute temperature. Calibration of the secondary sides' temperature sensors have not been verified. The temperature data are recorded by two separate data collection systems: the primary side (for billing purposes by the utility company) and the secondary side (for monitoring of the building by the SCADA system). The temperature sensors on the primary and secondary sides are not co-calibrated, and the measurements are also sampled with different intervals. The primary temperature measurements are instantaneous values, recorded once per hour whereas the secondary temperature measurements are hourly averages of more frequent readings during an hour.

Despite differences in how the data are recorded, the preconditions of this study are the data available from the buildings' substations and SCADA systems. The point of departure of this research is therefore the installed data collection systems and their obtainable data, however, recognizing the disparities and potential implications on the outcome.

3.3 Data Analysis Method

The analysis of the collected data has been done by exploring relationships between the different variables through data visualization, correlation plots and basic statistical methods. The domain knowledge from experts through meetings, workshops, and site visits have supported the data analysis throughout this research project. The experts are data analysts, business developers, technical managers, and operating engineers from both the utility company and the property company. The analysis of the data is therefore a mix between knowledge-driven and data-driven methods.

3.3.1 Data handling and preprocessing

Since most of the data this thesis is based on is operational data, there are some issues accompanied with the nature of the data. Preprocessing of the data have been done with domain knowledge (as opposed to solely using statistics) and include the following aspects:

- Missing data due to loss of connection between measurement equipment and storing software. Hours for when data have been missing were simply removed.
- Unreasonably low or high values. Such data were identified manually and were replaced by interpolation or removed, depending on selected analysis method.

- For temperature analyses, data recorded for chilled water flow rates less than the minimum cutoff, q_i, of the primary flow meter were removed as well as data measurements for when the signal from the control valve actuator was zero.
- Delta-T calculations based on data meeting the conditions $\dot{V}_{DC} > q_i$ and $\dot{Q}_{DC} > 0$ could still result in negative delta-Ts. Such data were checked for and removed.

For a comparative analysis between the primary and secondary sides of the heat exchanger, the datasets obtained from each side were merged into one dataset. This provided insights on problems with merging data from two separate data collection systems, especially when the differences between the temperatures are small, as in district cooling systems.

When analyzing some of the temperature data, it was extracted for daytime operation using two different time periods, 7:00-17:00 and 10:00-16:00. The reason for daytime data extraction is to follow typical office work hours and increase the likelihood of having a stable cooling demand. However, due to a large diversity among the buildings' control strategies and operating conditions, the choice of daytime period for which the data should be analyzed is arbitrary.

3.3.2 Primary side data

The data on the primary side of the substation were analyzed by exploring the relationship between the variables cooling power, $\dot{Q}_{DC}$, chilled water flow rate, $\dot{V}_{DC}$, and primary delta-T, Δt_{DC} (see Table 2 for details). The analysis was done by adopting a method by Thuillard et al. (2014) which is based on the cooling power of the heat exchanger being a non-linear function of the flow rate due to the impact of delta-T, see Figure 7. The non-linearity is related to the chilled water flow being constant or variable on either or both sides of the heat exchanger. According to Skagestad and Mildenstein (2002), for a variable flow on both sides of the heat exchanger, delta-T should slightly decrease for an increased flow. The plot in Figure 7 is called the "primary plot" and was used to characterize the performance of the substations according to four different trends of the delta-T. Moreover, the best performance point could be identified (Jangsten 2020) along with defining and evaluating the saturation zone.

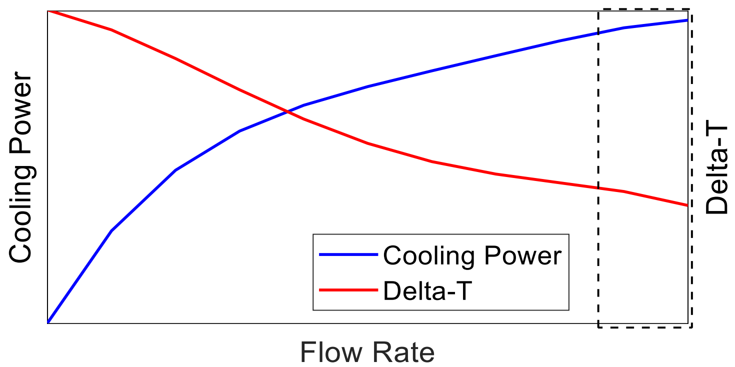

Figure 7: Theoretical "primary plot" which is a correlation plot of cooling power, flow rate and delta-T of the primary side of the substation, with saturation zone indicated by dashed lines (Jangsten 2020).

The saturation zone for district cooling substations is defined as chilled water flow rates greater than what is needed to deliver the maximum cooling power. It means the cooling power has become saturated and an additional chilled water flow rate does not contribute to a higher cooling power, but instead causes the delta-T to deteriorate (Thuillard, Reider, and Henze 2014), see area marked with a dashed lines in Figure 7. The maximum cooling power, called the reference point, beyond which the saturation zone starts, can be defined depending on preference. In the study by Thuillard et al. (2014), the reference point was 85% of the maximum cooling power and in Jangsten (2020) the reference point was 90% of the maximum cooling power. The reference point can be selected based on an individual substation analysis. It can also be selected based on preferences of the utility company, for example to encourage the customers to reduce the maximum cooling power used. For well-functioning substations and for buildings with certain requirements, for example hospitals, the reference point can or should be equal to the substation's maximum cooling power as measured.

Performance Indicators Primary Data

To describe and summarize the performance of the substations, Performance Indicators (PIs) were developed. Four PIs, based on data from the primary side of the substation, were developed and tested on 26 substations with data from the years 2018-2021. The PIs were developed in close collaboration with the utility company through an iterative process. Representatives from the utility company have through meetings and presentations acted as discussion partners providing feedback, recommendations, experiences and practical limitations. The rationale for the selected PIs demonstrates outcomes of the collaborative research process together with the utility company. The primary side PIs are the following and are further described below:

- Primary (mean/median) delta-T for peak cooling loads, $\Delta t_{DC,PI}$ [°C].
- Saturation zone, $SatZone$ [%].
- Overflow, $Overflow$ [%].
- Best-case (mean/median) delta-T, $\Delta t_{DC,best-case,PI}$ [°C].

The temperature difference on the primary side is the most relevant and important indicator of the substation's performance. From the DC utility company point of view, the most important operating scenarios are high cooling loads, also called peak cooling loads. During such hours the DC system's installed capacity is utilized close to its maximum and it is crucial that all substations achieve their highest possible delta-Ts to avoid excessive strain on the system. The PI is therefore defined as the mean or median (depending on the dataset's resemblance of a normal distribution) primary delta-T:

$$\Delta t_{DC,PI} = mean\ or\ median\ (t_{DC,return} - t_{DC,supply}) \tag{10}$$

for peak cooling loads, defined as the hours when the cooling power is 75-100% of the maximum measured power. This delta-T is also used to define the reference model (also called operating line) of the substation which is equal to the heat transfer equation for heat exchangers (Eqn. 2) and is illustrated in Figure 8 on the next page.

The saturation zone explained above, is as a PI defined accordingly:

$$SatZone = \frac{\dot{V}_{max} - \dot{V}_{corresponding}}{\dot{V}_{corresponding}} \tag{11}$$

The saturation zone is thereby defined based on two values of the analyzed dataset, which can be obtained from the primary plot as shown in Figure 8. Using only two values of the entire dataset makes this PI sensitive for hourly disruptions. Regardless, the data analyzed are also used for billing purposes whereby it is essential to identify hourly measurements causing a flow in the saturation zone. However, a well-functioning substation could be mistaken for a poorly performing substation if this PI is used alone without the reference model and the other PIs.

As pointed out above, a variable flow on either or both sides of the heat exchanger should result in a slightly decreasing delta-T for an increased flow (Skagestad and Mildenstein 2002). However, the design delta-T of the DC system is constant at 10 °C regardless of full-load or partial operation and non-steady state. If this delta-T is to be achieved for all operating scenarios, the relationship between cooling power and water flow rate needs to be linear as described by Eqn. 2, with the target delta-T being equal to the DC system design delta-T of 10 °C. However, utilizing 10 °C as the target delta-T for every substation when assessing the performance could lead to a mismatch between realistic improvements of the substation with respect to the DC system design criteria and the substation's design. Instead, a reference model based on the ideal realistic delta-T of each substation has been used, which is the PI primary delta-T for peak cooling loads, $\Delta t_{DC,PI}$, as described above. An example of the reference model/operating line can be seen in Figure 8.

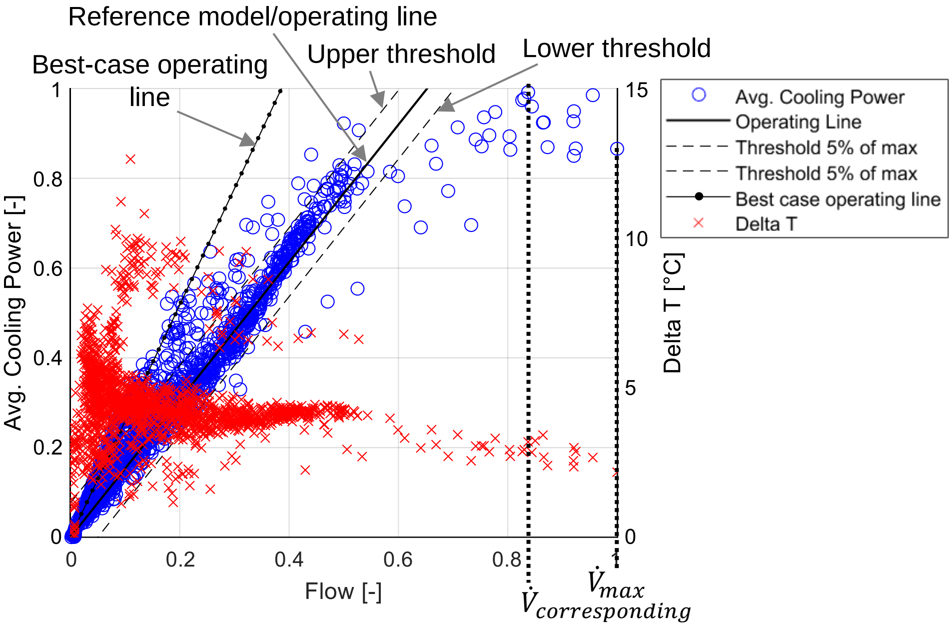

Figure 8: Primary plot with reference model/operating line, thresholds and best-case operating line based on operational data from one substation (Jangsten, Lindholm, and Dalenbäck 2022a).

The reference model as shown in Figure 8, can be used to calculate the overflow of the substation using the residuals below the lower threshold. The thresholds of the operating line are selected to be $\pm 0.05 \cdot \dot{V}_{max}$. The PI overflow is defined as:

$$Overflow = \frac{\sum_{i=1}^{N}(\dot{V}_{actual_N} - \dot{V}_{ideal_N} \geq 0.05 \cdot \dot{V}_{max})_i}{\sum_{i=1}^{N} \dot{V}_{actual_i}} \quad (12)$$

Where:

$$\dot{V}_{ideal_N} = \frac{\dot{Q}_{DC,actual_N}}{\rho_{water} \cdot c_{p,water} \cdot \Delta t_{operating\ line}} \quad (13)$$

Where $\Delta t_{operating\ line}$ corresponds to the PI primary delta-T for peak cooling loads, $\Delta t_{DC,PI}$ and N indicates all hours of the dataset.

Using the residuals above the upper threshold of the reference model, the best-case operating line can be defined, if applicable. This operating line corresponds to operating scenarios with a higher delta-T than that achieved for peak cooling load operation. This PI is called $\Delta t_{DC,best-case,PI}$ and is the mean or median value, based on the residuals (data points) above the upper threshold of the reference model in Figure 8.

The Price Model

The data from the primary side of the substation is as already mentioned used for billing purposes. The billing is done using a price model (PM) composed of three components: energy, power, and flow. The energy is charged per MWh used and the price has three levels depending on the season: winter (January, February, March, December) spring/fall (April, October, November), and summer (May through September). The power component charges for the maximum power used, based on the substation's hourly maximum power as measured the past 12 months. The price level of the power component is divided into five intervals depending on the power used and consists of two parts: a fixed base price per year and a variable price per kW and year. The flow component charges for the flow rate per cubic meters used per month (Göteborg Energi AB 2022). This component currently provides the customers with incentives to maintain efficient substations.

Based on the literature review in section 2.1.2, another price model component suitable as incentive for efficient substations is a temperature component. Four new combinations of a DC price model with a temperature component, either delta-T or return temperature, were developed, and evaluated on 26 substations. The delta-T or return temperature component and were either added to or replaced the flow component of the existing price model. The temperature components were energy weighted using hourly data from the primary side of the substation and arranged to be revenue neutral with respect to the design temperatures of 10 °C and 16 °C respectively. This means delta-T or return temperatures higher than the design temperatures generate a bonus, and temperatures lower than the design temperatures result in a fee.

To evaluate the price model with respect to the substation performance, "proper" function was defined using the performance indicators primary delta-T for peak cooling loads, $\Delta t_{DC,PI}$, and overflow. To enable a comparison between the substations' cost and performance, the cost was normalized based on the total energy delivered to the substation. The normalization was done using only the cost components energy, flow, and delta-T or return temperature if applicable. This is because the relationship between the power cost and the power level is non-linear as well as the substations have different maximum power demands regardless of their performance.

3.3.3 Primary and Secondary Sides Data

Data from both primary and secondary sides were analyzed in parallel with a comparative temperature-temperature plot. It was composed of two plots, one with the primary supply and return temperatures as a function of the outdoor temperature and one with the secondary supply and return temperatures as a function of the outdoor temperature. The outdoor temperature was measured by the SCADA system. Moreover, data from both primary and secondary sides were used to conduct a temperature effectiveness-NTU analysis, see Eqns. 3-9 .

Performance Indicators Primary and Secondary Data

The need to evaluate the temperature approaches between the supply and return temperatures on either side of the heat exchanger is attributed to the analysis outcome using the comparative temperature-temperature plot. If data are available from the secondary side of the heat exchanger, the performance of the substation can be further assessed and some potential causes to a poor substation performance can be identified. Based on data from the years of 2018 and 2021 from both sides of the heat exchanger of 26 substations, extracted for weekdays 10:00-16:00, the following performance indicators were developed and tested:

- Median supply temperature approach for peak cooling loads, $\Delta t_{1,PI}$ [°C].
- Median return temperature approach for peak cooling loads, $\Delta t_{2,PI}$ [°C].
- Heat exchanger temperature effectiveness on the primary side multiplied with the normalized primary return temperature, called heat exchanger coefficient of performance $HXCOP_{DC}$ [-], median value for peak cooling loads, described below.

The most important PI from the perspective of the DC system is the temperature effectiveness on the primary side of the heat exchanger. This is because it reveals the potential of achieving the highest possible return temperatures on both secondary and primary sides along with the greatest temperature difference of the heat exchanger. If not utilizing the flow rate ratio, R, as in Eqn. 3, the temperature effectiveness on the primary side, η_{DC}, can also be expressed by:

$$\eta_{DC} = \frac{\Delta t_{DC}}{\Delta t_{max}} \tag{14}$$

where:

$$\Delta t_{max} = t_{CHW,return} - t_{DC,supply} \tag{15}$$

Another important indicator of the substation performance is a high primary return temperature. Ideally it should as a minimum be equal to the design return temperature of the DC system. For this reason, the actual substation primary return temperature has been normalized with the design return temperature of the DC system and multiplied by the primary side temperature effectiveness from Eqn. 14. This is because it is possible for a substation to have a high temperature effectiveness, yet a low primary return temperature. The variable is called heat exchanger coefficient of performance ($HXCOP_{DC}$) and is defined as:

$$HXCOP_{DC,PI} = \frac{t_{DC,return}}{t_{DC,return\ system\ design}} \cdot \eta_{DC} \tag{16}$$

The design temperatures of the DC system in Gothenburg are 6±1 °C for the primary supply temperature and ≥16 °C for the primary return temperature. According to the technical guidelines of the DC substation, secondary supply temperature should be 8 °C and the secondary return temperature should be 18 °C (Göteborg Energi AB 2021; Energiföretagen Sverige 2019). The design value of $HXCOP_{DC,PI}$ is then equal to 0.83 and the supply and return temperature approaches are equal to 2 °C.

Predictions of Secondary Flow Rates

As alternatives to measuring the flows on the secondary side of the heat exchanger, the flows can also be calculated or predicted. Two different methods to predict the secondary flow rates based on the field measurements were tested and compared. The first method was a heat balance model of the heat exchanger, Eqn. 2, where the input were the primary chilled water flow rate and the primary and secondary supply and return temperatures found in Table 2. The second method was a support vector regression (SVR) model which is a machine learning algorithm based on structural risk minimization. If the data cannot be sufficiently described using linear regression it can be mapped to a high-dimensional feature space by the use of kernels. In this high-dimensional feature space, linear regression can be performed on the data to predict new values (Vapnik 2000; The MathWorks Inc. 2021b):

$$y(x) = \sum_{i=1}^{N} (\alpha_i^* - \alpha_i) K(x_i, x) + b \tag{17}$$

where α_i^* - α_i are the coefficients of the support vectors, x_i is a vector from the training data set, $K(x_i, x)$ is a kernel function and b is a coefficient determining the position of the separating hyperplane in the high-dimensional feature space. The SVR model was developed with MATLAB's regression learner application using the ε-insensitive loss function (The MathWorks Inc. 2021b). The variables of the train and test datasets can be found in Table 2, with $\dot{V}_{CHW}$ being the response variable and variables 2-8 being the predictor variables. Data from 10 different buildings were used to build the model. The dataset was split into a training and testing dataset with 70% of the data used for training and 30% for testing. The available kernels within MATLAB's SVR application were each tested and the one yielding the highest R^2-value and lowest root-mean-square error (RMSE) was selected, which was the Gaussian kernel (Chang and Lin 2011). The model training was done with cross-validation to protect against overfitting (The MathWorks Inc. 2021a). After training, the model was tested with the test dataset, which resulted in an RMSE of 0.266 and an R^2-value of 0.92. After testing, the model was used to predict the secondary flow for each of the 10 buildings separately. See Paper III for further details.

The uncertainties pertaining to the field measurements as discussed in section 3.2.3 also affected the outcome of the secondary flow predictions. However, the uncertainties were the same for both models. Moreover, transient conditions affect the flow measurements but also the applicability of the heat balance model since it assumes steady-state conditions.

3.3.4 Secondary Side Data

In addition to analyzing the secondary side data in relation to the primary side data, it was also analyzed separately. Data variables available from the buildings' SCADA systems, besides supply and return temperatures, were the signal from the control valve(s) on the primary side and the outdoor temperature, see Table 2. These four variables were analyzed in a correlation plot extracted for daytime operation between 7:00-17:00. The secondary supply and return temperatures were plotted a function of control valve signal and clustered into four outdoor temperature intervals, see Paper I for details. To provide insights on the actual supply and return temperatures on the secondary side, boxplots were used, arranged for different outdoor temperature categories. In some of the investigated buildings' CHW systems, the supply and return temperatures to the end terminals of the different subsystems were monitored. For these subsystems the temperatures were analyzed separately, and the subsystems' compositions and end terminals were compiled.

4

Results

In this chapter, the main results are summarized, structured to align with the aim of the thesis. In section 4.1, the results of the characterization of the substations and their performance are presented, based on papers I, III and IV, intending to explain how the substations are operating. In section 4.2, knowledge about the substations and the systems on the secondary side of the substation are provided, primarily based on papers I, II and V as well as the interviews with the consultants. This section serves to provide some insights as to why the substations are operating as observed in section 4.1. Lastly, in section 4.3, the results from papers III, IV and VI are presented as potential solutions on what can be done to improve the performance of the substations by increasing the return temperatures and thereby resolving some of the low delta-Ts.

4.1 Characterization of the Substations' Performance

In this section, the main results from paper I, III and IV are summarized to characterize the substations and their performance, to explain how the substations are operating.

4.1.1 Primary Side

The primary plot, can easily and quickly summarize the performance of the substation, see Figure 9. The reference model/operating line of the substation is calculated using the PI primary delta-T for peak cooling loads. This PI is also used to calculate the overflow of the substation (see section 3.3.2 for definitions of the PIs). In Figure 9, examples of the primary plot with reference model can be seen for four different substations, based on data from 2021 (building 8) and 2018 (buildings 28, 23 and 17), and the PIs are summarized in Table 3. Building 28 demonstrates a clear linear relationship between the variables cooling power and chilled water flow rate, with few data points below the lower threshold. Moreover, there are no data points above the upper threshold (zero-flows not accounted for), whereby the best-case operating line is non-applicable. The delta-T is high regardless of operation condition and the substation is therefore performing well. For building 28 there are some cooling power data with zero flow which is due to missing flow rate data for those hours and is an example of shortcomings with operational data, further discussed in section 5.1.

For building 8, the relationship between cooling power and chilled water flow rate is instead non-linear, and at least two operating modes can be observed. One is indicated by the substation operating line with PI $\Delta t_{DC,PI}$ equal to 5.7 °C. The other operating mode is indicated by the best-case operating line with a

PI equal to 9.1 °C. For building 23, the delta-T can be seen to increase for an increased cooling power, which was observed for buildings with a constant flow on the secondary side. However, the PI $\Delta t_{DC,PI}$ is very low. Building 17 is an example of poor substation performance since the relationship between cooling power and flow neither are linear or non-linear. It can be seen that delta-T is scattered and also very low for high cooling powers. It can also be seen there are hours with zero delta-Ts along the y-axis which are temperature data recorded for hours when the cooling power and flow rate are zero.

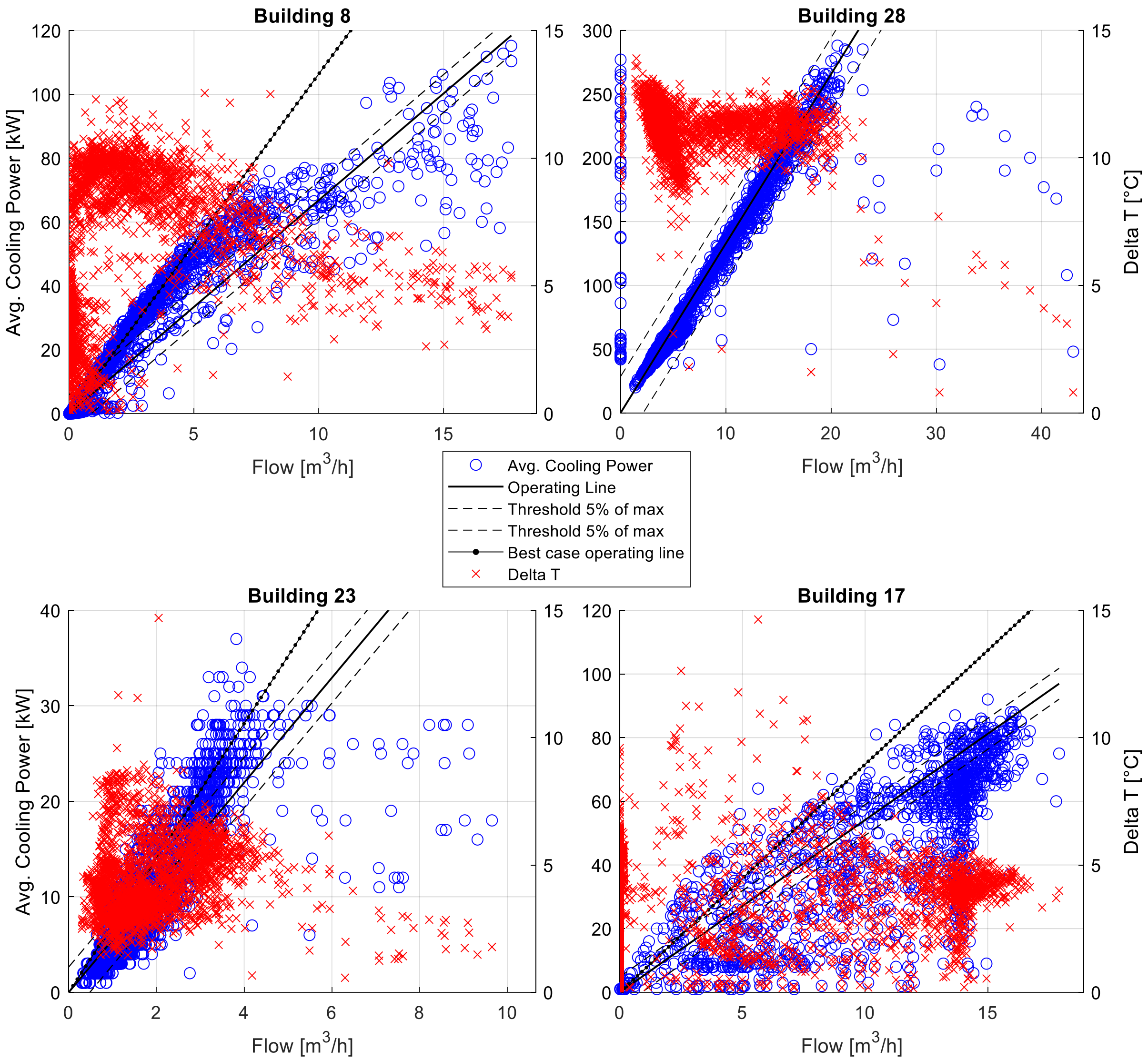

Figure 9: Example of primary plot with reference model for four different substations. Building 8 is based on data from 2021 and buildings 28, 23 and 17 are based on data from 2018. The figure is adopted from Jangsten (2020) and Jangsten, Lindholm, and Dalenbäck (2022a).

The saturation zone for each substation in Figure 9 can be observed by identifying the maximum flow rate and the corresponding lowest flow rate for the maximum cooling power, depending on the reference point used to assign the maximum cooling power. The reference point for the saturation zone PIs in Table 3 are based on the maximum hourly cooling power as measured in each substation. Based on this calculation, the saturation zone includes data points for which the cooling power not necessarily is saturated, such as for building 28. The saturation zone indicates there are hours with a chilled water flow rate greater than what is needed to achieve maximum cooling power (not to be interchanged with the overflow), which subsequently cause low delta-Ts.

Table 3: Performance indicators for four different substations. Building 8 is based on data from 2021 and buildings 28, 23 and 17 are based on data from 2018.

Performance Indicator (PI)	Building 8	Building 28	Building 23	Building 17
Delta-T for peak cooling loads	5.7 °C	11.4 °C	4.7 °C	4.6 °C
Saturation Zone	0 %	109 %	153 %	19 %
Overflow	4.7 %	2.3 %	8.2 %	21.8 %
Best-case delta-T	9.1 °C	NA	6.0 °C	6.1 °C

The PI overflow is also reported in Table 3 and ranges from 2.3% to 21.8% for the different substations. This PI is calculated using the PI delta-T for peak cooling loads as opposed to using a common target delta-T, for example the design delta-T of 10 °C. Thereby the conditions of each substation are accounted for, since a design delta-T of 10 °C may not be realistic for all substations to achieve.

Based on primary side data from the years 2018-2021, an individual substation performance assessment was carried out on 26 substations for each of the years. The output from the assessment is the primary plot with substation reference model as shown in Figure 9, along with the PIs shown in Table 3. The output PIs are summarized in Figure 10 and Figure 11 and can be used to compare the performance of the substations over the four years analyzed. In Figure 10, the PI delta-T for peak cooling loads can be seen to range from a low of 3.3 °C to a high of 13.9 °C, and only five substations have a delta-T of 10 °C or more, conforming to the DC system design criteria. Overall, variations of delta-T between the analyzed years can be seen for 19 substations, whereas six have worsened and one is unchanged. However, any changes done to the buildings and their CHW systems, which could lead to improvements or deteriorations, are unknown. Regardless, the output can be used by the utility company to facilitate continuous follow-up of the substations' performance and initiate a collaboration with the property managers for improvement implementations, see section 4.3.2.

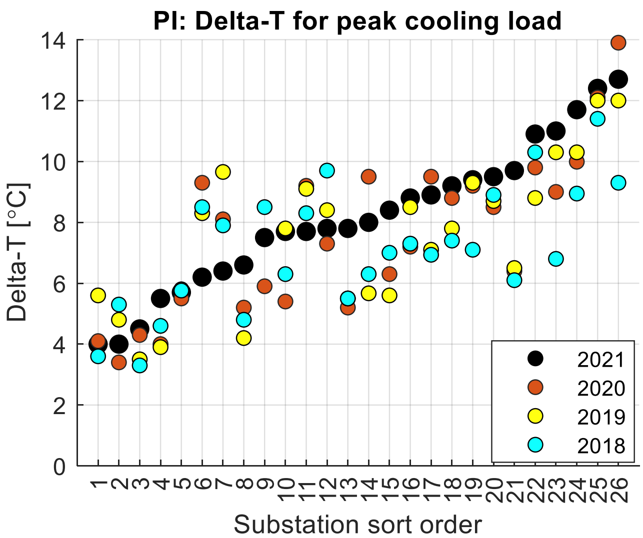

Figure 10: Performance indicator delta-T for peak cooling loads for 26 substations from the cooling seasons of 2018-2021 (Jangsten, Lindholm, and Dalenbäck 2022a).

In Figure 11 the PIs saturation zone and overflow can be seen for 26 substations. The individual substation performance assessment is conducted independent of the data from previous years. The saturation zone is therefore calculated based on the respective maximum flow and corresponding flow for the time period selected for analysis, and the absolute values most likely vary between different time periods analyzed. The same is applicable for the PI overflow since it is calculated using the ideal

$\Delta t_{operating\ line}$ which equally may vary between different time periods. This is a result of altering conditions in the building between the years and cooling seasons, for example changes of tenants and cooling demands, renovations, and energy efficiency implementations. Regardless, the PIs indicate the performance of the substation and improvements, such as a reduced saturation zone, can be seen for substations 1 and 6 for 2021 compared to the three previous years. The opposite can be observed for substations 21, 23, 25 and 26. This can be due to unique hourly events affecting the saturation zone and a detailed analysis using the primary plot as shown in Figure 9 is needed to understand the deteriorated performance as indicated by this PI. For the PI overflow, 18 of the analyzed substations have reduced the overflow in 2021 compared to previous years. This does not necessarily mean that $\Delta t_{operating\ line}$ has improved for each of those substations, but the substation control is functioning better than previously. The lowest overflow obtained from the four cooling seasons of the 26 substations is 0.1%, indicating an overflow close to zero is possible to achieve.

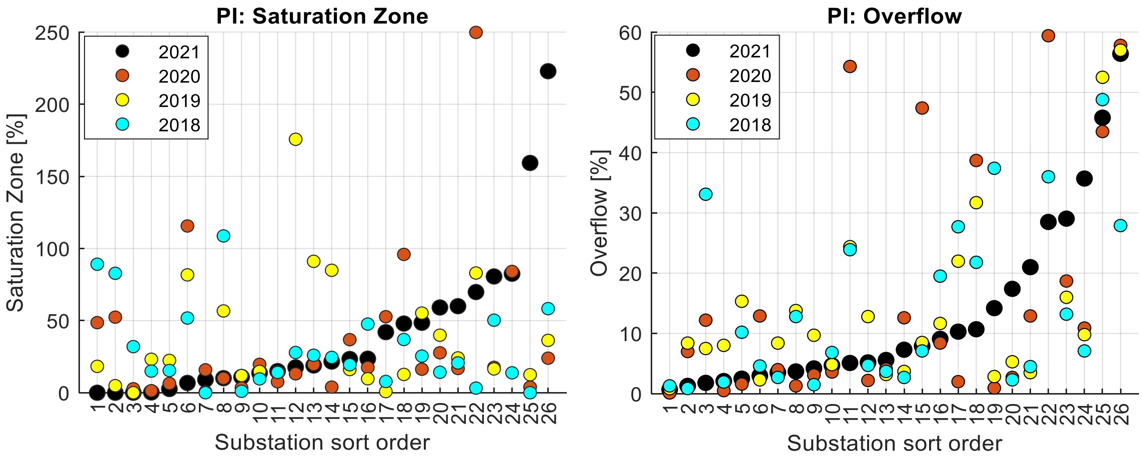

Figure 11: Performance indicator saturation zone (left) and overflow (right) for 26 substations from the cooling seasons of 2018-2021 (Jangsten, Lindholm, and Dalenbäck 2022a).

The PI saturation zone in Figure 11 shows that no substations manage to avoid the saturation zone, and excessively high flow rates have been used. This could be related to control issues during peak load operation. It could also be a result of unstable control during part load operation causing the flow rate to increase (see example of building 28 in Figure 9). Both of these issues could sequentially be a result of primary supply temperatures increasing above the specified 6±1 °C. A flow limitation control strategy can effectively eliminate the saturation zone (see section 4.3.1). The control strategy could therefore be a simple solution to compensate for potential flow control issues, especially during peak load operation. The PI overflow in Figure 11 indicates the substation performance based on both part and peak load operation. As can be seen, only one substation has the ideal position of close to 0% overflow. This implies it is possible to consistently achieve a stable control resulting in almost no overflow. However, for the remaining 25 substations, optimizations and improvements during both part and full load operation can be done to reduce the amount of overflow.

4.1.2 Comparison Primary and Secondary Sides

By using the comparative temperature-temperature plot as described in section 3.3.3, operational traits attributed to the heat exchanger could be identified, see example of building 8 in Figure 12. The secondary return temperature is high, whereas the primary return temperature is low. Therefore, low primary return temperatures are not solely caused by low secondary return temperatures. Instead, such low delta-T emerges across the heat exchanger. Because of this, and if temperature data from both sides of the heat exchanger are available, the temperature approaches of the heat exchanger should be calculated. For building 8 the PI supply temperature approach is 1.0 °C and the PI return temperature approach is 7.2 °C. The temperature approaches can then further aid the performance assessment of the substation and identify potential causes to low primary return temperatures.

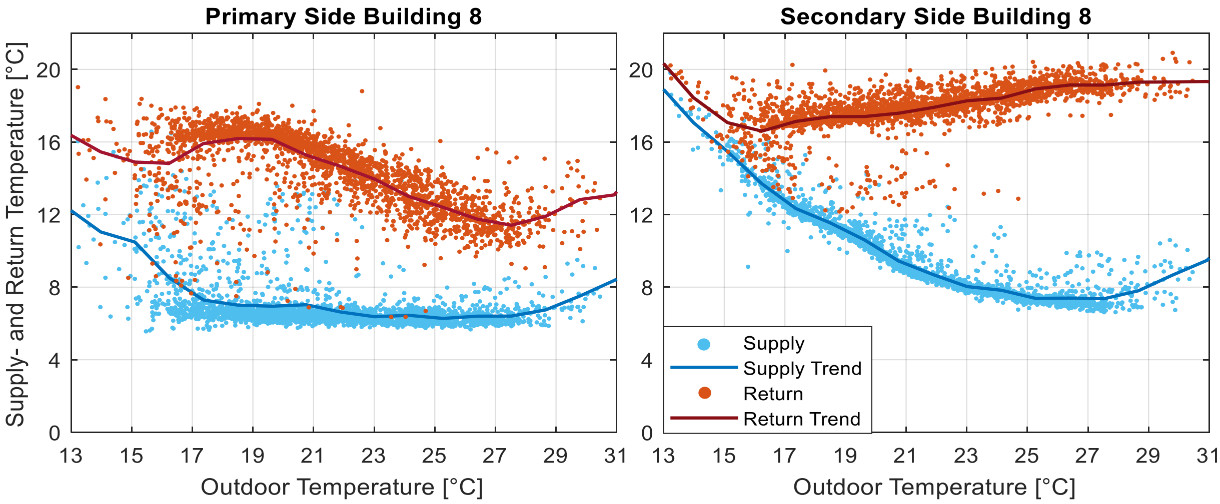

Figure 12: Example of a comparison temperature-temperature plot of the primary and secondary sides supply and return temperatures as a function of outdoor temperature (Jangsten 2020).

The performance indicators as explained in section 3.3.3, based on both primary and secondary data, were tested on 25 substations as part of the individual substation performance assessment, using data from the cooling seasons of 2018 and 2021. The PIs supply and return temperature approaches can be seen in Figure 13. For PI supply temperature approach, it can be observed that four substations have a value less than 2 °C for 2021. It suggests these buildings have setpoints violating the requirement of maintaining a minimum of 2 °C between the primary and secondary supply temperatures, which in turn could cause a low primary return temperature. Conversely, the remaining 21 buildings have supply temperature approaches greater than 2 °C, which is desirable since it enables a high primary return temperature.

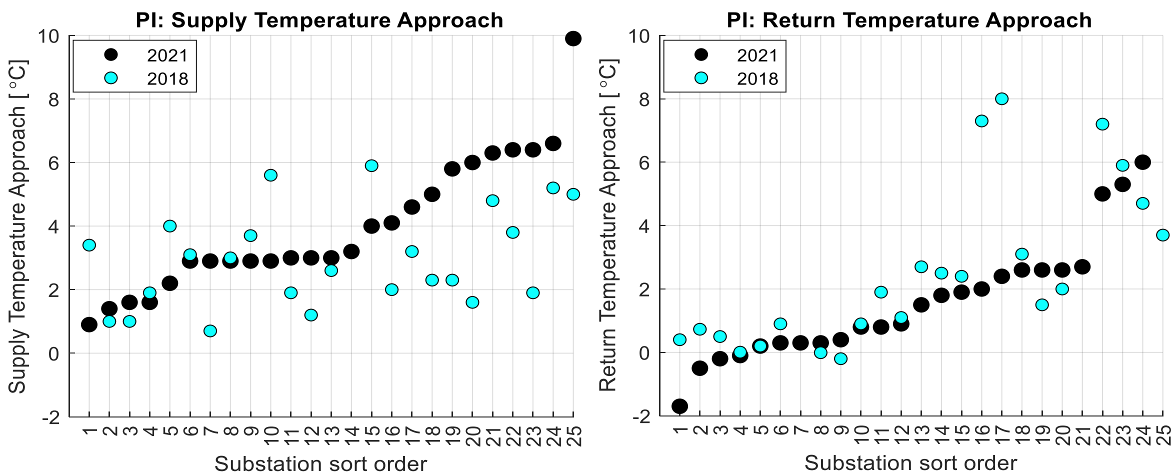

Figure 13: Performance indicators supply temperature approach (left) and return temperature approach (right) for 25 substations from the cooling seasons of 2018 and 2021 (Jangsten, Lindholm, and Dalenbäck 2022a).

For PI return temperature approach in Figure 13 it can be seen that values of zero or less than zero are obtained for four substations. This is impossible since it violates the thermodynamical laws. Instead, it highlights problems with merging temperature measurements from two separate data collection systems on either side of the heat exchanger, despite extracting daytime-data for office hours and peak cooling loads when calculating the PIs. Lastly, in most substations, the supply temperature approaches have increased and the return temperature approaches have decreased, which is a positive outcome between the two years.

In Figure 14, PI $HXCOP_{DC}$ is shown for 24 substations. Based on the design temperatures of the DC system, the minimum optimal value is 0.83. Ten substations reach 0.83 or more and five have a value greater than 1, which is possible with a primary return temperature greater than 16 °C. The remaining 14 substations have values less than the design value. It is possible the heat exchanger has a high temperature effectiveness, but still returns a low primary return temperature. The temperature effectiveness alone as a PI could therefore indicate a satisfactory substation performance when the primary return temperature would suggest the opposite. Some of the low $HXCOP_{DC}$ values could therefore be due to primary return temperatures being significantly lower than 16 °C or return temperature approaches being high (greater than 2 °C).

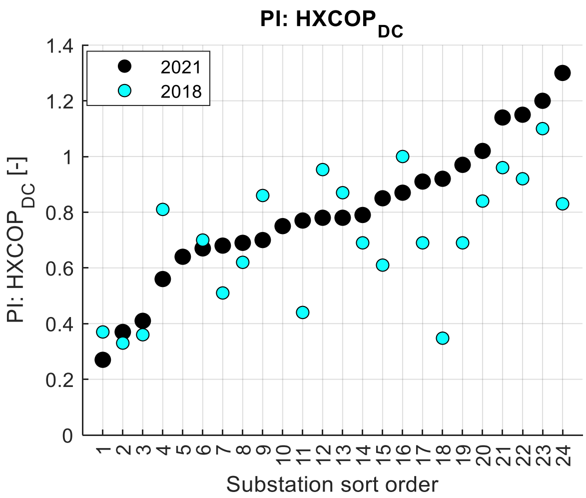

Figure 14: Performance indicator $HXCOP_{DC}$ for 24 substations from the cooling seasons of 2018 and 2021 (Jangsten, Lindholm, and Dalenbäck 2022a).

Based on Figure 14, $HXCOP_{DC}$ has increased in a majority of the substations in 2021 compared to 2018. This indicates improvements of the heat exchanger's performance are possible without replacing the heat exchanger (assuming this was not undertaken by the building owner between the two years). It could also be due to the extremely warm summer of 2018 causing a worse performance compared to the summer of 2021, which was less warm than 2018.

4.1.3 Secondary Flow Rates

The results from the secondary flow measurements were grouped into four categories based on the following trends observed: 1) higher primary flow and lower secondary flow, 2) lower primary flow and higher secondary flow, 3) balanced primary and secondary flows and 4) other trend observed. The number of substations for each category can be seen in Table 4, where half of the substations had a lower primary flow rate compared to the secondary flow rate. Examples of categories two and one can be seen in Figure 15 left. An example of the trend observed for one substation belonging to the category "other" were primary flow rate spikes during nights and weekends leading to a flow rate ratio, R, as high as 62 for the spikes. The reason to this behavior could be issues with the regulation of the control valve on the primary side during non-office hours.

Table 4: Results from the field measurements of the secondary flow.

Category: trend observed	Number of Substations
Higher primary flow, lower secondary flow	3
Lower primary flow, higher secondary flow	8
Balanced flows	2
Other	3

Using the primary and secondary flow rates along with both primary and secondary supply and return temperatures, a temperature effectiveness-NTU analysis was conducted for the 16 buildings, see Eqns. 3-9. An example of the temperature effectiveness-NTU analysis can be seen for two of the buildings in Figure 15. In the right graphs the HX temperature effectiveness (Eqn. 3) as a function of NTU (Eqn. 6) can be seen to decrease for an increased R (flow rate ratio between primary and secondary flows, Eqn. 4). The design temperature effectiveness is 0.83, and for building 2 it is ≥0.83 for almost all hours. Conversely for building 5, a temperature effectiveness ≥0.83 is only achieved with R≤1 and a sufficiently large NTU. Similar trends could be observed for the remaining 14 buildings, where the design temperature effectiveness only could be reached with an R≤1.

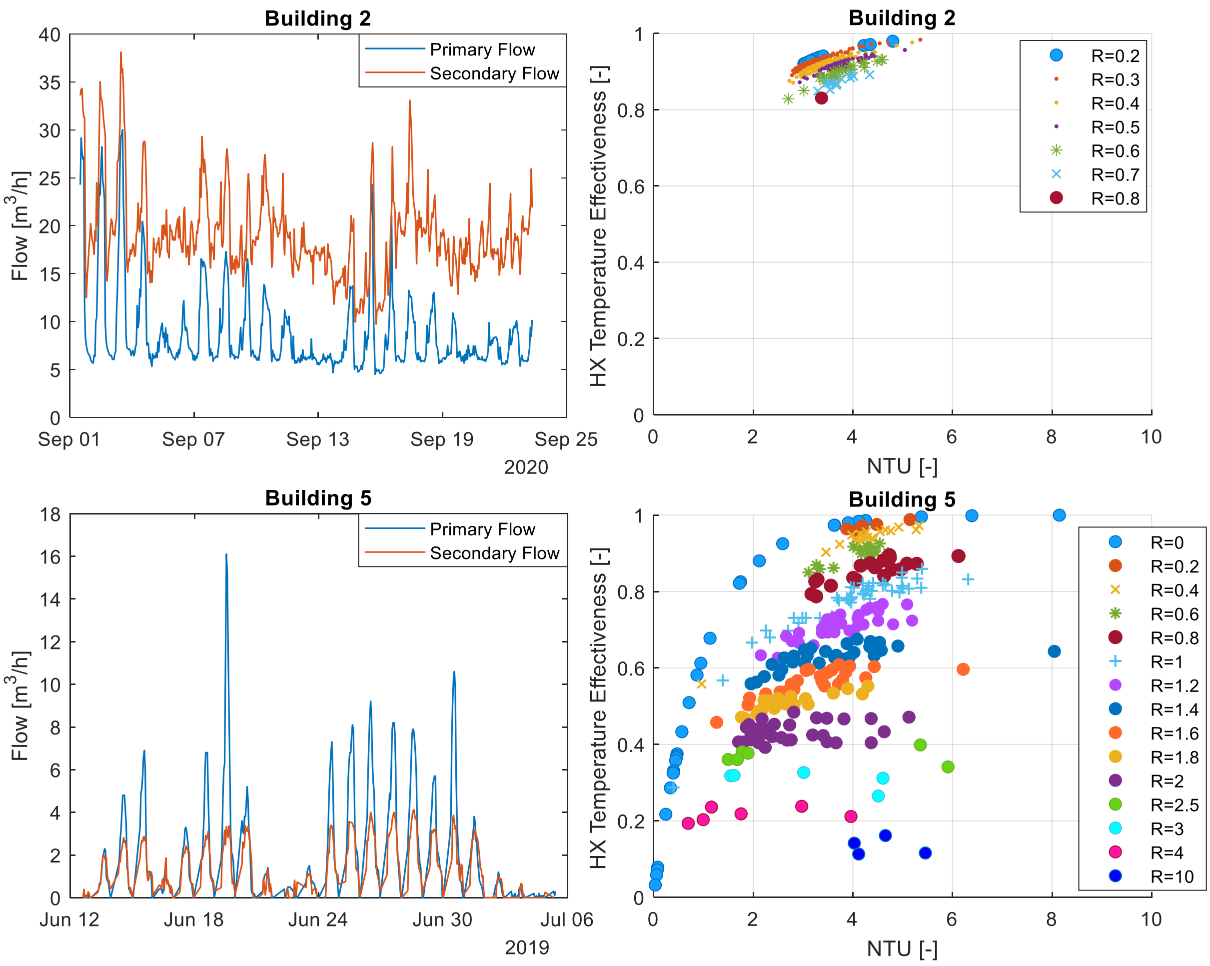

Figure 15: Left: primary flow rates and secondary flow rates from field measurements for buildings 2 and 5. Right: Heat exchanger temperature effectiveness as a function of NTU and flow rate ratio R for buildings 2 and 5 (Jangsten, Lindholm, and Dalenbäck 2022c).

The dynamic range, q_i:q_p for the permanent flow meters in buildings 2 and 5 are 0.4-40 and 0.10-10 m^3/h respectively. As shown in the left graphs of Figure 15, the primary flow is within this range for building 2. However, for building 5 both upper and lower limits of the dynamic range are exceeded, and such data may be less accurate than data within the range.

As recommended in the technical guidelines, the flow rates on the primary and secondary sides of the heat exchanger should be balanced (Energiföretagen Sverige 2019). However, as shown in Table 4, only 2 of 16 substations exhibited balanced flows. The outcome from the temperature effectiveness-NTU analysis showed the HX design temperature effectiveness only could be achieved with a flow rate relation between the primary and secondary flows greater than or equal to 1, in agreement with Kandlikar and Shah (1989) and Frederiksen and Werner (2014). These results highlight the need to evaluate the flow rate relation to further improve to poor substation performance and resolve low delta-Ts.

4.2 Evaluation of the Substations and the Buildings' CHW Systems

In this section the main results from papers I, II and the interviews with the consultants are summarized. These results intend to provide knowledge about the substations and the buildings' chilled water systems to better understand why the substations are operating as characterized in the previous section.

4.2.1 The Substations

The buildings had one or two heat exchangers in the substation, with two exceptions to this occurring among the 42 buildings investigated. As confirmed by the interviews with the consultants, two heat exchangers are primarily used for two reasons: 1) for redundancy, to keep the CHW system in operation in case of failure or during maintenance and 2) if the base load cooling demand is significantly lower than the cooling demand for the provision of thermal comfort. All investigated substations had supply and return temperature sensors on the primary side as well as supply temperature sensors on the secondary side. However, return temperature sensors on the secondary side were absent in six substations, one of which was rectified after mentioning it to the property manager. Most of the substations had variable speed pumps on the secondary side, but at least three were identified with constant speed. The control valves installed in the substations are pressure-dependent.

Based on results from the interviews with the consultants, the knowledge and awareness of the technical guidelines among the consultants designing DC substations were identified as high. Newer buildings, built after the technical guidelines were established and designed to be supplied by DC, are designed according to the requirements in the guidelines. However, some buildings designed for DC nevertheless fail to meet the requirements as stipulated by the guidelines. This could be a result of poor system design, failing to comply with design during the construction phase along with issues during start-up and commissioning of the systems. Moreover, some buildings and substations are designed for higher temperatures than those required by the guidelines, which has resulted in exceeding the temperature requirements in the guidelines.

Buildings not designed for DC are typically older buildings, either built before the technical guidelines were established or originally built to be supplied by a local chiller. Local chillers were usually designed for lower temperatures than those in the DC guidelines. Such buildings were not necessarily upgraded prior to being connected to the DC system, which is therefore a reason to non-compliance with the temperature requirements. However, not all older buildings fail to meet the temperature requirements. Despite not being designed for DC, some older building CHW systems and substations both meet and exceed the DC temperature requirements.

Oversizing

Inaccurate calculations of the building's cooling demand result in oversized systems and components in the substation, which can cause failure to meet intended design operation. In the interviews with the consultants, it was pointed out that oversizing of the CHW systems and the substations are common. Moreover, the peak load conditions for which the systems are designed for, only come into effect a few hours per year. Therefore, the CHW system is operating in part load for most of the year, whereby the installed capacity is excessive of what normally is required. To provide insights on potential oversizing, the size of the permanent flow meter and accompanying q_p and q_s flows were analyzed together with the maximum primary flow using data from 31 substations from the summer of 2018. The analysis showed that 16% appeared to be undersized, 23% were oversized and 61% were of correct size. Five substations had a maximum flow greater than q_s, whereby such flows are outside the tolerance limit for the flow meter and the maximum permissible error could be exceeded.

4.2.2 The CHW systems

There was a variety of different control systems (also called SCADA systems or BMS) among the buildings investigated. The most common types from which the data on the secondary side were collected in this thesis were KTC, Kabona, Webport, Nordomatic, Keylogic and ExoWeb along with a couple of older analog systems. The data availability from the aforementioned SCADA systems varied as well as the timestamp resolution for which the data were recorded. The different SCADA software had diverse storage capabilities in terms of size and time, which also was dependent on the data timestamp resolution. For example, data with an hourly average resolution were for one SCADA system stored for one month, and data with a 24-hour average resolution were stored longer. Another SCADA system stored hourly data for several years. One SCADA system stored 3-minute resolution data for 3 months.

The SCADA systems had building specific control strategies for the chilled water systems depending on the demands and requirements for each building. However, the most common control strategies observed for the buildings investigated were the following:

- *Time schedule operation*. Different time schedules are utilized for the chilled water pump and HVAC system based on day of the week and cooling demand present in the building, usually determined using the outdoor temperature.
- *Pump on/off*. In addition to the time schedule operation, the CHW system pump is started and shut down based on different conditions. Examples include a pre-set outdoor temperature condition, the present cooling demand of the end terminals and summer/winter conditions. For some of the investigated buildings, the CHW system pump also operates continuously.
- *CHW supply temperature setpoint*. For the investigated buildings, different strategies on determining the setpoint of the CHW supply temperature were found. Examples include a constant setpoint if the system is in operation, outdoor temperature compensated curves and calculation of the setpoint based on building parameters and a cooling demand being present.
- *Heat recycling*. For chilled water systems with integrated in-building chillers for refrigeration purposes, the CHW system was used to cool the condenser side of the chillers. This was done using a heat recycling control strategy, set to operate for either a summer/winter condition or a certain outdoor temperature.
- *Free cooling.* Based on the interviews with the consultants, three of seven consultants reported they usually design the CHW systems with an option for free cooling from the outdoor air. A common free cooling arrangement was using a cooling coil connected to the CHW system, located in the duct before the AHU. The cooling coil thereby

exchanged heat from the CHW system with the incoming outdoor air. A free cooling arrangement and control strategy were observed in at least three of the investigated buildings.

Another control strategy, discussed in the interviews with the consultants, was a cooling power restriction. This control strategy is more common among district heating supplied buildings, but less common in DC supplied buildings. Only two of seven consultants implement this control strategy as a standard when designing DC substations. It is typically not requested by the property manager but instead suggested by the consultant. Depending on the type of business in the building, allowing the indoor temperature to rise above a certain limit may not be possible. Many property managers therefore prioritize maintaining the indoor temperature as opposed to restricting the cooling power.

Based on the analysis method as described in section 3.3.4, it was found that 71% of the analyzed buildings use outdoor temperature compensated curves to control the secondary supply temperatures. In Figure 16, the actual supply and return temperatures of the building chilled water systems in 37 of the investigated buildings are shown. 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 verifies that outdoor temperature compensated curves are used for the secondary supply temperature setpoint for most buildings.

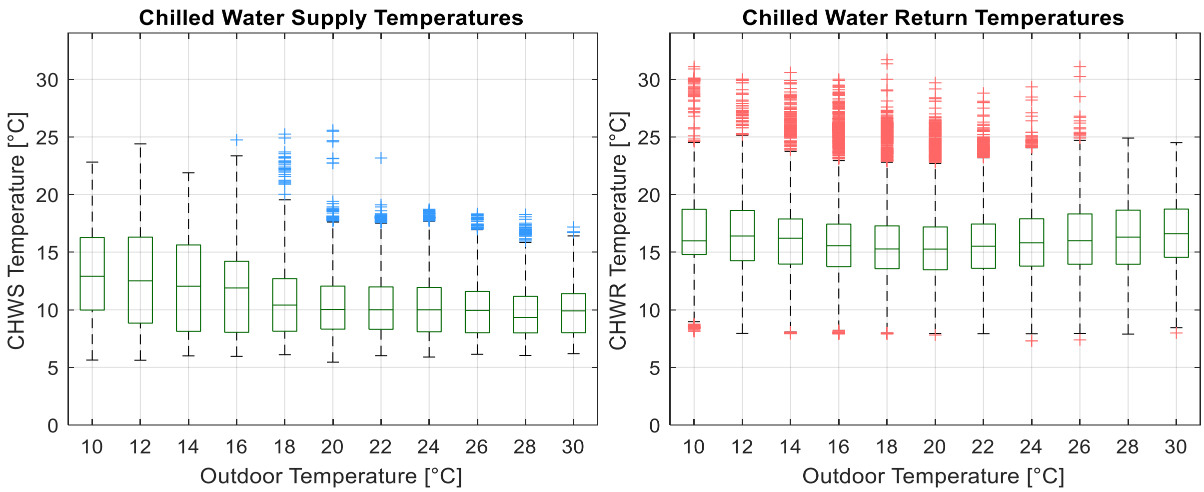

Figure 16: Boxplot of the actual chilled water supply and return temperatures on the secondary side of the heat exchanger in the substation for 11 outdoor temperature categories. Each data point is an hourly measurement recorded during April to September of 2018. Left: chilled water supply (CHWS) temperatures. Right: chilled water return (CHWR) temperatures (Jangsten et al. 2020).

For the CHW return temperatures in the right diagram in Figure 16, a larger spread among the values for all outdoor temperature categories can be observed, compared to the CHW supply temperatures. Moreover, the technical guidelines recommend the CHW return temperatures to be 18 °C and the upper quartile value varied between 17.5-18.5 °C for all temperature categories. This means 75% of the CHW return temperatures are lower than the requirements in the guidelines. It can also be seen that there is a significant number of outliers in both left and right boxplots of Figure 16. This is due to the distribution of the temperature measurements not resembling a normally distributed dataset. The reason there are very high supply and return temperatures (>20 °C and >26 °C respectively) could be due to a low or absent cooling load, but nevertheless a primary flow rate. It could also be a result of recycling heat from the condenser side of in-buildings chillers.

In Figure 17, a compilation of the most common building chilled water system configuration among 37 of the investigated buildings is shown, including the different subsystems, end terminals and associated temperature ranges. The investigated buildings showed a large diversity of CHW system composition, and no chilled water system was identical to another. Nevertheless, the CHW systems were typically composed of a combination of an all-air system together 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 37 buildings, three buildings had CHW systems supplying only cooling coils for AHUs and two buildings had CHW systems composed of only FCUs and/or chilled beam systems. In two buildings, the condenser side of local chillers for refrigeration purposes was connected to the CHW system.

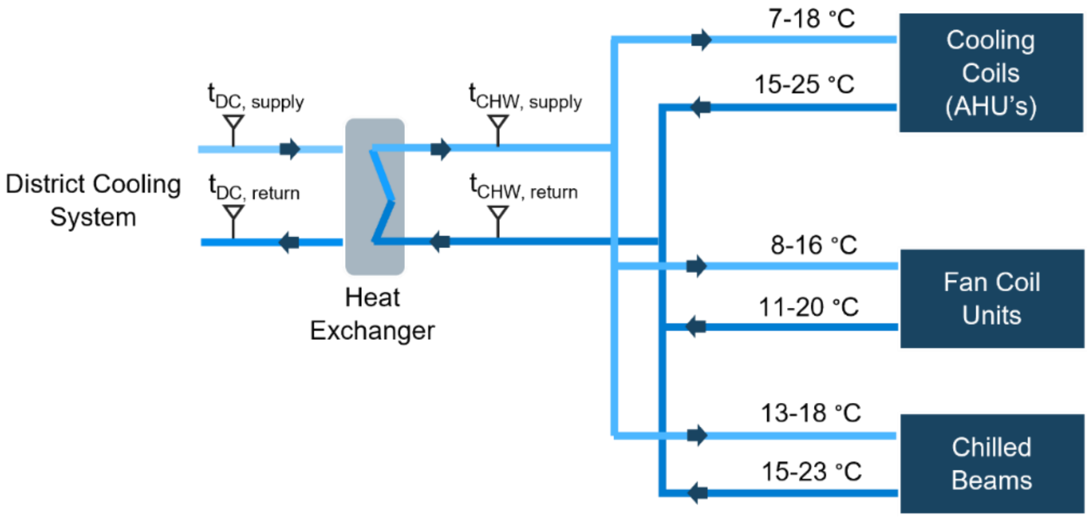

Figure 17: Typical configuration of the chilled water systems of the buildings connected to the district cooling system, with subsystems and associated supply and return temperatures (Jangsten et al. 2020).

The required chilled water temperatures in a building's chilled water system are decided by the type of end terminal supplied. The temperature ranges as shown in Figure 17 were based on average temperatures for an outdoor temperature of ≥25 °C, for buildings with individual monitoring and data available for the shown subsystems. For the cooling coils in the AHUs, the supply temperature range was relatively large. However, based on 37 buildings, only eight buildings with a total of 17 subsystems had individual temperature monitoring and data accessible for the cooling coils. Out of these, only 11 subsystems measured the return temperature as well. For the remaining buildings without individual monitoring for the AHUs, the cooling coil supply temperature was the secondary chilled water temperature as measured directly at the outlet of the heat exchanger ($t_{CHW, supply}$ in Figure 17). According to the interviewed the consultants, cooling coils with supply and return temperatures of 12/18 °C are commonly selected, even if the building is supplied by district cooling with lower chilled water temperatures available.

Similar to the cooling coils, only six buildings with a total of 11 subsystems had individual temperature monitoring of the FCUs. Some of the FCU subsystems had low supply temperatures (down to 8 °C), which was also commonly observed for the AHU cooling coils. However, some of the FCU subsystems had higher supply and return temperatures (up to 16 °C) which likewise was observed for some of the cooling coils, but more typical for the chilled beam subsystems. Based on the interviews with the consultants, FCUs are used for specific cooling purposes in the buildings, such as in mechanical, electrical and server rooms with a constant baseload. FCUs are also used in laboratories, atriums, and hotels. Oftentimes the choice of using FCUs is subject to the opinions and previous experience of the property owner.

For the chilled beam subsystems, temperature data were more frequent compared to the subsystems cooling coils and FCUs. Out of 34 buildings with chilled beam subsystems, 19 buildings had data available for a total of 28 chilled beam systems (some buildings had more than one chilled beam system). Supply temperature data were available for all 28 systems, which is a result of regulating the CHW supply temperature based on the dew point temperature of the return air, since there is no condensation removal system for the chilled beams. Of the 28 chilled beam systems, 19 had data available for the return temperature as well. In Figure 17, the range of actual temperatures to and from the chilled beams are shown to be 13-18 °C supply and 15-23 °C return. Six of the seven interviewed consultants design chilled beam systems for a supply temperature of 14-15 °C and a return temperature of 17-18 °C.

High Temperature Cooling Systems

In high temperature cooling (HTC) systems as described in section 2.2, the sensible and latent cooling loads are decoupled. A high temperature water-based cooling system typically handles the sensible cooling loads with chilled water supply temperatures of approximately 16 °C and up. For the chilled beam systems, higher chilled water temperatures from 14 °C are obvious due to dew point regulation, yet some fan coil unit systems and cooling coils also used such high supply temperatures. Despite the chilled beam subsystems using high temperatures, the accumulated return temperature of the building chilled water system 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 typically 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's CHW system. Based on the buildings' CHW subsystem temperatures encountered in Figure 17, 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 larger compared to the temperature range recommended by the technical guidelines (Energiföretagen Sverige 2019), as well as there is a substantial overlap between the three subsystems' temperature ranges.

Buildings with CHW systems composed of cooling coils in AHUs and chilled beam subsystems have decoupled cooling loads, which was a majority of the buildings investigated in this thesis. The sensible cooling demand is primarily handled by the chilled beam subsystems, and the latent loads (but also part of the sensible load) are removed by the AHUs. For this reason, the building CHW systems in this thesis already have a somewhat similar composition as that of HTC systems. Based on the interviews with the consultants, HTC systems are not specifically requested by the property developers. Regardless, it is common that the consultants design for higher temperatures than the technical guidelines suggest, for example if large amounts of free cooling from the outdoor air are designed for. For such CHW systems it is typical with a warmer CHW system handling the sensible cooling loads and a colder CHW system being used for dehumidification. One of seven consultants use higher temperatures up to 17 °C supply and 20 °C return for the chilled beam systems. Only one property developer requests HTC systems in their buildings, with supply temperatures of 21-22 °C for the chilled beams. However, such buildings are typically designed for a different cooling supply source than district cooling.

4.3 Potential Solutions to Improve the Substation Efficiency

In this section, the main results from papers III, IV and VI are summarized to provide some potential solutions to improve the performance of the substations. The solutions are focused on increasing the return temperatures of the substations and thereby resolving some of the low delta-Ts.

4.3.1 Control Strategies

In this section, three aspects pertaining to the control of the substation to resolve low delta-Ts are presented. The three aspects involve 1) the CHW supply temperature setpoint, 2) the primary water flow rate and 3) the flow rate relation between the primary and the secondary chilled water flow rates.

CHW Supply Temperature Setpoint

By analyzing the temperature approaches of the heat exchanger with the comparative temperature-temperature plot in section 4.1.2, the secondary setpoint was shown to be a potential reason to low delta-Ts. Therefore, a solution to the identified problem could be to ensure a sufficient temperature approach between the primary and secondary supply temperatures. This can be achieved by implementing a control strategy where the setpoint of the CHW supply temperature always should be at least 2 °C higher than the primary supply temperature and automatically adjust accordingly if the primary supply temperature changes. Such a control strategy, called "setpoint minimum limitation" is suggested in the technical guidelines, see section 2.1.1 and explained in section 3.2.1. The results, comparing the supply temperature approach and the primary return temperature before and after the control strategy implementation, are shown in Figure 18. The data have been extracted for weekdays between the hours 10:00-16:00 to eliminate potential temperature inaccuracies due to low or absent cooling demands.

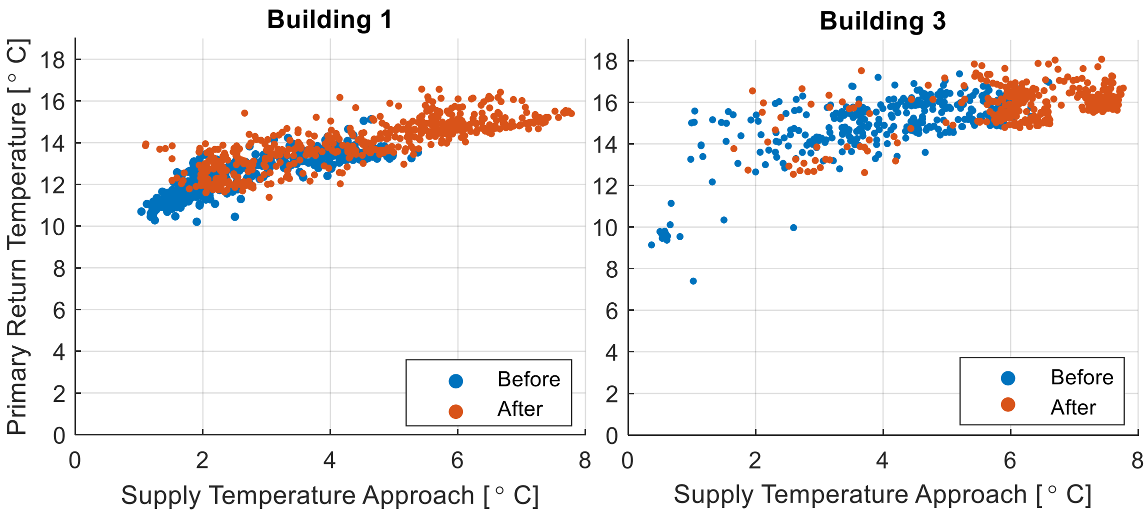

Figure 18: Supply temperature approaches vs. primary return temperatures for two of the buildings where the control strategy was tested (Jangsten, Lindholm, and Dalenbäck 2022c).

As can be seen in Figure 18, the control strategy successfully limited the $t_{CHW, supply}$ setpoint to a minimum of $t_{DC, supply}$ +2 °C. The number of hours with a supply temperature approach lower than the limit of 2 °C were fewer with the control strategy compared to without. The supply temperature approaches have been calculated based on hourly average values of the secondary supply temperature, and instantaneous values for the primary supply temperature. The spread of the data points, along with temperature approaches <2 °C despite the setpoint limitation, are due to the primary side temperatures being instantaneous measurements.

Figure 18 shows the primary return temperature and the supply temperature approach increased after the control strategy was implemented. However, this increase was not solely the result of implementing the setpoint limitation control strategy. During the summer of 2021, new secondary supply temperature setpoint curves were also tested and implemented by the building owner in the buildings, contributing to the increased temperatures. It is therefore important to optimize the supply temperature curve of the building to achieve the highest possible primary return temperature.

Primary Flow Limitation

As pointed out in section 4.1.1, the saturation zone can potentially be eliminated by a control strategy limiting the primary flow through the heat exchanger (explained in section 3.2.1). The goal with the control strategy was to limit the flow to increase beyond the lowest flow for maximum cooling power, thereby avoiding flow in the saturation zone and increasing the primary delta-T. The data from the test period were compared with data from the reference period using the primary plot for analysis, see Figure 19.

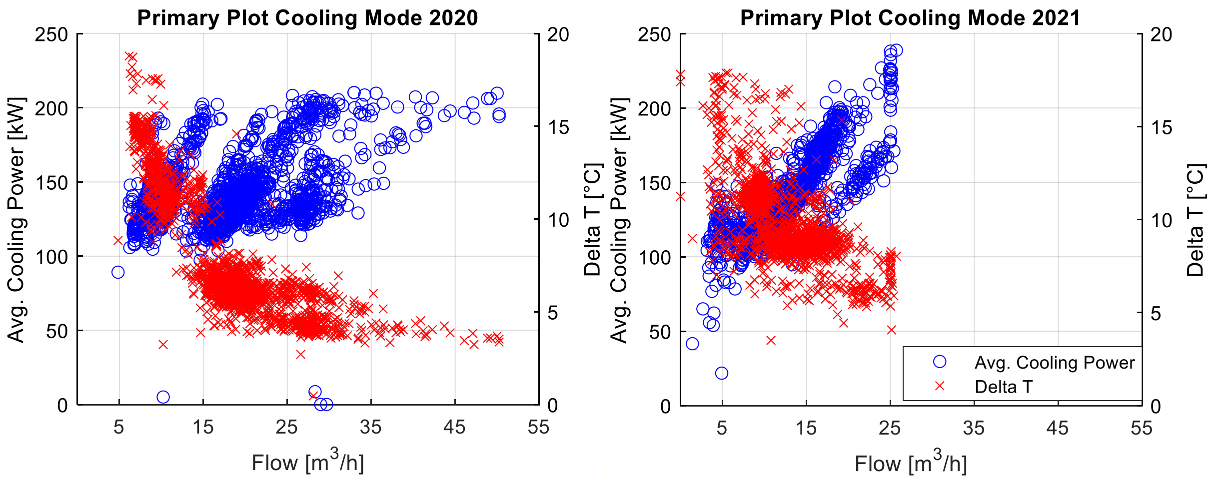

Figure 19: Evaluation of flow limitation control strategy as tested in one building. Left: reference period without the flow limitation control strategy. Right: test period with the control strategy (Jangsten, Lindholm, and Dalenbäck 2022c).

In Figure 19, the primary plots for evaluating the flow limitation control strategy can be seen for the reference period (without flow limitation) and for the test period (with flow limitation). The control strategies for this CHW system included heat recycling depending on the outdoor temperature and a cooling mode using a constant CHW setpoint. The data in Figure 19 were extracted for operation in cooling mode by selecting data for which the outdoor temperature was greater than the predetermined condition for heat recycling. The CHW supply temperature setpoint was during the reference period set to 8 °C for outdoor temperatures >15 °C, but for the test period it was changed to 10 °C for the same outdoor temperatures, as a result of CHW system optimization by the building owner.

The flow limit was set to 25 m^3/h as this flow rate was considered to be the corresponding lowest flow for the maximum cooling power based on data from 2020 (see Figure 19 left). During the test period, the flow limitation control strategy came into effect during at least nine days. It successfully restricted the primary flow to remain below the flow limit, and completely eliminated the flow in the saturation zone. This can be seen when comparing the left and the right graphs of Figure 19. During the test period the maximum flow was halved, and the primary delta-T increased. Using data from Figure 19, the median primary delta-T for flow rates >20 m^3/h increased from 5.3 °C to 6.5 °C. However, the primary return temperature increased from 11.6 °C to 14.5 °C for the same flow rates which is due to a primary supply temperature increasing above 6.0±1°C. Moreover, the total volume during the test period was reduced with 44% compared to the reference period. In addition to the flow limitation control strategy, the change of the CHW setpoint from 8 °C to 10 °C was a major contributing factor for the large differences in primary flow between the two periods.

The Relation Between Primary and Secondary Flow Rates

Another aspect regarding the control of the substation to resolve low delta-Ts pertains to the flow rate relation between the primary and the secondary flows. As shown in section 4.1.3, substations with a flow rate ratio greater than 1 (meaning the primary flow rate is greater than the secondary flow rate), had a low temperature effectiveness on the primary side of the heat exchanger. A low temperature effectiveness creates unfavorable conditions for the highest possible primary return temperatures to be achieved and causes low delta-Ts. Since data on the secondary flow rate cannot be obtained from the SCADA systems, it can be measured by temporary equipment. Another less time-consuming method is to calculate or predict the secondary flow rate based on the four inlet and outlet temperatures of the heat exchanger and the primary flow rate. In Figure 20, the results of the predicted secondary flow using the HX heat balance model and the SVR model as described in section 3.3.3 can be seen. Fitting a linear model to the predictions by the SVR and the heat balance models resulted in R^2 and RMSE values of 0.89 and 4.19 for the SVR model and 0.79 and 7.32 for the heat balance model. This shows the SVR model was able to predict the secondary flow rate to a higher accuracy than the HX heat balance model. A reason for the higher R^2 value of the SVR model could be its ability to capture some of the non-linearity occurring during dynamic operating conditions.

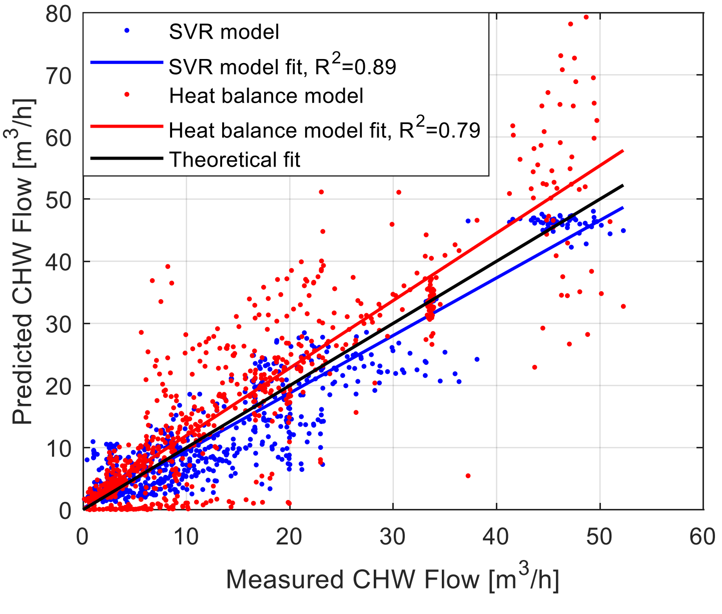

Figure 20: Predicted secondary flow with heat balance and support vector regression model vs. measured secondary flow.

Based on the above results, the SVR model is the more accurate method to predict the secondary flow rate, however the heat balance model is the simpler method. By predicting or measuring the flows on the secondary side, potential unbalances between the primary and the secondary flow rates, which in turn cause low delta-Ts, can be identified. If so, aiming to achieve balanced water flows or a higher secondary flow than the primary, is a potential solution to resolve some low delta-Ts.

4.3.2 Systematic Follow-Up

Another potential solution to increase the delta-T is to employ a systematic follow-up of the substations' performance. This can be done using an individual substation performance assessment method, proposed based on the developed performance indicators in sections 3.3.2 and 3.3.3. The method is outlined in Figure 21 and is executed individually on one substation in an offline mode using an algorithm developed in MATLAB. Input dataset 1 contains primary data from all hours for a predetermined time period for which the substation performance is selected to be analyzed, for example, the previous cooling season. The data simply have to be accessed from the utility company's database used for billing purposes and no prior data treatment is needed. The algorithm calculates the PIs and underlying variables such as the maximum cooling power and the corresponding flow. Potential flaws with the operational dataset, such as missing values, are accounted for by the algorithm by omitting those hours.

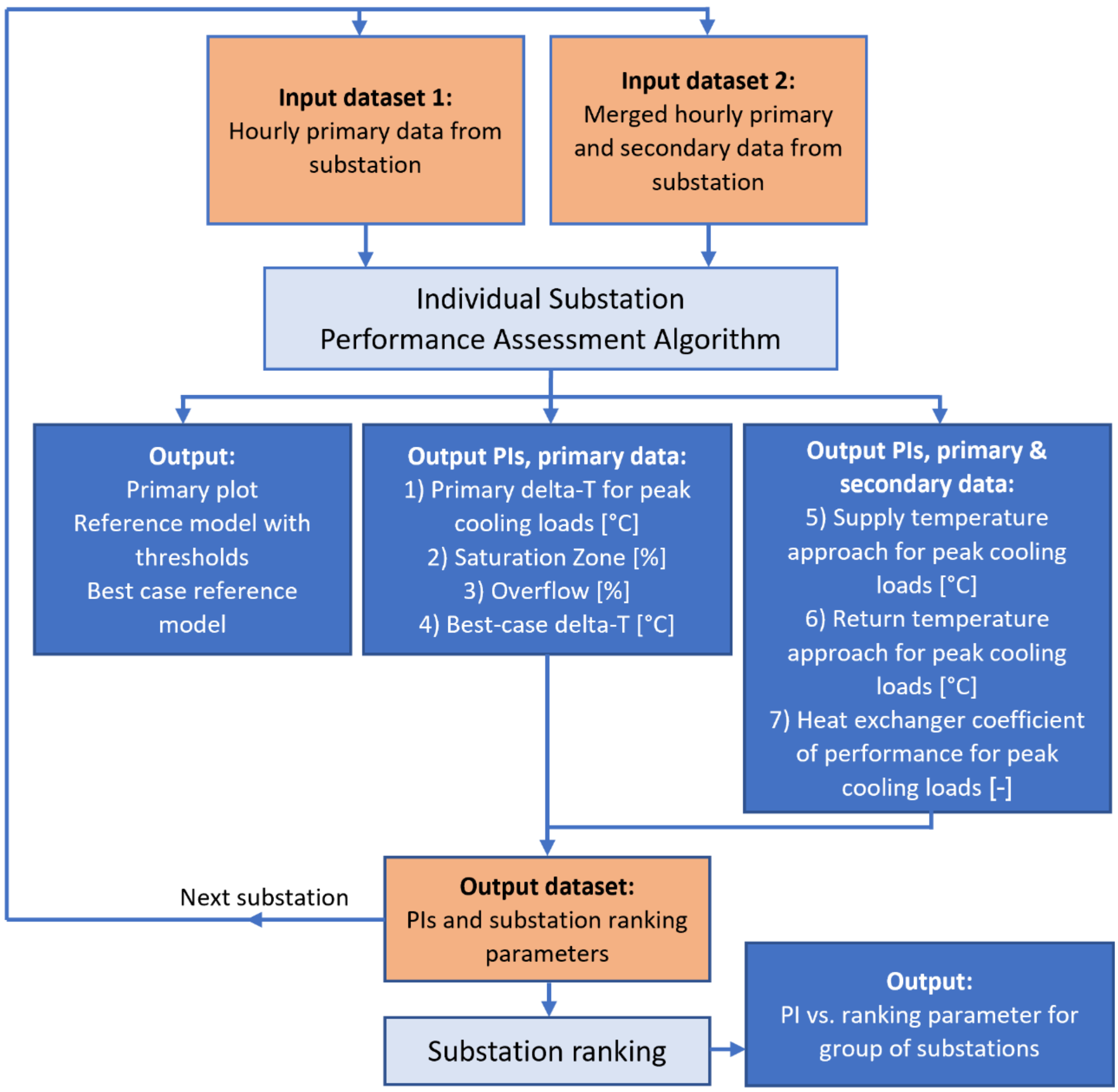

Figure 21: Outline of performance assessment method algorithm with steps and order of calculations along with required inputs and resulting outputs (Jangsten, Lindholm, and Dalenbäck 2022a).

If secondary side data are available from the substation, input dataset 2 in Figure 21 with both hourly primary and secondary data, has to be merged manually. The algorithm extracts the data for weekdays between the hours 10:00-16:00, checks for one or two heat exchangers and any missing temperature sensors on the secondary side. The performance indicators obtained as the output dataset are stored separately for compilation if more than one substation are to be compared for ranking purposes. The method was tested on 26 substations using primary data from the four years 2018-2021 and secondary data from the years 2018 and 2021.

As shown in Figure 21, the last steps of the method involve the substation ranking. Ranking of the substations can be done if many substations are analyzed successively. An order of importance needs to be established to aid the decision-making process on which substation to prioritize for interventions. From the utility company's perspective, the most poorly performing substation with the greatest impact on the entire DC system should be addressed first. Therefore, ranking the output based on the substation's size can direct the efforts to the substation with the largest improvement potential on the DC system. After each individual substation performance assessment is executed, the output PIs are saved to an output dataset. In addition to PIs, ranking parameters specifying the size of the substation are also obtained as part of the performance assessment method and saved to the output dataset. The ranking parameters include the maximum hourly cooling power and total chilled water volume and can be used depending on the preference of the person conducting the analysis. Moreover, to reduce the number of PIs to analyze for ranking purposes the two PIs overflow and delta-T for peak cooling power are suggested to be combined accordingly:

$$Combined\ PI = \frac{Overflow_{PI}\ [\%]}{\Delta t_{DC,PI}\ [°C]} \tag{17}$$

The combined PI indicates which substations exhibit the poorest performance in terms of both overflow and delta-T. The ranking is subsequently done by extracting the substation numbers from a plot with the combined PI vs. for example the maximum hourly cooling power, see Figure 22.

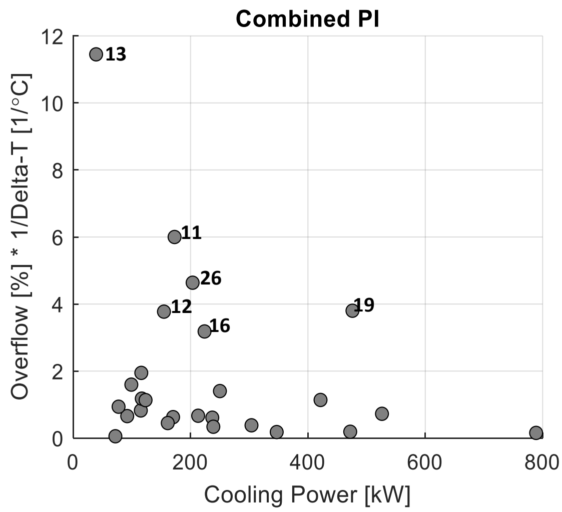

Figure 22: Combined PIs overflow and delta-T vs. maximum hourly cooling power to rank 26 substations based on data from the cooling season of 2021 (Jangsten, Lindholm, and Dalenbäck 2022a).

To improve the performance and delta-T of the substations, a collaboration between the utility company and the DC customers can be one solution. Also, since a majority of the substations in Gothenburg DC system are owned by the property managers, the utility company are legally unable to perform upgrades to most substations. For a utility company with more than 180 substations, and a majority of these performing poorly, a systematic assessment of the substations' performance and ranking can aid the decision-making process on which customer to contact first. Moreover, to continuously ensure proper substation performance and avoid ad hoc attempts, the substation assessment needs to be done recurringly, for example once per month or after each cooling season. The average performance assessment execution time for input dataset 1 was a couple of seconds per substation. Since the dataset input to the performance assessment method is data used for billing purposes, no further preprocessing of the dataset is needed, other than what is already done by the utility company's data collection system for generating invoices.

4.3.3 Economic Incentives

Another potential solution to increase the substation efficiency and resolve low delta-Ts is to provide clearer economic incentives for the DC customers. This could be a complement to the previously described systematic follow-up of the substations and collaboration with the DC customers. For simplicity, the economic incentives should be provided through the DC price model, where DC customers with well-performing substations with high delta-Ts should be rewarded with lower costs.

In Figure 23 the shares of the existing price model's components can be seen for 26 substations along with the PI delta-T for peak cooling loads. The flow component is what incentivizes the building owners maintain efficient substations. It can be seen that some of the substations with high delta-Ts also have a lower share of the flow component.

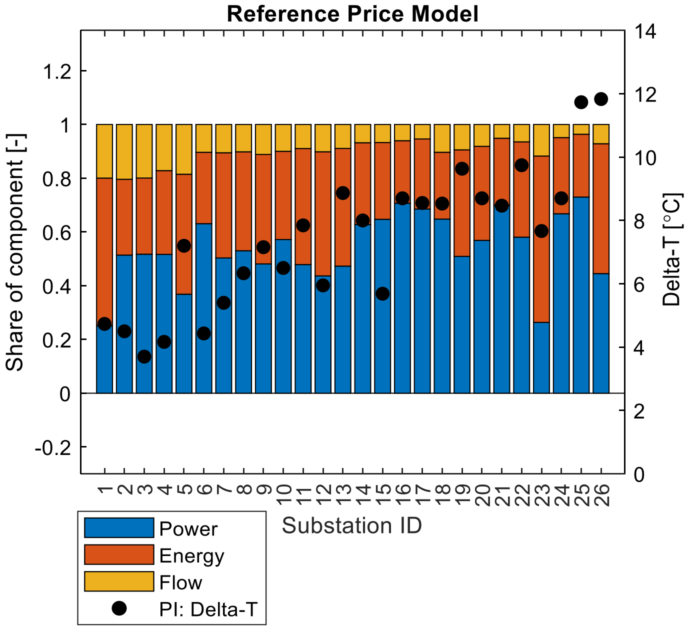

Figure 23: Reference price model: shares of components for 26 analyzed substations. Also, shown is the performance indicator (PI) delta-T for peak cooling loads (Jangsten, Lindholm, and Dalenbäck 2022b).

In Figure 24, the shares of the new price models 1A and 2A can be seen. For price model 1A, the flow component was replaced with a delta-T component and for price model 2A the flow component was replaced with a return temperature component. It can be seen that four of the substations have negative shares for the delta-T or return temperature components. Since these price model components are revenue neutral for substations with temperatures equal to the design temperatures (10 °C for delta-T and 16 °C for the return temperature), the negative shares show these substations exceed the design criteria. For a few of the substations the costs increase with a delta-T, or a return temperature component as opposed to a flow component, which generally also are substations with low delta-Ts.

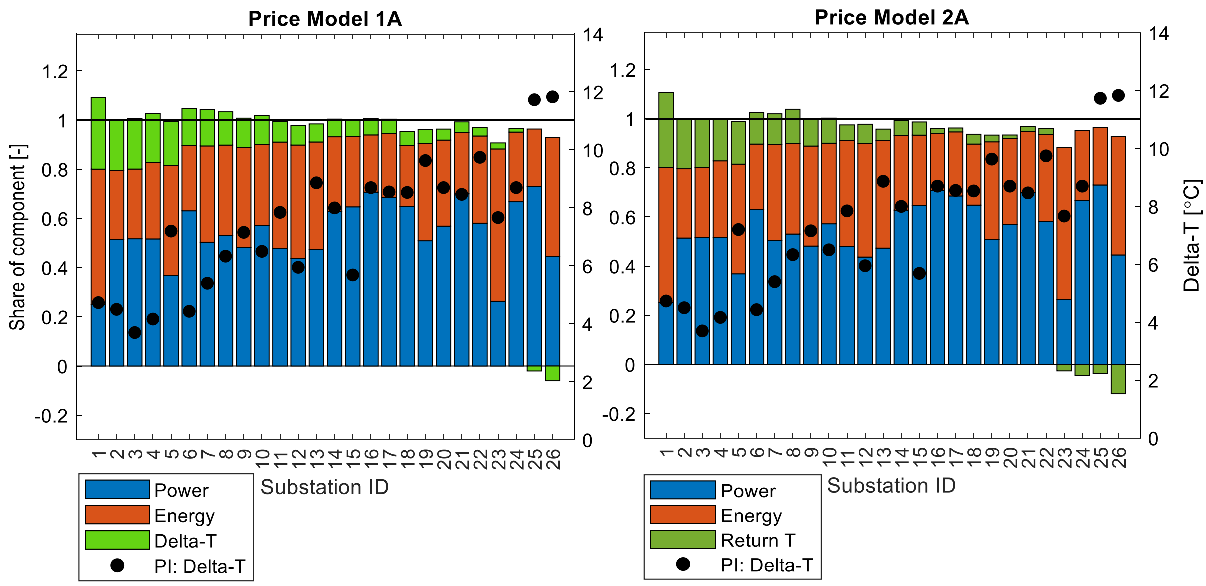

Figure 24: Share of price model components for new price model 1A with a delta-T component, and price model 2A with a return temperature component, replacing the flow component of the existing price model (Jangsten, Lindholm, and Dalenbäck 2022b).

Price models 1A and 2A resulted in lower total costs for the 26 analyzed substations compared to the reference PM. This is because the temperature components generated a zero cost or a bonus for hours when the substation's temperature was equal to or greater than the design temperatures. Contrarily, the existing PM generated a cost for such hours since the flow component charges for every cubic meter of chilled water used. Based on the investigation of new price model combinations, it was found that price models with a temperature component arranged to be revenue neutral with respect to the design temperatures, provide clearer incentives for the DC customers to maintain efficient substations, compared to the existing price model.

5

Discussion

The discussion serves to explore some aspects of the results presented in the Chapter 4 and clarify possible implications of the research outcomes. It also relates to some of the literature reviewed in Chapter 2, to provide context for the results. The chapter is structured to first provide insights on practical aspects regarding analyzing the data with its accompanied uncertainties. Second, the results regarding the design and operation of the substation are discussed in relation to the technical guidelines. Third, the suggested method for substation follow-up and collaboration with the district cooling customers is discussed. Lastly, the applicability of the results on other district cooling systems is reflected upon.

5.1 Practical Aspects on Analyzing the Data

The basis for the research in this thesis is operational data collected used for billing purposes (primary side) and control of the buildings' HVAC systems (secondary side) and is measured by permanently installed equipment. Despite this, the operational data have some shortcomings affecting its validity. Moreover, merging data from two separate data collection systems with different timestamps, measurement techniques and sampling frequencies further affect the data validity. Examples of deficiencies pertaining to the analysis of operational data from the primary side have been identified as part of this thesis and include the following:

- Too low resolution of the energy meter's integrator (order of 10-100 kW instead of 0.1 kW). For the first year of the data collection, a few substations' energy meters had low-resolution integrators. For such substations the cooling power instead was calculated based on the measured temperature difference and water flow rate. These integrators were replaced with high-resolution integrators during the years 2018-2019.
- Different sampling frequencies of the variables for data storage purposes. The supply and return temperatures are recorded instantaneously, once per hour, whereas the flow and thus the energy are calculated as averages during an hour.
- The temperature sensors are only co-calibrated to ensure an accurate delta-T but are not calibrated with respect to the absolute temperature. Therefore, individual measurements of the supply and return temperatures may be considerably less accurate than the reported accuracy of the temperature sensor.

- The minimum temperature difference for which the accuracy of the energy meter is guaranteed is 2 °C. For lower temperature differences the maximum permissible error could be exceeded.
- In some of the CHW systems, the CHW pump shuts off according to the time schedule operation, but the control valve on the primary side remains open. This leads to a flow on the primary side but not on the secondary side.
- Very low flow rates during long periods of time on the primary side could be due to control valves leaking but also a result of low cooling demands in the building.
- The tolerance of the flow meter is only valid for flow rates within the range q_i:q_p and for short periods of time for flows up to q_s. Flow rates lower than q_i and larger than q_s were observed among the analyzed buildings. Such data may be accompanied with errors exceeding the maximum permissible error for the flow meter.

The setpoint minimum limitation control strategy utilizes the primary supply temperature. To apply this control strategy in the substations it is of outmost importance that the primary supply temperature sensor is calibrated with respect to the absolute temperature. Moreover, the instantaneous temperature measurements lead to a high dispersion of data points when analyzing the temperatures on the primary side. To reduce the dispersion, a more useful recording method may be hourly averages of frequent temperature measurements during an hour.

Related to the data from the secondary side, the following potential issues have been identified:

- The temperature sensors are not required to be calibrated since the data are not used for billing.
- Faults due to broken, deteriorated or incorrectly installed equipment as well as unintended short cut flows may be present but not necessarily evident in the datasets. Also, potential faults have not been validated.
- Missing temperature sensors (for example secondary return temperature sensor).
- Lack of information on type of temperature sensor and accuracy since this is not necessarily part of the substation documentation.

When calculating the temperature approaches of the HX, the uncertainty is affected by the propagation of errors as explained in section 3.2.5. Given that the temperature sensors of the primary side have an accuracy of ±0.1 °C and the temperature sensors on the secondary side have an accuracy of ±0.2 °C, the uncertainty becomes $\sqrt{0.1^2+0.2^2} = \pm 0.22$ °C (Spitler et al. 2021). However, since the temperatures are obtained from two different data collection systems, issues pertaining to merging data from the primary and secondary sides arise. Therefore, the temperature approaches as shown in Figure 13, which are calculated to the tenths place (0.1 °C), are in fact less accurate than the reported uncertainty of ±0.22 °C. Additionally, in Figure 13, negative temperature approaches were observed for four substations, despite accounting for the propagation of error. Such data are thermodynamically impossible but can occur due to the following reasons as identified in this thesis:

- The calibration of the primary and secondary temperature sensors is not done together.
- The calibration of the secondary temperature sensors may be lacking, done incorrectly or has not been followed up and revised over time.
- Different sampling frequencies and recording methods between the primary and the secondary sides data acquisition systems.

- There could be a mismatch between the timestamps of the datasets from either side, for example from clocks not accounting for daylight savings time.

The PIs based on data from both primary and secondary sides give an indication on how efficiently the heat exchanger is working. They also give an indication on how well the secondary side is operating in relation the primary side, as shown in section 4.1.2. However, subject to the aforementioned uncertainties, it may not be useful for the utility company to directly connect the temperature sensors on the customer's side to its data acquisition system, even if it would be technically and contractually feasible. Firstly, the uncertainties from the temperature measurements on the secondary side in relation to the primary side need to be reduced to ensure an accurate substation performance assessment. This can be done by addressing the reasons to the uncertainties as outlined above.

In some of the data observed, primarily during nights and weekends, there were inconsistencies between the different variables, for example zero power and delta-T but not zero flow. This is potentially a result of a low cooling demand in the building. Therefore, to increase the validity when analyzing the temperature data, it was necessary to extract data for hours when the CHW system was in operation and a cooling demand was present (as described in section 3.3.1). However, selecting the hours for when a cooling demand was present was an arbitrary choice, despite having access to the time schedules of some of the HVAC systems. In this thesis two different time schedules were used, 7:00-17:00 and 10:00-16:00. An alternative is to find the start and stop hour for the specific building to be analyzed based on changes in the cooling power. Such a method was developed and tested on 13 buildings. The time schedule operation strategy was apparent for 4 or 6 of the investigated buildings. This means one specific hour could be assigned as the start hour and one as the stop hour. However, it was indistinguishable for the remaining buildings. Increases and decreases of the cooling power also reoccurred throughout the day in some of the buildings which lead to fluctuations and transient conditions of the secondary chilled water system despite utilizing time schedule operation strategies. Nevertheless, a risk with extracting data to be analyzed for a predetermined time period is missing potential issues occurring during the hours before or after the selected time period.

Despite the identified uncertainties, the operational data are what is available from the primary and secondary sides of the substation. A single temperature measurement may be invalid and unreliable, but the temperatures analyzed, and the performance indicators calculated, are based on a large amount of data (such as the entire cooling season). The trends observed and the average or median values calculated are considered to be valid. This is also applicable to the temperature analyses for which the data were extracted for weekdays. Due to the minimum temperature difference of the energy meter, delta-Ts less than 2 °C and delta-Ts for zero flow are data accompanied with high uncertainty. For the flow rate and cooling power data, single data points may be caused by sudden events affecting their validity. However, the customer is billed for such hours, whereby they have been included in the analysis and the calculation of the performance indicators. Statistical methods for the removal of outliers have for this reason not been used as part of the analysis.

5.2 Design and Operation of the DC Substation

Based on the interviews it was evident the knowledge about the technical guidelines is good among consultants designing district cooling substations. The consultants follow the guidelines and oftentimes design for higher temperatures than what is required. The buildings' CHW systems are designed according to the guidelines most of the time, but due to miscellaneous issues during installation and commissioning, for example incorrect hydronic balancing, the intended design of the CHW system is not always achieved. In older buildings, converted from previously being supplied by local chillers, the building's CHW system is not always adapted to meet the technical guidelines. An issue raised is the difficulty to accurately calculate the cooling power demand of the building, which oftentimes lead to oversizing. Moreover, peak cooling conditions only occur a few hours per year, whereby the systems operate in part load most of the time.

The control strategies setpoint and flow limitation, as presented in section 4.3.1, were shown to be successful solutions to increase delta-T in the four buildings they were tested. A version of the control strategy setpoint limitation is already required according to the technical guidelines (Energiföretagen Sverige 2019), but its implementation among the buildings is unknown as well as it was absent in the discussions with the consultants during the interviews. The flow limitation control strategy is not required according to the technical guidelines, but can help eliminate the saturation zone of the entire district cooling system if implemented in all substations (Jangsten, Lindholm, and Dalenbäck 2022c). If the setpoint limitation is applied to all substations' control systems, it can be argued the flow limitation control strategy would be redundant. However, a temperature approach <2 °C was not the only reason to a flow in the saturation zone. For this reason, it is recommended to be added to the technical guidelines.

Some building owners may be resistant to implementing either of the control strategies, suspecting problems with the indoor thermal comfort as a consequence. However, if the primary supply temperature rises to 8 °C for a few hours due to problems in the district cooling production plants, it is thermodynamically impossible for the heat exchanger to produce a secondary supply temperature setpoint of 8 °C. Instead, the control valves will open fully, cause a flow in the saturation zone and subsequently a low delta-T. It will also be more challenging to improve the operational situation in the DC network and in the district cooling production plant. With both control strategies implemented as safety features, such an operation scenario can be avoided.

The control valves installed on the primary side of the substation are pressure-dependent, although the type of control valve to be used is not specified in the technical guidelines. Instead, the valve selection is done by the HVAC consultant and/or the building owner. In one of the interviews with the consultants, the issue with selecting the right control valve size was raised. The differential pressure on the primary side of the substation varies between 100-600 kPa. This makes it challenging to select a pressure-dependent control valve working properly for all operating conditions within the specified differential pressure interval. A potential solution to resolve poor substation performance due to control problems, is to use pressure-independent control valves, something which is more common in DC systems the in USA and the Middle East (IDEA 2008; Moe 2005). The use of pressure-independent control valves is unknown in Gothenburg DC system but is anticipated to be non-existent based on the investigated buildings and collaboration with the property owners.

High temperature district cooling (HTDC) with supply temperatures of 12-14 °C and return temperatures of 20-22 °C were proposed in Paper II (Jangsten et al. 2020). This development is in line with the temperature reduction in district heating systems (Lund et al. 2014) and enables an increased utilization of natural free cold sources, which is also the aspiration of smart energy systems (Østergaard et al. 2022). Although higher temperatures, and in particular high supply temperatures, may not be feasible in certain climates and for all district cooling systems, it is important to reconsider the usage of conventional low supply and return temperatures. The local technical guidelines for the DC system in Gothenburg, Sweden, were updated in 2021. The supply temperature curve, which previously was defined for two temperature levels depending on month of the year, was changed to vary with the outdoor temperature as described in section 3.1.2 (Göteborg Energi AB 2021). The new supply temperature curve shows the vision of HTDC already is being implemented in existing DC systems, with the aim to increase the use of free cooling.

To be able to supply the buildings with a high supply temperature of 12±1 °C, it is essential to ensure the buildings' feasibility. Since buildings with CHW systems composed of cooling coils in AHUs and chilled beam subsystems have decoupled cooling loads (which was a majority of the buildings investigated in this thesis), the conditions are favorable. This is because such a composition is similar to that of HTC systems where high supply temperatures can be used to handle the sensible cooling loads by the chilled beam systems. If only a small number of buildings in a DC system require a 6 °C primary supply temperature regardless of outdoor temperature, it may be advantageous for the utility company to invest in local chillers or desiccant cooling for those specific buildings. It may also be valuable to investigate if alterations could be made to the systems on the secondary side to enable the use of higher primary supply temperatures, something which would require a collaboration effort between the utility company and the customer, as discussed in the forthcoming section.

5.3 Substation Follow-Up and Customer Collaboration

In section 4.3.2, a systematic follow-up of the substations' performance was suggested as a potential solution to increase the substation efficiency and resolve low delta-Ts. Moreover, according to the consultants, the utility company is involved in the development and construction phases of the substation, but not during the operational phase. There is a need to follow up the substations' performance to verify the intended operation is achieved once the building is in operation. Also, there is a need for operation optimization due to potential issues during part load operation. In the technical guidelines, the building owner is obliged to set up a functional check routine of the substation to be conducted once per year. The functional check should follow a supervisory program as suggested in the appendix of the technical guidelines. It should be documented and any potential deficiencies and improvement measures done should be recorded (Energiföretagen Sverige 2019). However, this functional check was never raised during workshops and meetings with the property owners, whereby its adherence is doubted. Even if the substation is owned by the property manager, its performance affects the entire DC system. If the substations' efficiency is improved, the utility company can avoid installing additional chillers and replacing pipelines to larger sizes if the network becomes congested. Therefore, it is also in the interest of the utility owner to maintain efficient substations despite not being responsible for their performance.

As shown in this thesis there is an interest among the property owners to improve and optimize their CHW systems and substations. For example, in meetings and workshops with the property owners, problems and operational characteristics of the substations were identified and potential solutions discussed. Some of these solutions were adopted by the property owners who, for example, initiated optimizations of the temperature curves and setpoints of the secondary supply temperatures. However, it was also pointed out that cooling is a small share of the total energy expenditure of the buildings. Moreover, optimizations are oftentimes dependent on knowledgeable and engaged personnel with the possibility of dedicating time to such tasks as well as they have to be justified economically. For this reason, it may be necessary for the utility company to engage and possibly help the customers with optimizations and improvements. It has previously been established that increased delta-Ts from the substations can be achieved through good customer relationships (Månsson, Johansson Kallioniemi, et al. 2019; Buffa et al. 2021) and by continuous work of the utility company (Zinko et al. 2005; Petersson and Dahlberg-Larsson 2013). The method proposed in section 4.3.2 is a suggestion on how a DC utility company systematically can follow up the substations' performance in collaboration with the DC customers. However, the data from both sides of the heat exchanger are more easily accessed by the property manager if connecting the primary side's data to the SCADA system using the customer access port. Therefore, the performance assessment method can be used by the property manager as well as it can complement the supervisory program suggested in the technical guidelines.

Previous studies proposing individual substation analysis methods have been based on DH substations (Zinko et al. 2005), but no method have exclusively been developed for DC substations. Although analysis methods such as the excess flow (explained in section 2.3.4) can be used for DC applications as well, the performance assessment method proposed in section 4.3.2 and Paper IV has been developed based on the operational characteristics of an actual DC system. The method accounts for the diversity and complexity of the secondary sides' CHW systems. It also accounts for the smaller temperature differences in DC systems compared to DH and the resulting need to assess data from both sides of the heat exchanger. The reference model (based on the heat balance of the heat exchanger, Eqn. 2) considers the individual conditions of the substation, such as the method proposed by Zinko et al. (2005) for DH substations. However, it is a simpler model which can easily be applied using only historical data as input. The reference model assumes a linear relationship between the cooling power and the flow rate and may be more applicable for some substations than others, but it was shown to be effective for substations that perform well. The method suggested is however not exhaustive and cannot be used to detect the actual faults causing the operational characteristics observed in the substation. However, having knowledge about the substation performance is a prerequisite to be able to detect and diagnose faults in DC substations. Using the suggested method, the performance of the substation can be established, and some potential solutions can be identified depending on the analysis outcome. Together with the proposed ranking method, it can be used a systematic method for decision-making on which substations to address first.

In section 4.3.3, new price model combinations were presented with a temperature component added to or replacing the flow component of the existing price model. The temperature component created stronger incentives for high delta-Ts by rewarding such substations with lower costs and penalizing poorly performing substations with increased costs. However, the temperature component may not have the indented effect in practice. The main competitors to district cooling are heat pumps and local chillers. According to the consultants, if district cooling is available where a new building is built, it is the most common cooling supply source to use. However, the choice is oftentimes dependent on opinions and preferences of the property owner. One of the most crucial aspects when introducing a new price model is communication (Leoni, Geyer, and Schmidt 2020; Petersson and Dahlberg-Larsson 2013). If a price model change is not well-communicated to the customers, the risk of rejection can be critical. Therefore, if a temperature component was to be added to the price model, it would need to be preceded with proper communication and preparation of the DC customers. Perhaps more importantly, it should be accompanied with a collaboration effort from the utility provider. For example, by proposing improvement measures and investments needed, especially for buildings faced with large price increases. Otherwise, the ultimate risk is a damaged reputation for district cooling with heat pumps or local chillers becoming the preferred cooling supply choice for more property owners.

5.4 Applicability of the Results

The work of this thesis is solely based on the district cooling system in Gothenburg, Sweden, and some of the buildings connected it. Currently, the district cooling system has around 180 substations, and approximately 40 were part of the initial analysis. This number has been smaller for the different papers and their focus, but the results have been generalized for the entire district cooling system based on the substations analyzed. The technical guidelines for district cooling substations apply to all DC systems in Sweden. However, the DC systems are accompanied with their own conditions and requirements which have to be accounted for as well as local guidelines with for example specific temperature levels. Moreover, many DC systems in Sweden are small with only a few customers, and the DC system in Gothenburg is one of the larger in Sweden. Although the outcomes of this research may be applicable to district cooling systems in Sweden in general, it may be more applicable to DC systems of similar size, a comparable number of substations and a resembling production mix. For many DC systems outside of Sweden, it is common the property owner and the DC operator belong to the same organization with the building being connected directly without a heat exchanger in the substation. The results of this thesis are less relevant for those types of systems. However, for DC systems arranged similarly as the DC system investigated in this thesis, it would be interesting to apply the results of this thesis for further generalizations.

6

Conclusions

The aim of this thesis was to develop a systematic approach on how to evaluate and improve the performance of district cooling substations with heat exchangers to achieve higher delta-Ts. This was mainly done by analyzing data from both sides of the heat exchanger of approximately 40 buildings connected to the district cooling system. Moreover, related information, field measurements, field tests and interviews with consultants were conducted to support and refine the analysis and its outcomes with a deeper understanding.

It can be concluded the operation of a district cooling substation is complex, with a large diversity among the systems on the secondary side and no one being the same as another. Despite the substation's technical guidelines mostly being followed during the design phase, they are not fulfilled during the operational phase, and very few substations perform well and achieve the desired delta-Ts. One reason is because the buildings' control systems lack an operational compatibility with the primary side. Furthermore, there are no follow-ups or optimizations of the operation of the buildings' systems and the substations, as well as no consequences if the operation deviates from the requirements.

Two solutions to achieve higher delta-Ts are the control strategies setpoint minimum limitation and primary flow limitation. Another solution is to ensure the flow rates on both sides of the heat exchanger are balanced, or if not, that the secondary flow is higher than the primary flow. Additionally, the economic incentives to maintain efficient substations can be enhanced with a temperature component of the price model. The substations' performance can be systematically assessed and summarized with the developed performance indicators together with the primary plot and the substation reference model. The ranking method can be used to compare the substations' performance and generate priority lists to aid the decision-making process on which substation to address first. This method can be used by the property owner, or by the utility company in collaboration with the property owners, to follow up the performance of the substations on a continuous basis.

This thesis contributes with knowledge about the operation of an actual district cooling system with buildings connected via heat exchangers. It provides some suggestions on how operational data from both primary and secondary sides of the substation can be handled and analyzed. It challenges the use of conventional supply and return temperatures of 6 and 16 °C and shows there are some opportunities to use higher temperatures. It also exemplifies what can be achieved through a collaboration with the common goal to achieve higher delta-Ts and an increased efficiency.

7

Future Research

The outcomes of this thesis have generated some ideas for future work. The tested control strategies achieve in best case increased return temperatures; however, a control strategy which would actively regulate for higher return temperatures is a control strategy controlling the secondary return temperature. Such a control strategy is likely already implemented in some buildings with district cooling; however, it needs to be tested before it potentially can be recommended as a control strategy in for example the technical guidelines.

A potential solution to many of the poorly performing substations is the use of a pressure-independent control valve as opposed to the currently used pressure-dependent valves. The use of pressure-independent control valves was not tested as part of this thesis although they are common in district cooling systems outside of Sweden. Further studies and tests should be conducted to justify if they should be recommended for Swedish district cooling systems.

The proposed follow-up method in this thesis has not been tested in practice. Moreover, the method is only a suggestion on how the substations' performance can be assessed. There are many ways in which this can be done, and it is up to each utility company to define their processes. Regardless of method adopted, it would be interesting to further investigate the outcomes of a systematic follow-up method applied along with collaboration efforts together with the customers. This could help establishing best-practice on how to successfully employ follow-ups and collaborations which lead to increased delta-Ts and improved substation efficiency.

As pointed out in Chapter 2, no previous research has specifically been conducted on fault detection and diagnosis for district cooling substations. The method to assess the substations' performance as suggested in this thesis serves as a foundation to this research domain since knowledge on the actual operation of the substations is needed to further define potential research areas. Next steps in this research domain could be to analyze time series data, something which was very sparsely done in this thesis, although it has commonly been deployed for research on district heating substations. Moreover, labelled data is needed to employ automatic fault detection and diagnosis in district cooling substations and as already suggested for district heating substations, this is something that needs to be collected for district cooling substations as well.

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