DALARNA
UNIVERSITY

# Degree Project

Bachelor's level thesis

## Optimizing the Performance and Efficiency of District Heating Substations

## A Study of the Cooling Process and Overall System Improvements in Ludvika

Author: Marwan Ali & Eema Sheykhi Narani
Supervisor: Tomas Persson
Examiner: Johan Heier
Subject/main field of study: Energy technology
Course code: EG2004
Credits: 15
Date of examination: 4 June 2023



Dalarna University – SE-791 88 Falun – Phone +4623-77 80 00

## Abstract:

The concept of future sustainability is driving efforts toward the efficient improvement of energy systems. District heating systems play a key role in balancing the energy system by improving performance and flexibility. As system efficiency increases, fuel consumption decreases, resulting in reduced greenhouse gas emissions and mitigating potential climate impacts, especially when using fossil fuels.

In Sweden, district heating has shown significant growth, with a 75 % increase in total heat production over the last 30 years. Furthermore, carbon dioxide emissions have been reduced by approximately 50 % for each delivered kWh in the past 20 years, while renewable energy sources have doubled in the district heating sector.

This thesis focuses on optimizing the cooling process to achieve lower return temperatures and higher system efficiency. It also emphasizes the importance of implementing an efficient heat consumption strategy to reduce peak loads and improve overall system efficiency. This approach involves managing demand to minimize peak heat requirements and distribute the load evenly throughout the day, leading to a more resource-effective and efficient system.

The case study examines district heating supplied by VB Energy to Ludvikahem AB buildings, using data from Dec 2022 to Jan 2023. Quantitative data from district heating substations and the district heating plant are collected and analyzed to generate qualitative insights. The study proposes theoretical optimization measures based on the findings.

The evaluation of substation performance reveals 20 poorly performing substations with various issues. Eight of these substations have technical problems related to substation components, while another eight experience management issues not aligned with specific activity profiles.

The load shifting simulation demonstrates a 3 % reduction in heat rate peak levels, resulting in approximately 7 kW of subscribed heat rate savings. Energy usage savings reach approximately 0.9%, leading to an increase in energy usage effectiveness. The cost savings amounted to about 3000 SEK over two months for a single building.

This research emphasizes the importance of routine control, inspection, and documentation of substation performance to ensure optimal efficiency. Furthermore, indicates that the poorly performing substations that contribute to inefficiencies in the district heating network. Additionally, real-time regulation and load-shifting strategies are vital for optimizing customer consumption and maintaining an efficient district heating system, benefiting both suppliers and consumers.



## Keywords:

Energy efficiency in multi-family buildings, District heating efficiency, Sustainability, District heating control, Cooling process

# Abbreviations

| Abbreviation | Description |
|---|---|
| **CHP** | Combined heat power |
| **CCCP** | Conventional central circulating pump |
| **DVFSP** | Distributed variable-frequency speed pump |
| **DH** | District Heating |
| **DHW** | Domestic hot water circuit |
| **HC** | Heating circuit |
| **GW** | Global warming |
| **GHG** | Greenhouse gases |
| **HEX** | Heat Exchanger |
| **HP** | Heat pump |
| **KPI** | Key Performance Indicator |
| **MPC** | Model Predictive Control |
| **PED** | Positive energy districts |
| **RES** | Renewable energy sources |
| **RT** | Return temperature |
| **ST** | Supply temperature |
| **SEK** | Swedish Currency Krona |
| **T** | Temperature |

# Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| $CO_2eq$ | Carbon dioxide equivalents | |
| $\boldsymbol{P}$ | Heat load, Heat rate | kW |
| $\boldsymbol{P_h}$ | Heating Heat Rate demand | kW |
| $\boldsymbol{P_{tw}}$ | Tap hot-water Heat Rate demand | kW |
| $\dot{\boldsymbol{m}}$ | Mass flow rate | kg/s |
| $\dot{\boldsymbol{V}}$ | Volume Flow | $m^3/h$ |
| $\boldsymbol{T_s}, \boldsymbol{ST}$ | Supply temperature | °C |
| $\boldsymbol{T_r}, \boldsymbol{RT}$ | Return temperature | °C |
| $\boldsymbol{A}$ | Area of the Heat Exchanger | $m^2$ |
| $\boldsymbol{K}$ | Heat Transfer Coefficient | $W/m^2$ °C |
| $\boldsymbol{UA}$ | Coefficient of Heat Transmission for all Area | kW/°C |
| $\Theta_{LMTD}$ | Logarithmic Mean Temperature Difference | °C |
| $\Theta_{GTD}$ | Greatest Temperature Difference | °C |
| $\Theta_{LTD}$ | Least Temperature Difference | °C |
| $\boldsymbol{NTU}$ | Number of Thermal Units | |
| $\boldsymbol{k_{vs}}$ | Flow Coefficient (k-value) | |
| $\Delta\boldsymbol{P}$ | Pressure Drop | kPa |
| $\boldsymbol{q}$ | Flow | $m^3/h$ |
| $\boldsymbol{q_p}$ | Maximum Flow Rate (in continuous function) | $m^3/h$ |
| $\boldsymbol{E}$ | Heat Energy | kWh |
| $\boldsymbol{E_h}$ | Heating energy demand | kWh |
| $\boldsymbol{E_{tw}}$ | Tap hot-water energy demand | kWh |

| | | |
|---|---|---|
| $\boldsymbol{t}$ | Time | h |
| $\boldsymbol{\rho}$ | Water Density | $kg/m^3$ |
| $\Delta\boldsymbol{T}$ | Temperature Difference | °C |
| $\Delta\boldsymbol{\theta}$ | Thermal Difference | °C |
| $\boldsymbol{E_c}$ | Calculation Device Error | |
| $\boldsymbol{E_t}$ | Temperature Sensor Error | |
| $\boldsymbol{E_f}$ | Flowmeter Error | |
| $\boldsymbol{G_t}$ | Heating degree hours | °C h |

# Table of Contents

**Appendix**

# 1 Introduction

The concept of future sustainability expands nowadays within the efficiency improvement of energy systems. It requires both efficient and flexible system solutions, where district heating systems will play a key role in balancing the energy system. The district heating principle is recommended by the EU Commission to centralize energy resources, leading to less environmental impact than individual energy source solutions. Integration of renewable energy sources (RES) into district heating systems is highly sought after [1]. Therefore, optimizing the thermal behavior in district heating systems to build low-temperature operating conditions is one of the challenges [2].

Lund et al. [3], Rezaie and Rosen [4] have argued that district heating systems, widely implemented in Sweden and Denmark, will play a significant role in achieving a sustainable future by facilitating the integration of renewable energy sources (RES). Research has indicated that district heating systems are crucial for enhancing sustainability due to reduced fuel consumption. The implementation of RES is also considered safer, thereby conserving resources for future generations and mitigating the impacts of climate change.

Ludvikahem AB and VB-energi AB are collaborating with Dalarna University to conduct perform this study and implement the results in their area, for a brighter future of sustainability and to motivate other companies towards an efficiency improvement perspective of the entire system, and to open the door for experts to take steps towards efficiency and sustainability development.

The study aims to identify the optimization possibilities of the performance of the district heating substations, in an apartment buildings area and premises locations in Ludvika. Optimization of the cooling process is the most focused purpose as analysis of shortcomings in the cooling process and analysing improving the cooling process towards lower return temperature and higher system efficiency.

Additionally, implementing a more efficient heat consumption strategy by reducing peak loads plays a crucial role in improving the overall system's efficiency [5]. This strategy involves managing the demand in a way that minimizes peak heat requirements and distributes the load more evenly throughout the day. By doing so, the system can operate more efficiently and effectively utilize its resources.

A pre-study to this thesis report was performed as a project within the course Sustainable Energy Systems (10 credits) [6]. Part of that work has been integrated in this report, either as is or partly rewritten. The sections originally from [6] are part of the introductory section above, the background (Section 1.1) which contain parts from the background and discussion of the originally pre-study report, and the theory section on literature review (Section 2.3) all parts. A part of the method capital was written in the course Research Method (2.5 credits) [7]. Part of that work has been integrated in this report, either as is or partly rewritten. The sections originally from [7] are the majority of the literature review method section (Section 4.1).

## 1.1 Background

The growth of the human population and lifestyle development lead to an increase in energy demand to achieve the desired indoor climate, both for residential and commercial buildings. Technical solutions are moving towards electrification, but the generation of this energy depends on fossil fuels, as shown in Figure 1.1 [8]. Continuous growth in energy generation and consumption exceeds environmental limits, and environmental problems have begun to affect life on Earth. Therefore, the need for a satisfactory indoor climate is one of the major causes of environmental problems, due to the large energy demand for heating/cooling (approximately 50%) and electricity (approximately 25%), as shown in Figure 1.2 [9].

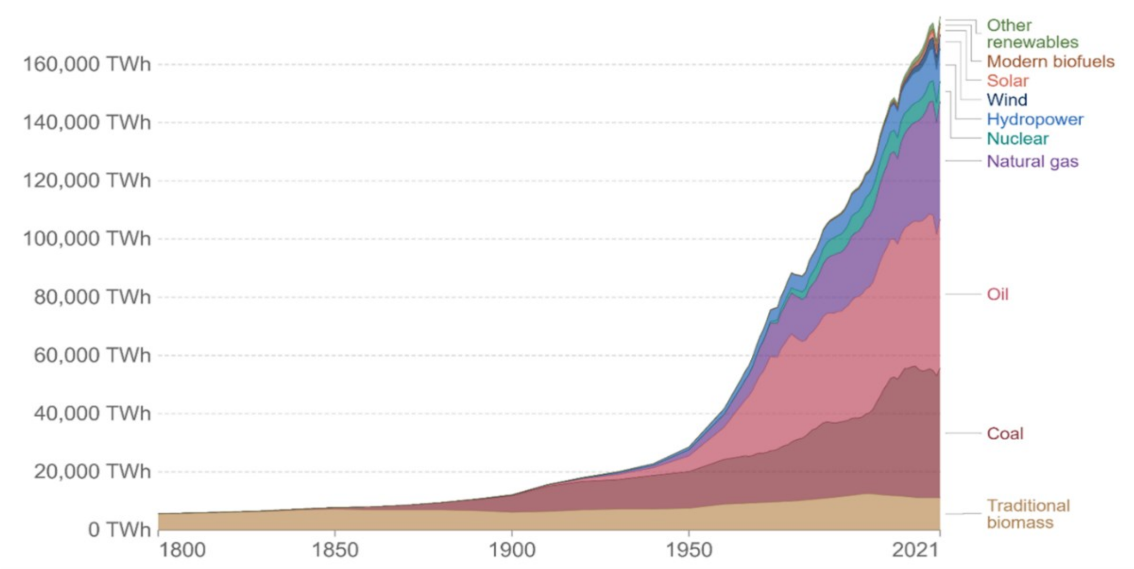



*Figure 1.1: Global primary energy consumption by source [8]*

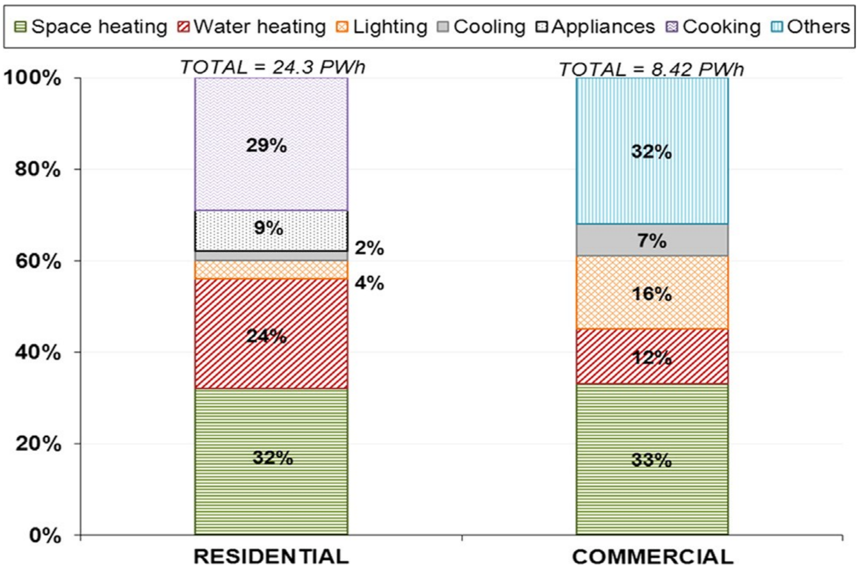



*Figure 1.2: Global Share of Heating and Electricity of Energy use by end users in 2010 [9]*

In general, environmental problems are issues that create environmental impacts around people. They are caused by human activity, which results in an uncertain future and a risk of resource depletion. The United Nations identified 17 sustainable development goals related to environmental impacts and challenged all countries to work on them with an agenda for 2050. Environmental impacts related to a building's energy balance include climate change issues, especially global warming (GW) and greenhouse gases (GHG) represented by $CO_2$eq (carbon dioxide equivalents) emissions as a measure. The goal is to reduce global emissions by 43% by 2030, drops to net zero by 2050, to keep global warming below 1.5°C through 2050 and to stop climate change [10].

Ola Alterå, CEO of Svensk Fjärrvärme, described district heating as "*District heating and district cooling create efficient and environmentally friendly energy solutions that take advantage of resources that would otherwise be lost, and provide customers with simple, safe, and comfortable heating and cooling.*"[11].

In Sweden, district heating has increased by 75 % in the last 20 years and cover 50 % of the heating demand in Sweden. Which reduced carbon dioxide emissions by about 20 % for each kWh delivered in the last 20 years [11], and RES has doubled in the district heating sector, according to Figure 1.3 [12].

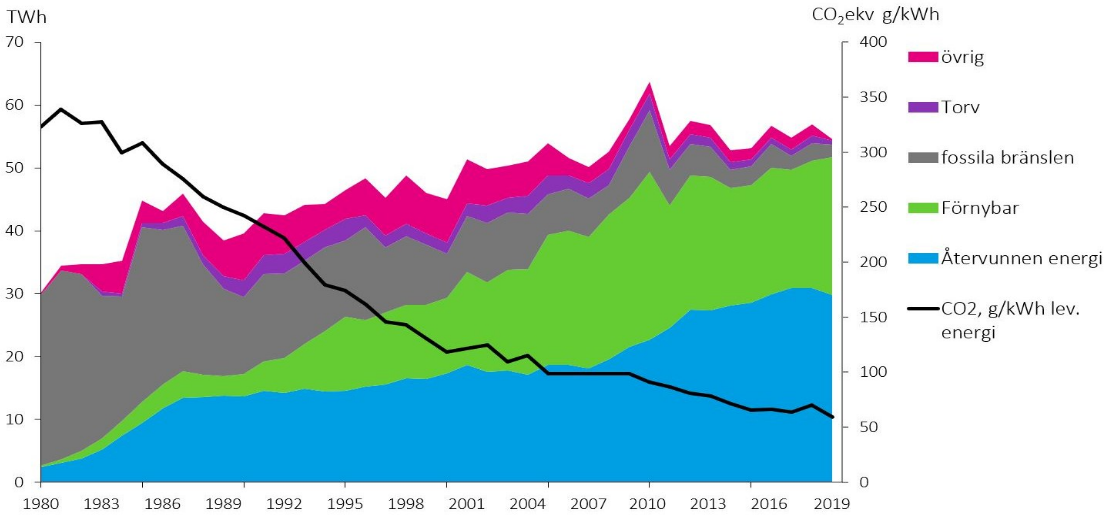



*Figure 1.3: Supplied Energy to Production of District Heating 1980–2019 [12]*

The performance of the district heating system has an inverse relationship with fuel consumption, so an increase in system efficiency leads to a decrease in fuel consumption, and therefore reduced GHG emissions and leads to less potential climate impact if fossil fuels are used [13]. Systems with low operating temperatures increase system efficiency and improve thermal performance, resulting in less climate impact. Strengthening RES requires low-temperature systems (low supply and return temperatures) to extract low-temperature heat energy [2].

Reduction of fuel consumption can be achieved by increasing the flexibility of the system and utilizing other residual products such as waste heat [14] or increasing the utilization of delivered heat as much as possible [15]. Flexibility increases with the integration of several technologies that convert losses into useful energy forms such as cogeneration which convert heat losses to electricity or flue gas condensation [16] [17]. Alternatively, the system can be combined with thermal storage to save heat energy for peak load times instead of increasing heating heat rate [18]. It may also involve reducing losses, such as electrical energy to pumps, which are counted as energy losses [19].

District heating is a system used to provide heat to multiple buildings by circulating either hot water or low-pressure steam through district networks.

District networks consist of an underground pipe system that connects one or more central energy sources to industrial, commercial, and residential consumers. The heat is transported to building substations where it is utilized for space heating and domestic hot water purposes.

The district heating system can be divided into two parts: the physical part and the virtual part. The physical part includes various components such as the energy production source, the distribution network, and the substations, all of which are interconnected from a technical standpoint. On the other hand, the virtual part encompasses management, organization, and control, which are integrated with sensor and regulation components.

The DH substations' components have to perform properly and also have to interact with each other to get a good cooling process. The cooling process in the district heating substation is the energy extracted per unit volume of district heating water passing through the heat exchangers [20].

The cooling process plays a significant role in the energy efficiency of the system, as return temperatures are a result of heat energy exchange in the district heating substation [2]. Low-return temperature is an interesting topic that can be achieved with the help of the right cooling process [17], which can be affected by cooling errors in both customers' heating systems and district heating substations.

Lauenburg et al. [21] have developed and tested a control algorithm for radiators connected to a heat exchanger (HEX) in the district heating substations with cooling valves. The aim was to achieve the lowest possible return temperature, and the control development resulted in 2 °C lower return temperature.

Additionally, effective control strategies can significantly increase DH efficiency. Studies have demonstrated that the control strategies and operational schedules of DH systems play a crucial role in improving energy efficiency [22]. By managing peak load hours and consumption diversity, these strategies lead to a reduction in heat losses without the need for increased production capacity.

For more efficient management, some studies have shown that methods for predicting and determining heat demand need to be developed for better operational conditions and production schedules, resulting in reduced fuel consumption.

Di Lascio et al. [23] proposed methodology by using approach of *mixture copula algorithm* with weather forecasting data to enhance the production schedule for the nest days. And results an accurate expectation for the demand.

Li et al. [15] have discussed both energy analysis and exergy analysis of a modeled DH network. Energy analysis focuses on the thermodynamic and hydraulic balance within the system, while exergy analysis assesses the work potential of the system when it reaches thermodynamic equilibrium with its environment. The findings of the analysis indicate that a lower supply temperature has a significant impact on the exergy of molecules, and reducing exergy losses results in a substantial increase in system efficiency, reaching almost 60 %.

Regulation methods are also a contributing factor, with the development of methods including advanced algorithms and the implementation of additional system variables, resulting in a more stable system and better energy flow conditions.

Birk et al. [24] have developed a multivariable control system and implemented it in the Luleå district heating network. The system controls the network's relationship between circulation pump speed and supply temperature. Testing of the multivariable control system resulted in preventing network fluctuations and stabilizing the system faster than traditional programs.

Tunzi et al. [13] have investigated the "Set Back" strategy on radiators for optimizing small district heating networks in the UK. The results of calculations and simulations have shown that reducing the return temperature from 55 °C to 35.6 °C led to 10% less heat loss and 9% less fuel consumption by the heating boiler in the system.

Actual measurement data for a specific period, provided by case study locations, could be used in this report to assess the performance of both the entire district heating network and each individual substation. Additionally, this collected data helps in investigating the impact of management and control strategies on network stability and effectiveness, and in determining the economic returns that can be achieved by improving the control system.

## 1.2 Aims

The study aims to analyse shortcomings in the substations' cooling process and more efficient heat consumption strategy by shifting the peak loads. The research questions discussed in this report are:

1- Which substations indicate lower efficiency, when using the average cooling as an indicator, and what are the possibilities to improve it?
2- How are the poorly performing substations affecting the whole network?
3- Can real-time adjustment of indoor temperature setpoints based on outdoor temperature effectively reduce peak heat rates, lower subscribed heat rate costs, and save energy consumption?
4- Are there more effective calculation methods to decrease the subscribed heat rate in the district heating cost pricing model?

## 1.3 Limitations

The study is limited to district heating supplied by VB energy to Ludvikahem AB buildings, and the data is limited to periods from December 2022 until January 2023.

Another limitation in the collected data is the presence of missing measurements at certain time steps, resulting in incomplete measurement series for some locations within a day (Section 4.2).

The specific distance between linking points in the distribution network was not provided, and there was also a lack of building construction specifications, sizing heat demand, and radiator sizes. These missing details limit the capability to use simulation programs effectively.

Analyzing the economic part 'Pricing Model' (Section 2.2) is limited to evaluate the subscribed heat rate calculation method. In this report, two methods based on the collected data period are used to compare results. The first method is the average of highest 5 daily average heat rate values, here called "Max 5", and the second method is P-signature.

# 2 Theory

## 2.1 District heating substations

District heating systems essentially distribute the heat energy from a heat source (such as a heating plant) to substations, which then distribute the heat energy to users. The heat energy is used to provide air heating and domestic hot water for the users such as residential buildings, industrial locations, and other facilities. These substations have an important role in controlling and managing the system, and they have both performance and economic impacts on the entire system.

The heat energy load is determined by the demand for heating and hot water, and the heat energy production must meet this demand according to Equation 1. The supplier can control two variables in the equation: the flow by regulating the pressure differences, and the supply temperature by increasing the burning in the boilers [2]. On the user side, heat demand can be controlled by effectively using energy or by implementing management strategies that ensure continuous coverage of the demand.

$$P = \dot{m} * C_p * (T_s - T_r) = \dot{m} * C_p * \Delta T \qquad equation\ 1$$

Where:
$P$ = Heat Demand [W]
$\dot{m}$ = Mass Flow rate [kg/s]
$C_p$ = Specific Heat Capacity Coefficient [J/kg K]
$T_s$ = Supply Temperature[°C]
$T_r$ = Return Temperature [°C]

The heat energy demand varies over time due to several factors, with outdoor temperatures being the most important, to compensate for heat rate losses in buildings and meet the hot water needs. Energy storage provides the opportunity for better management when the demand increases without the need to produce more energy [18]. Energy can be stored in the district heating (DH) network, as well as in the building's mass or by using external energy storage, such as accumulator tanks (as is the case in VB-energy).

The concept of a substation involves the transformation of energy from a higher level to a lower level. The key components of substations include heat exchangers for transferring heat energy, mixing equipment for temperature and pressure lowering, control valves, and safety equipment [2].

The substation receives the flow of heat energy from the network, known as the primary side, and then delivers the heat energy to the user side, known as the secondary side. The secondary side consists of two circuits: an air heating circuit and a hot water circuit. Substations sizing depends on both circuits demand in this report focused on residential buildings and facilities buildings.

The sizing of the substation primarily depends on temperature requirements. For hot water, it needs to reach a temperature of 50 °C at the taps. In the case of buildings, the number of apartments or units decreases the maximum hot water flow rate. As for heating, the sizing is primarily determined mainly by the lowest outdoor temperature where the building is located, along with the building's insulation standard. [2].

## 2.2 Substation components

Typical substations for apartment buildings are equipped with components as shown in Figure 2.1 and are divided into four groups [25]:

1. Energy transfer group, which includes HEX and circulation pumps for each circuit.
2. Control equipment group, which consists of control valves, actuators, temperature and pressure sensors and regulators.
3. Safety equipment group, which includes expansion tanks, shut-off valves, vent valves, and drain valves. Additionally, filters are recommended.
4. Measuring equipment group, which consists of energy meters measuring energy usage in (kWh) and volume in ($m^3$), flow and temperature sensors also involves in measuring purposes.

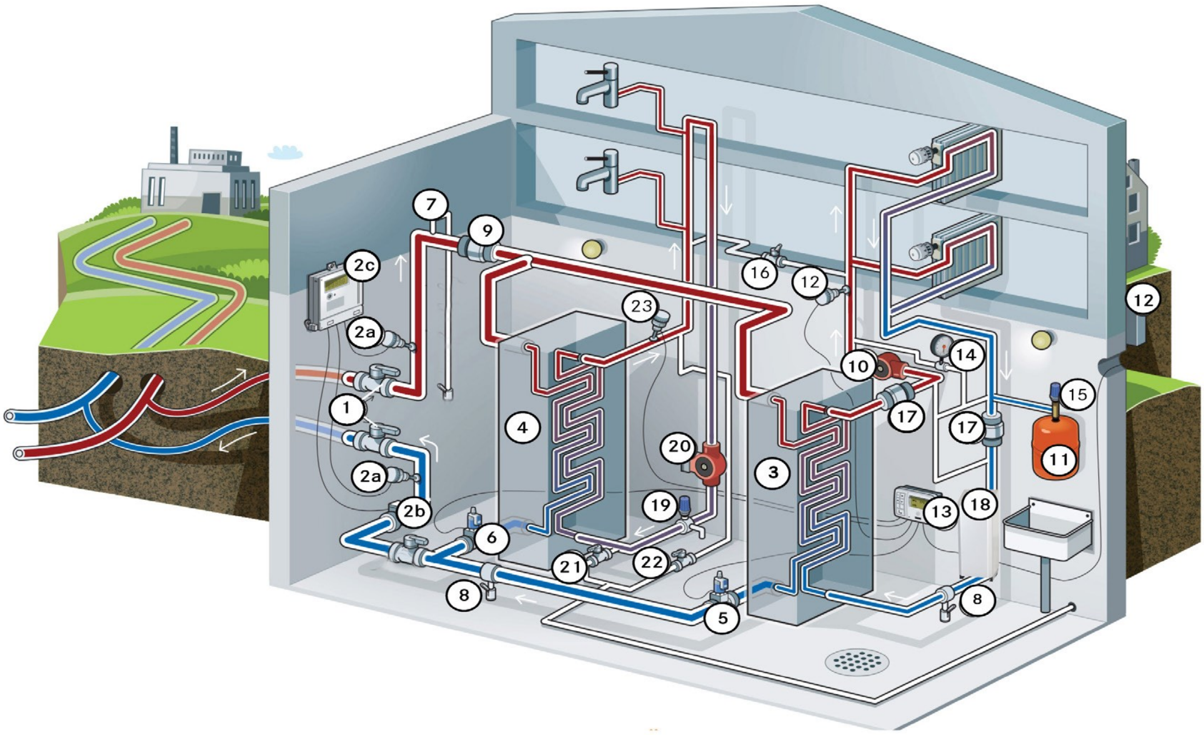



*Figure 2.1: Typical Substation Components (Used with permission from SEOM).*

DISTRICT HEATING CIRCUIT
1 Service valve (shut off valve)
2a Temperature sensor
2b Flow sensor
2c Energy meter
3 HEX for heat and ventilation system
4 HEX for hot water
5 Control valve heating and ventilation
6 Control valve hot water
7 Venting valve
8 Drain valve
9 Filter

HEATING CIRCUIT
10 Circulation pump
11 Expansion vessel
12 Temperature sensor
13 Regulatory center
14 Pressure gauge
15 Safety valve
16 Filling valve
17 Filter
18 Degasser

HOT WATER CIRCUIT
19 Safety valve
20 VVC Pump
21 Shut-off valve and backflow protection
22 Emergency connection
23 Temperature sensor

The hot water circuit, also called 'domestic hot water circuit' (DHW) supplies the users with hot water to the taps at the right level to avoid bacterial growth. The heating circuit (HC) in turn provides the customer with a comfortable indoor environment, primarily via the radiator circuit, but it can also be connected to underfloor heating or ventilation systems. District heating is used during the whole year round for heating the domestic hot water circuit, while for the heating circuit only during the colder periods of the year [2].

Control valves (parts 5 and 6 in Figure 2.1) regulate the HC radiators and DHW temperature, respectively. It is important to ensure the accuracy and proper functioning of the temperature sensors, regulator, actuator valve, and control valve to maintain the desired substation control.

DHW regulation is achieved by measuring the heat exchanger's incoming temperature (part 2a) and outgoing water temperatures using temperature sensors (part 23). The regulator (part 13) receives signals from the sensors, formulates them into a comparable value, and compares it to the prescribed value. The regulator controls the actuator valve, which is mounted to the control valve (see section 2.2.2), thereby controlling the position of the control valve. If the difference is positive, indicating that the water temperature is too low, a signal is sent to the actuator valve, causing it to open. This increases the flow of hot water, leading to increased heat exchange and, consequently, an increase in water temperature [2].

HC regulation follows the same principle but regulates the hot water temperature going to the radiators based on the outside temperature. The hot water temperature is measured on the secondary side of the heat exchanger (part 12), while an outside temperature sensor measures the actual outdoor temperature. Signals are sent to the regulator (part 13) to compare the values according to the temperature curve settings (see section 2.2.2, last paragraph). If the hot water temperature deviates too much from the temperature indicated by the temperature curve, a signal will be sent to the actuator to adjust the valve position to achieve the required flow in order to achieve the required water temperature [2].

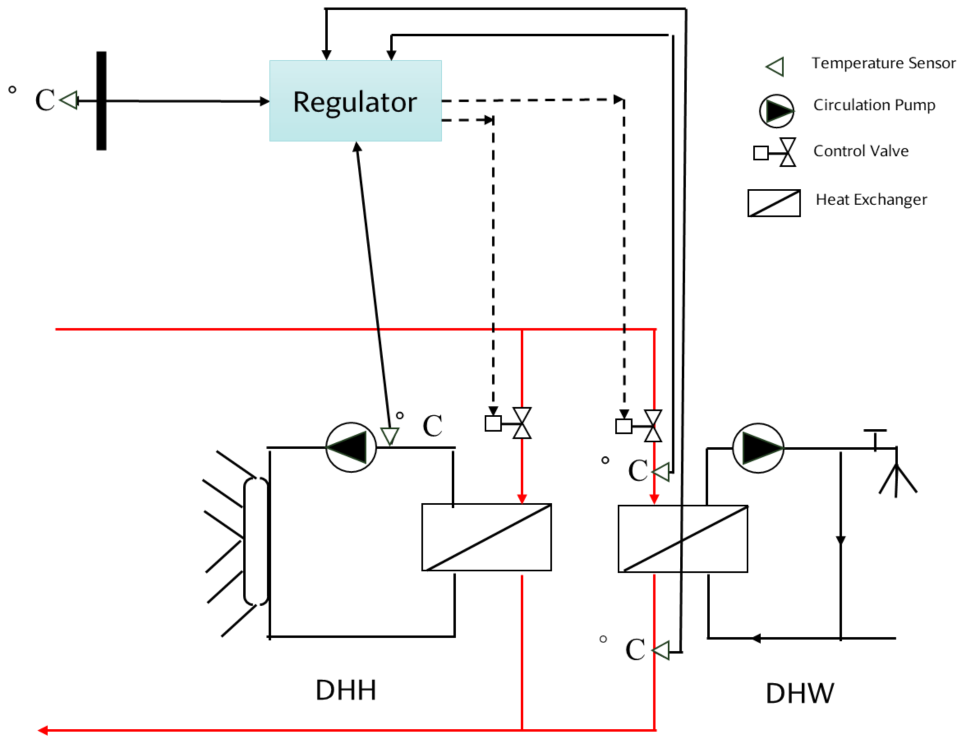



*Figure 2.2: Simplified Regulation Functionally*

### 2.2.1 Heat energy transfer equipment

The heat transfer from the primary side (supply) to the secondary side (consumption) occurs through HEXes. The working principle involves two separated water flows passing through conducting metals in two separated circuits and exchanging the heat from cold medium to hot medium according to the thermodynamics law (thermal equilibrium). There are several types of HEXes, such as gasket plate heat exchangers, brazed plate heat exchangers, shell and tube heat exchangers, spiral heat exchangers, and turbulent (tube-in-tube) heat exchangers, as shown in Figure 2.3 [26]. Generally, plate heat exchangers are used in district heating substations, as depicted in Figure 2.4, due to their compact size, high efficiency, ease of installation and maintenance, and lower risk of leakage compared to other types [2].

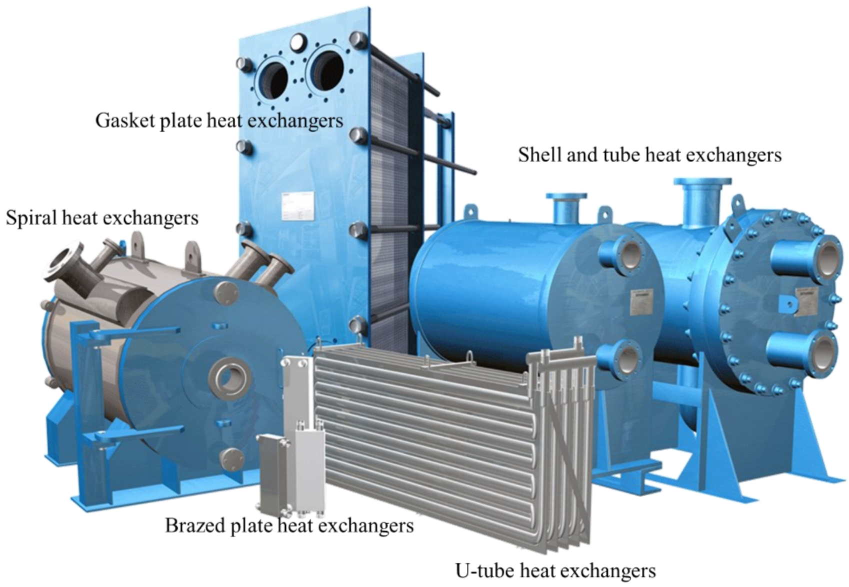



*Figure 2.3: Common Heat Exchanger Types [23]*

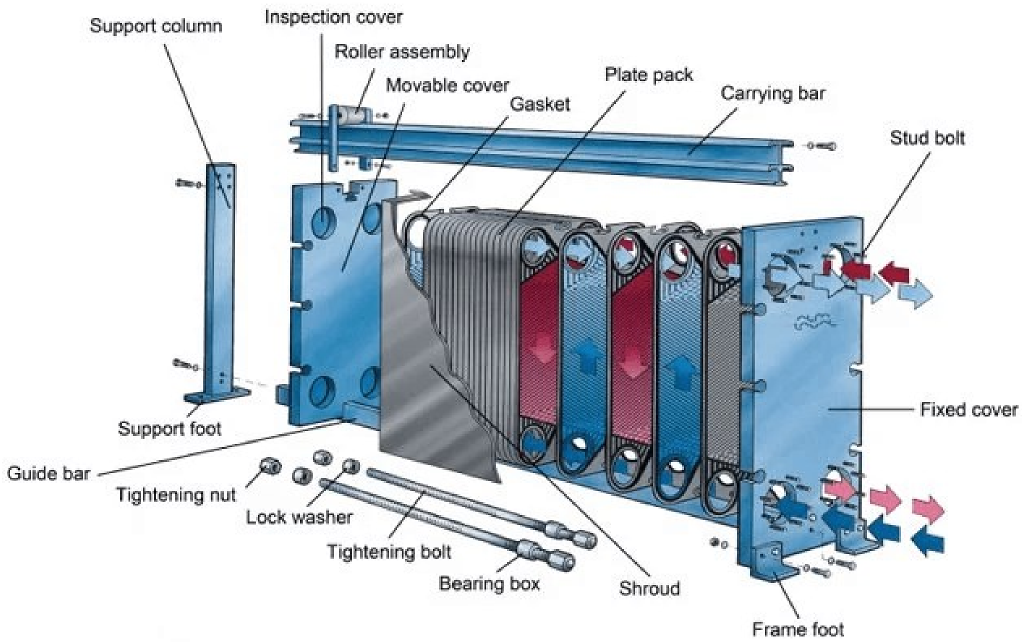



*Figure 2.4: Gasket Plat Heat Exchanger Exploded View and Working Principle (Figure from Alfa Laval Used with Permission)*

HEX size expressed by calculating the area of HEX, can be done by using equation 2 and 3, as shown below to ensure the least temperature difference lower as possible [2]:

$$A = \frac{P}{K * \Theta_{LMTD}} \qquad equation\ 2$$

Where:
$A$ = Area of the Heat Exchanger [m$^2$]
$P$ = Heat Demand [W]
$K$ = Overall Heat Transfer Coefficient [W/m$^2$ °C]
$\Theta_{LMTD}$ = Logarithmic Mean Temperature Difference [°C]

$$\Theta_{LMTD} = \frac{(\Theta_{GTD} - \Theta_{LTD})}{\ln(\Theta_{GTD}/\Theta_{LTD})} \qquad equation\ 3$$

Where:
$\Theta_{GTD}$ = Greatest Temperature Difference [°C]
$\Theta_{LTD}$ = Least Temperature Difference [°C]

A dimensionless HEX size expressed by the 'Number of Thermal Units' (NTU) or 'Thermal Length', can be calculated by using equation 4:

$$NTU = \frac{K * A}{\dot{m}_{dh} * C_p} = \frac{\Delta t_{dh}}{\Theta_{LMTD}} \qquad equation\ 4$$

Where:
$NTU$ = Number of Thermal Units
$\dot{m}_{dh}$ = District Heating Mass Flow Rate [kg/s]
$C_p$ = Specific Heat Capacity Coefficient of Water [J/kg K]
$\Delta t_{dh}$ = District Heating Side Water Cooling (Alternatively $\Delta t_{sp}$ Space Heating Cooling) [°C]

Circulation pumps play an important role in ensuring water circulation in the circuits at the desired flow rate. The operating flexibility of pumps is an important characteristic, with conventional or older pumps typically operating in an on/off mode at a specific designed speed. In contrast, modern pumps have speed-controlled operation, allowing them to vary between different speeds to achieve the desired flow rate.

Pumps need to be capable of overcoming head loss and pressure drop in the system. In the case of the hot water circuit, it is particularly important for the pumps to maintain a temperature of at least 50 °C [25].

### 2.2.2 Control equipment

Control valves are important components of the control system, enabling the regulation and manipulation of flow within the circuit to achieve the desired control objectives. There are two main types of control valves: mechanical valves (or self-operated valves) and motorized valves.

Mechanical valves utilize a spindle connected to a membrane to control the passage area between two pipes. By creating a closed volume of water when that closed volume changes due to pressure or temperature differences occur controlling the flow. The membrane expands or shrinks, this movement of the membrane causes the spindle to move, thereby regulating the flow.

On the other hand, motorized valves have a spindle that is controlled by an actuator. The actuator is driven electrically and responds to correction signals from a regulation system. This allows for precise control over the valve's position and enables adjustments to be made as required.

Sizing the control valves follows two criteria, specified maximum flow rate, and specified minimum pressure drop so the valve will open fully. This can be calculated by equation 5, or the conventional way using a manufactures diagram that defines the valve position based on flow and pressure drop over the valve [2].

$$\dot{V} = k_{vs}\sqrt{\frac{\Delta P}{1bar}} \qquad equation\ 5$$

Where:
$\dot{V}$ = Flow [$m^3/h$]
$k_{vs}$ = Flow Coefficient (k-value)
$\Delta P$ = Pressure Drop [kPa]

The control system also consists of temperature and pressure sensors placed at different positions in the substation. For example, a temperature sensor for the hot water circuit must be placed near the heat exchanger (HEX) to prevent time lag [2] and temperature sensor for the heating circuit must be placed after the circulation pump to prevent distortion from the turbulent flow [25]. These sensors work in combination with the regulator, which compares the measured values and sends signals to regulate the flow and maintain the desired temperature.

The regulator is an electronic device (PC box) capable of programming and setting the setpoints for each circuit. Conventional regulation methods often use a temperature curve to define a setpoint for indoor temperature based on the outdoor temperature [2]. However, advanced regulators offer additional functions such as setback or the ability to define different setpoints based on the time of day.

In recent years, an advanced control system has been developed that incorporates real-time data from the demand side. This involves monitoring and measuring indoor thermal conditions, specifically indoor temperature. Sensors are connected to indoor regulators, which in turn are linked to climate forecast services. These regulators, employing advanced control algorithms, determine the necessary heat rate while also ensuring thermal comfort. Furthermore, this system is interconnected with the regulator in the substation. It can update the required heat rate data and is even capable of being linked to the central control unit at the heating plant. This integration results in a high degree of control and regulation over the overall heat demand [2].

A similar system has been tested in Sweden involving 58 buildings. This system, referred to as a multi-agent system, treats each building as an agent and implements the demand side control. The results were promising, showcasing a reduction of approximately 20% in the total peak heat rate. These control systems prove highly beneficial for implementing load shifting strategies and preventing overheating during periods of low heating demand.[27].

### 2.2.3 Safety equipment

Safety valves protect the system from any damage that might occur when the system's pressure rises due to the increase in water temperature and flow rate. Vent, shut-off, and drain valves are needed when maintenance operation or manual adjustment operation of the system takes place.

Filters can be used to protect the heat exchangers, control valves, and other components from any particles that may cause damage or decrease the efficiency of the system.

The expansion vessel is a small container or tank divided in two by a rubber. One side is connected to the pipeline of the substation network and therefore contains water. The other, the dry side, contains air under pressure. When the network is empty or operating at the lower end of the normal working condition, the rubber is pressed against the water inlet. As the water pressure increases, the rubber moves, causing compression of the air on the other side of the rubber, and balancing the system pressure.

### 2.2.4 Measuring equipment

The measurement equipment, known as an 'Energy Meter', is primarily used for reading energy usage and water volume passing through the substation. The data is important for billing purposes and following up the DH function as well as statistic analyzation [28]. Energy meters consist of the basic elements: flowmeter (flow sensor), temperature sensor and calculator electronic device.

Reference [27], highlights important considerations and requirements when designing the metering area, including pipe routing, component placement, and electrical installation. Recognizing the flow profile's significance arises from its direct influence on the precision of flowmeter and temperature sensor readings, hence demanding the integration of straight pipe sections to alleviate these influences. Energy meter elements have some technical requirements and error limitations by the authorities, which are:

***Flowmeters***

Flowmeters (flow sensors) measure the flow or volume consumed of the water on the return side. Flow sensors used in the high temperature DH (defined as supply temperature over 65 °C) must be built to endure +120 °C and the predicted pressure of 1.6 Mpa. Flow sensors must comply with the EU directive 97/23/EC on pressure-bearing devices. There are several different solutions on which flow sensors base their measurement principle [28]. Measurement accuracy is an important property and according to the SS-EN 1434 standards limit the error defined as a function of the flow rate [2] as:

$$Klass\ 2\text{:}\ E_f = \pm\left(2 + 0{,}02 * {}^{q_p}/_{q}\right), \qquad Max\ limit\ between\ \pm 5\%.$$

Where:
$E_f$ = Flowmeter Error
$q_p$ = Maximum Flow Rate (in continuous function) [$m^3/h$]
$q$ = Actual Flow Rate (At testing) [$m^3/h$]

The most common type of flowmeter is the mechanical meters, although other types are also accepted and used in the last years, as [28]:

- Turbine flowmeter
  A turbine flowmeter is the main type of velocity flowmeter. It uses a multi-blade rotor (turbine) to sense the flow rate of the water, thereby deriving the flow or total amount of the instrument.
- Magnetic inductive meter
  The magnetic inductive meter flowmeter's operation is based on Faraday's law of electromagnetic induction, which states that when the magnetic field intensity and the distance between the two poles is constant, an induced electromotive force is generated in the direction perpendicular to the medium flow and the magnetic force line, and the induced electromotive force is proportional to the measured medium flow rate.
- Ultrasonic meter
  Ultrasonic flow meters are equipment that detects the impact of fluid flow on ultrasonic beams (or ultrasonic pulses) to determine the flow. Ultrasonic flowmeters used in closed pipelines are classed based on measuring principles such as time propagation, Doppler effect, beam offset, correlation, and noise.
- Fluidistor meters
  Fluidistor meters have a measurement housing with two alternate water channels. When the flow is redirected via one channel, the inlet flow is pushed such that the next partial flow is directed into the opposite measurement channel, and so on. The exchanges quantify the flow at a frequency proportionate to the volume flow.

***Temperature sensors***

These elements are always two sensors for the supply and return temperature at the primary side to calculate the temperature difference ΔT. Technical requirements when connection cables are given firmly connected (Fixed connected) to temperature sensors, the two cables must be of the same length and area, as well as of sufficient quality to allow signal transmission without impact or disturbance from the surroundings. The temperature sensor's terminal block and placement location in pipelines must be lockable. Measurement accuracy according to the SS-EN 1434 standards limit the error defined as a function of the thermal differences [28] as:

$$E_t = \pm \left(0{,}5 + 3 * {}^{\Delta\theta_{min}}/_{\Delta\theta}\right) \%$$

Where:
$E_t$ = Temperature Sensor Error
$\Delta\theta_{min}$ = Minimum Temperature Difference [°C]
$\Delta\theta$ = Actual Temperature Difference (At testing) [°C]

Regarding the temperature sensor type, the most common type is the resistance temperature detection (RTD), which operates on the fact that material resistance varies with temperature. Platinum temperature sensors are preferred because of corrosion resistance and material stability. The kinds most used are Pt100 and Pt500, the number refers to the electrical resistance measured in Ohms at 0 °C [2].

***Calculator device***

This element is an electronic device with a display, responsible for calculations of the measured data. The required output data is energy used (in kWh) and water volume consumed (in $m^3$), but there are additional properties depending on the manufactures, such as peck load max temperature etc. It also provides data storage, so the data will not be lost if electricity is lost in the substations, and the modern types are battery operated for more effective substation that doesn't consume electricity from the grid. Energy calculation is done within a particular period using measured data can be done with equation 6 as shown below [2]:

$$E = \int_{t1}^{t2} C_p * \rho * \Delta T * q \qquad equation\ 6$$

Where:
$E$ = Heat Energy [kWh]
$t$ = time [h]
$q$ = Flow [$m^3$/h]
$C_p$ = Mean Specific Heat Capacity Coefficient [J/kg K]
$\rho$ = Mean Water Density [kg/$m^3$]
$\Delta T$ = Supply Temperature ($T_s$) - Return Temperature ($T_r$) [°C]

Technical requirements a sampling time (time to obtain measurements) of about 30 seconds. Measurement accuracy according to the SS-EN 1434 standards limit the error defined as a function of the thermal differences as [28]:

$$E_t = \pm \left(0{,}5 * {}^{\Delta\theta_{min}}/_{\Delta\theta}\right) \%$$

Where:
$E_t$ = Temperature Sensor Error
$\Delta\theta_{min}$ = Minimum Temperature Difference [°C]
$\Delta\theta$ = Actual Temperature Difference (At testing) [°C]

## 2.3 Substation design

The design of substations is an important factor for system efficiency. There are two different ways to connect a district heating substation with end-users: direct and indirect connections. The direct connection, which is an open-loop system, is not preferred due to water and energy wastage, as well as hygiene reasons. The indirect connection, on the other hand, involves closed loops that circulate water in three different circuits as mentioned: the district heating (DH) circuit, heating circuit, and hot water circuit. The latter method is preferred as it eliminates water and energy wastage and meets the temperature requirements of the hot water circuit, which should be at least 50°C to prevent bacterial growth [2].

The layout of the substation primarily determines the connection of HEXes for both circuits, from the DH side to the end-users' side. The aim is to increase the ΔT, to utilize as much incoming heat energy as possible. Different connection methods, such as parallel, series, 2-stage, and 3-stage connections (as shown in Figure 2.5), can be employed [2].

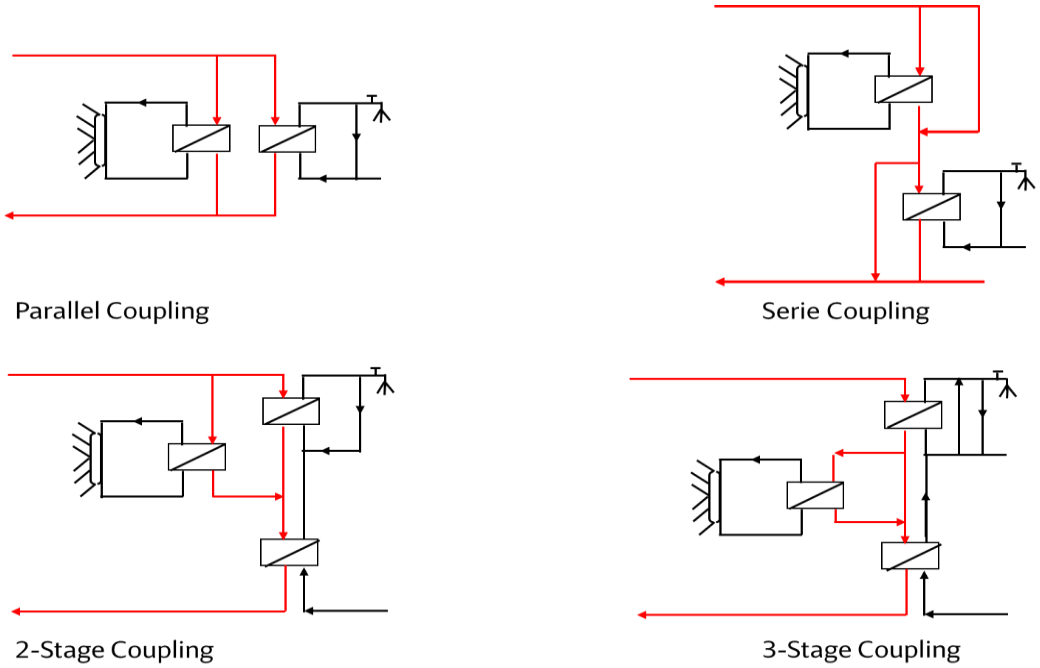



*Figure 2.5: Substation Connection methods (Diagram Drawing Inspirate of [2] Fredrickson and Werner)*

The most common method in Sweden is an indirect district heating substation with a parallel connection for the heating circuit and hot water circuit (see figure 2.5), similar to the case in the study location [2].

The series layout is used when the supply temperature is very high, around 150°C, and the heating demand is high. In this layout, the heating circuit utilizes the heat energy first and delivers a lower supply temperature to the hot water circuit. However, in lower supply temperature DH, this can result in a lower supply temperature for the hot water circuit, potentially below 65°C, which increases the risk of bacterial growth [2].

The parallel layout is the most commonly used due to its simplicity and lower cost compared to the 2-stage and 3-stage layouts. In the parallel layout, the two circuits operate independently and do not affect each other. This results in a lower flow rate through the heat HEX, which helps maintain the condition of the HEX and improves its overall lifetime [2].

The 2-stage layout consists of three heat exchangers, including an additional HEX which operates to preheater for the hot water circuit. The extra HEX receives a primary connection from the heating HEX and uses it to heat the cold water before it enters the hot water HEX. This results in a lower primary return temperature due to a larger heat energy exchange. Similarly, the 3-stage layout follows a similar concept. But the 3-stage layout is not suitable when the hot water demand is low or when the cold-water quality is rich in dissolved minerals, as this can lead to scale buildup, reduced efficiency, and shortened HEX lifetime [2].

## 2.4 Pricing model

For the DH to remain competitive, distribution costs must be lower than the cost difference between local and centralized heat production. It is the marginal distribution costs that restrict the competitiveness of district heating.

The pricing model provides a structure for determining how prices should be set for each customer. The key question is: How should the price model be designed to satisfy the preferences of both customers and suppliers? There are two fundamental principles: cost-based pricing (linked to the supplier's costs) and market-based pricing (linked to the prices of alternative market options).

Cost-based pricing establishes a price level based on the combined annual costs and a specific return on the DH system's invested capital. Market-based pricing can be direct or indirect. In Europe, a common market alternative is natural gas, where the district heating price becomes fully or partially proportional to the competing natural gas price. More advanced pricing models are employed in cost-based and indirect market-based pricing. The advantage of these models is that they are predetermined, ensuring that customers under the same conditions receive the same price. [2] What factors determine pricing? And what is the definition of each of these factors?

The price components included in today's price models for larger consumers are as follows [29], (see section 4.5):

1- Fixed price: Based on the customer's previous annual consumption per year.
2- Energy price: Typically, a constant energy price is maintained throughout the year.
3- Heat rate price: Usually calculated using the categorical number method, although heat rate price based on actual measured values at the daily (or hourly) level is becoming more common.
4- Flow price or temperature price: The customer pays a price based on the volume of district heating water that has passed through the heat exchanger in their property.

Pricing is a continually evolving and optimizing process. Today's price models usually consist of a fixed price, a heat rate price calculated using the categorical number method, and an energy price without seasonal differentiation. When transitioning to a new and cost-effective price model, assuming:

1- Shifting from a uniform energy price throughout the year to an energy price differentiated over two or three seasons, based on the marginal cost of district heating production [30].
2- Transitioning from a designated categorical number to a heat rate price based on measured heat rate, while also incorporating additional price components in a functional manner, such as return temperature, cooling, and flow [30].

## 2.5 Literature review

The literature review studied improving the efficiency of the district heating network towards more environmental sustainability, from the technical point of view and management of the system in both parts of the system.

Technical optimization investigates the optimization of components in different positions within the boundaries of the district heating system. In this study, optimization is divided into three groups: optimization of the heat plant, district heating substation, and system control (regulation and management of consumption).

### 2.5.1 Heat plant

District heating plants primarily supply heat energy from the combustion of fuel. The system becomes more sustainable and efficient if the heat energy losses are utilized as much as possible. By converting the heat losses to another form of energy or by improving the system performance to be more efficient. Sustainability through the integration of renewable energy sources and system efficiency leads to lower emissions, preserving energy resources and contributing to securing future for the coming generations.

Klaassen et al. [16] compared primary energy savings in a combined system with a separate system and showed that cogeneration plants is a technical alternative for providing heat and electricity in combination with a district heating network more efficiently than separated energy production plants. The EU introduced a regulation in 2004 to encourage and promote efficient cogeneration within Europe's liberalized electricity markets. The EU recognized that cogeneration is an attractive option for improving energy efficiency [31].

Bauer et al. [32] tested a combination of solar thermal plants with geothermal storage via district heating network, resulting in reduced carbon dioxide emissions. Chinese et al. [14] studied and developed a technical model for recovering waste heat from a furniture factory in Italy. The study showed that recovery significantly reduced GHG emissions by reducing fossil fuels and heating costs.

Pavlov et al. [18] clarify the concept of heat storage and its application possibilities. The purpose of heat storage is to shift the load. During peak loads, heat from the storage is used instead of increasing production. Heat storage can be accomplished through various methods, such as using a fixed container like an accumulator tank or utilizing underground heat energy storage (geothermal). These approaches may rely on an energy carrier to store heat and serve as a heat reservoir. Additionally, some storage methods involve utilizing the building's mass or phase change properties of certain materials in the building's construction to effectively store and release heat as needed.

Liu et al. [33] developed thermal analysis models for the decoupling of cogeneration plants and the integration of heat pumps, electric boilers, heat storage tanks, or low-pressure turbines to increase system flexibility. The analysis shows that energy efficiency increases with heat load, but exergy decreases with this increased flexibility.

Xing et al. [34] have highlighted that the relationship between dynamic district heating system storage capacity and discharge rate is affected by delay in pipeline systems or building storage capacity which varies over time. They proposed an evaluation method of real-time energy storage capacity by different indicators, such as heat shifting capability, available storage/release capacity, and available storage/release depth. The availability of dynamic storage or discharge capacity in a district heating system can be increased by extending the storage duration or discharge rate, eventually reaching the maximum capacity.

### 2.5.2 District heating substation (heat exchange station)

Both the design of the district heating substation and the control units affect the efficiency of the district heating system. One of the factors that plays a major role in efficiency is the return temperature from the district heating substation. The return temperature from a radiator system can potentially be as low as room temperature to maximize the amount of heat from the district heating system.

Historically, return temperatures in the district heating system have been much higher, even during the cold part of the year. This is the result of incorrect adjustment of radiator systems and short-circuiting between the supply and return lines [35]. Deviations between actual and theoretical return temperatures are caused by [2]:

- Short-circuiting flows between the supply and return lines in the network (also called bypass, shortcuts, or loops).
- Low supply temperature to peripheral district heating substations due to temperature drops in the flow direction due to high pipe heat losses.
- Cooling errors in customers' heating systems.
- Cooling errors in customers' district heating substations.

Cooling is an important process that directly affects the return temperature. Frederiksen and Werner [2] divided cooling errors into two parts: customers' heating systems and customers' district heating substations. The most common cooling errors in customers' heating systems are no thermostatic valves in radiator systems, no hot water circulation, and three-way valves bypassing in radiator systems, which results in a high return temperature in the radiator system.

Cooling errors in district heating substations can also occur due to functional errors, construction errors, and setpoint errors. Frequent functional errors are leaking valves, defective actuators (valve motors), and defective temperature sensors. Construction errors in the control chain are due to oversized valves, improperly installed temperature sensors, and improperly selected actuators. Setpoint errors include when customers' operators expect significantly higher temperatures from district heating substations than what they need in their heating systems.

Gadd et al. [36] have analysed the temperature difference in the distribution system of 140 district heating substations of the district heating network. The analysis shows that a low return temperature is achieved if the district heating substation works without errors and to maintain a low supply and return temperature, errors must be detected quickly and easily, leading to a more efficient district heating system. The method used for error detection (Novel method) is based on temperature difference observation for one year.

Another method for optimizing the cooling process involves implementing a third pipe system within district heating substations. This strategy entails dividing the return pipes into two separate return pipelines. The third pipeline creates an additional hot water circulation route that maintains a lower return temperature during periods of reduced heat demand, such as in the summer or when there are variations in hot water requirements among end-users.

This system is particularly advantageous for heat recovery scenarios involving high return temperatures from industries. This method introduces "supply-to-supply connections" or "return-to-return connections," which prove especially effective when expanding the network to accommodate different temperature levels. This approach enhances heat transfer efficiency and significantly boosts heat recovery capabilities within the district heating system. [17].

Kuosa [37] et al. investigated a new control system called 'mass flow control' that uses inverter-controlled pumps to adjust both primary and secondary flows instead of control valves. This results in more energy-efficient supply and return temperatures for both districts heating network and building radiator systems.

Secondary side pump speed is regulated to maintain a constant return temperature from radiators at a given outdoor temperature, while primary side water flow is adjusted to maintain a constant secondary side supply temperature by varying the rotation speed of the primary side pump. With mass flow control, smaller mass flows are possible for domestic hot water due to greater cooling of district heating water, resulting in lower pressure losses with the same pipe dimensions compared to traditional control systems. This, combined with lower pressure losses in customers' substations, leads to an average of 49.2% lower pumping power with mass flow control than with the traditional control system [37]. However, when comparing the required pumping power to the total heat demand of the network, it is only an average of 0.2%.

### 2.5.3 District heating system control

The regulation method varies based on the regulation devices and the managing strategy of the substations. Conventional regulation involves the implementation of heat demand curves that regulate the indoor temperature setpoint in response to the outdoor temperature. Improving the regulation of the heat load by implementing an effective control system is essential. Advanced control algorithms, real-time regulation, and smart monitoring systems can be employed to optimize heat consumption based on demand patterns, weather forecasts, and other relevant variables. These control strategies help to balance heat production and consumption, minimize energy wastage, and ensure a more sustainable and environmentally friendly operation of the DH system.

Diversity is an important concept in many aspects and leads to load variation, human activity varies over time, and temperature differences between indoors and outdoors vary with seasons, as well as the building envelope varies depending on the construction year and materials used.

Weissmann et al. [38] simulated the heat demand rate for a single residential building as well as for a cluster of 144 residential buildings, considering the climatic conditions in Germany. The results showed that increasing diversity leads to better system performance. The system becomes more efficient when the variation increases in human lifestyle or in the condition of buildings such as insulation capacity, or other factors in construction. The study reasoned that peak load needed for all consumers should be distributed at different times, so that the total peak load becomes lower for the entire system.

The accuracy of heating demand (heat demand) is the most important dimensioning parameter, which determines the delivered heat rate capacity and flow, and the schedule of the plant becomes more efficient. Heat demand depends on outdoor temperature, which varies with season and time, so the accuracy of heat demand determination is greatly influenced by outdoor temperatures. Di Lascio et al. [23] proposed a statistical application of a probability law for determining the heat demand for district heating systems. The application improves the heat production schedules.

Therefore, the control in district heating plants plays an important role in optimizing control strategies, some of which are:

- Install flow restrictors in district heating plants to increase the temperature level in the secondary supply and reduce return temperature [2].
- Prioritize domestic hot water by turning off the building heating circuit during peak load [39].
- Low flow settings of the building heating system, by maximizing ΔT between primary supply and return temperatures. This strategy leads to less flow in the heating system and does not affect the domestic hot water circuit [40].

Adaptive control techniques are optimization of control units, to be more accurate in measuring the actual values of quantities and interacting with other quantities. Some studies on the development of adaptive control include:

- Birk et al. [24] developed Control Configuration Selection and Adaptive Control. The application was tested and proved to be able to stabilize the system faster than traditional programs. Oscillations in control schemes can be greatly reduced by using the proposed control.
- Arce et al. [41] designed the AMBASSADOR project to create a fixed simulation model for the district heating/district cooling network and regulate the system in real-time. The aim is to optimize the system process. The model caught the related dynamic variables and heat transfer with a reasonable degree of accuracy.
- Dancker et al. [42] proposed a method for energy flow calculations for both thermal and hydraulic flow together. To achieve a steady-state energy flow, improved quasi-steady-state heat rate flow calculation is mentioned.
- Idowu et al. [43] Developed a data-driven methodology through programming to analyze and forecast the combined heating and hot water demands of buildings, with the goal of enhancing production schemes. The method was tested using actual data from 10 residential buildings in Sweden. The results showed that 7 out of 10 buildings provided accurate forecasts due to the input of district heating plant variables (supply temperature, difference between supply and return temperature, and flow rate).

# 3 Case Study Locations

## 3.1 VB Energi

The VB Energy plant does not produce electricity, just boilers for heat energy production. It consists of four boilers, two of which are considered base boilers that primarily serve Ludvika city. The other two boilers function as peak boilers, which are rarely used, Table 3.1 gives details of the boilers. In most cases, the base boilers, along with an accumulator tank, are sufficient to meet the heating demand. The peak boilers are only activated during low outdoor temperatures (below -8 °C) or when maintenance work is being carried out on the base boilers.

*Table 3.1: Heat Energy Plant Details at VB-Energy*

| *Facility* | *Boiler type* | *Fuel Type* | *Heat Output* | |
|---|---|---|---|---|
| *Lyviksverket LVC 4* | Bio boilers 2 pcs<br>Flue gas condenser<br>Accumulator tank | Biofuels RES<br>Recycling | 2* 10 MW<br>5 MW<br>2000 $m^3$ | ST up to 165 °C |
| *Folketshus Ludvika LCV5* | Oil boiler | Fuel oil | 7 MW | Peak Facilities |
| *Lasarettet Ludvika LCV2* | Bio Oil boiler<br>2 pcs | Fuel oil<br>(Vegetable bio-oil) | 5 MW<br>10 MW | Peak Facilities |

The accumulator tank is connected to the industrial facilities, and the tank is directly connected to the base boilers. The heat stored in the tank is distributed to the district heating network without any significant delay. The accumulator tank has a storage volume of 2000 $m^3$ and a maximum heat output of 160-170 MW. In this manner two temperature levels feed the district heating network. Figure 3.1 shows a simplified diagram for the plant.

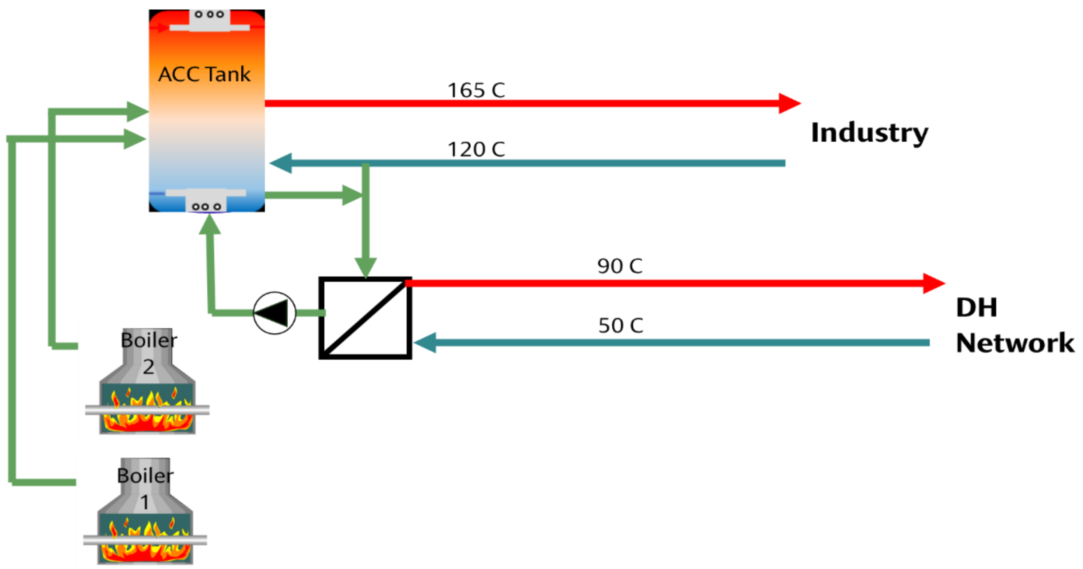



*Figure 3.1: Simplified VB-Energy plant Diagram*

The distribution network has a volume of 3000 $m^3$ under pressure of 11 bar. Single pipe design (separate pre-insulated supply and return pipes). Central pumps circulate water throughout the network. The pressure within the network is regulated by the central pump to prevent any under-pressure conditions. Additionally, the pumps change the direction of feeding or excessing the heat from the accumulator tank.

## 3.2 Ludvikahem AB

Ludvikahem AB is a housing company that manages residential buildings and facilities buildings such as sports locations and premises with an area of 450 $m^2$. They are responsible for 90 district heating (DH) substations, which consist of two circuit heat exchangers (HEXes) connected in parallel. These substations are equipped with various control units, and approximately 50% of them have the capability to control indoor temperature setpoints at multiple levels.

The indoor temperature setpoint for the buildings is set at 21 °C, whether it is in each apartment of the multifamily buildings or in every office of the premises buildings. Control valves with automatic motorized controls are used to adjust the flow based on demand when the indoor temperature deviates from the setpoint, when there are changes in the outdoor temperature. The pumps in the substations are speed-controlled and will stop operating when the outdoor temperature reaches 14 °C.

The hot water circuit is equipped with hot water circulation (VVC), ensuring a continuous flow of hot water. During nighttime hours (between 23:00 and 06:00), the ventilation system in the facilities buildings is shut off. It is important to note that there are no accumulator tanks in the buildings.

The control of the HEXes is carried out manually by controllers who measure the temperature difference before and after the HEXes. The aim is to maintain a temperature range of approximately 44°C to 42°C. However, monitoring is limited to the primary side measuring sensors, making it difficult to detect faults in the DH substations.

Overall, Ludvikahem AB focuses on efficient temperature control and energy management in their substations to ensure optimal comfort for residents and efficient operations of the district heating system.

# 4 Method

Method sections are divided according to the theory parts, and research subject.

## 4.1 Literature review

The literature review method is used in this report to explore the research on district heating efficiency improvement and development for more sustainable energy systems. Results and conclusions from the related studies and articles summarized.

Basic research aims to optimize district heating towards more efficient and sustainable systems. The research focuses on scientific articles in the Dalarna University Library and other online research databases in collaboration with Dalarna University, as well as physical searches of books from the library.

Sources are credible, the validation strategy is 'content validity,' which means validating the content of the documents and the sources of the documents. Triangulation is used to validate the data with other documents for further factual strengthening [44].

### 4.1.1 Literature

The search included scientific articles, textbooks, and official reports.

- Scientific articles: The search was conducted in the online literature database (Högskolan Dalarna Library), which links to other databases such as 'Science Direct', 'Elsevier' and 'Research Gate.' These databases are reliable and provide original articles.
- Textbooks: The search is conducted in the Högskolan Dalarna Library, both e-books and printed books. These books are good primary sources of information.
- Official reports: The search is conducted on Google using keywords from articles that have referenced them. Official documents are often ideal for qualitative research, and keeping up with report updates is important [44].

### 4.1.2 Search strategy

Search technique is to obtain fewer results but highly related to the desired question, using (AND) and (quotation marks). The search is limited to full text in English and Swedish, and publication years up to 10 years, in some cases up to 5 years.

### 4.1.3 Search reporting

The search results are presented according to the recommendation of Umeå University Library [45] in Table 4.1, below:

*Table 4.1: Results of Keywords Searching*

| Number | Search words | Number of results | Filtration used |
|---|---|---|---|
| 1 | Optimizing energy efficiency in apartment buildings | 23 | 10 year / Fulltext |
| 2 | Energy balance AND building | 5669 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 3 | Passiv house | 42 | 10 year / Fulltext / Eng/Sve / Book/Articles |

| | | | |
|---|---|---|---|
| 4 | "Energy balance" AND "Life cycle assessment" AND buildings | 48 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 5 | Environmental impact AND Building | 39203 | 5 year / Fulltext / Eng/Sve / Articles |
| 6 | Byggnaden utsläpp | 22 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 7 | district heating | 10 | 10 year / Eng/Sve / Book |
| 8 | diversity in district heating | 71 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 9 | capacity utilization in district heating | 123 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 10 | outdoor temperature AND district heating | 188 | 10 year / Fulltext / Eng/Sve / Book/Articles |
| 11 | District heating factors | 227 | 10 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 12 | power AND flow AND district heating | 168 | 5 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 13 | temperature AND flow AND district heating | 205 | 5 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 14 | "district heating" AND "sustainability" | 17 | 10 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 15 | "district heating" AND "substation" | 114 | 5 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 16 | UN The Sustainable Development Goals Report 2022 | 1 | |
| 17 | Miljöindikatorer – aktuell status | 1 | |
| 18 | EU Directive 2004/8/EC of 11 February 2004 | 1 | |
| 19 | the world energy consumtion by sector | 1 | |
| 20 | Pricing of district heating | 15 | 10 year / Fulltext / Eng/Sve / Book/Articles / district heating |
| 21 | Lillaprismodellen | 1 | |

### 4.1.4 Handling of search results

The selection of articles has been conducted in several steps. First, the relevance to the subject and objectives of the study is determined by reading the article titles. Then, the content of the articles is assessed for alignment with the study's questions by reading the abstracts. Additionally, considerations such as research years, completeness (covering the question thoroughly or extensively), and evaluating the content of the selected articles are necessary

[46]. The chosen articles are saved and read in their entirety, with interesting sections marked. The articles are grouped into folders based on topics, as shown in Table 4.2.

*Table 4.2: Number of Selections per Groupe*

| Gruop | Number of selected articles |
|---|---|
| **Substation** | 8 |
| **District heating system** | 15 |
| **Low RT and flow** | 8 |
| **Control** | 9 |
| **District heating plant and cooling** | 7 |
| **Method** | 3 |
| **Priceing model** | 5 |
| **Return DH** | 6 |
| **Limit Flow** | 6 |
| **Heat rate equalization** | 3 |

### 4.2 Data processing

Data analysis is often employed to obtain an understanding of specific problems or challenges. If the data utilized for analysis is of poor quality, it may not offer a clear picture of the problem and might hinder the identification of causes. High-quality data increases the possibility of correctly identifying and evaluating problems. Data quality evaluation and compilation process is done in four stages to get good-quality data, steps show in Figure 4.1.

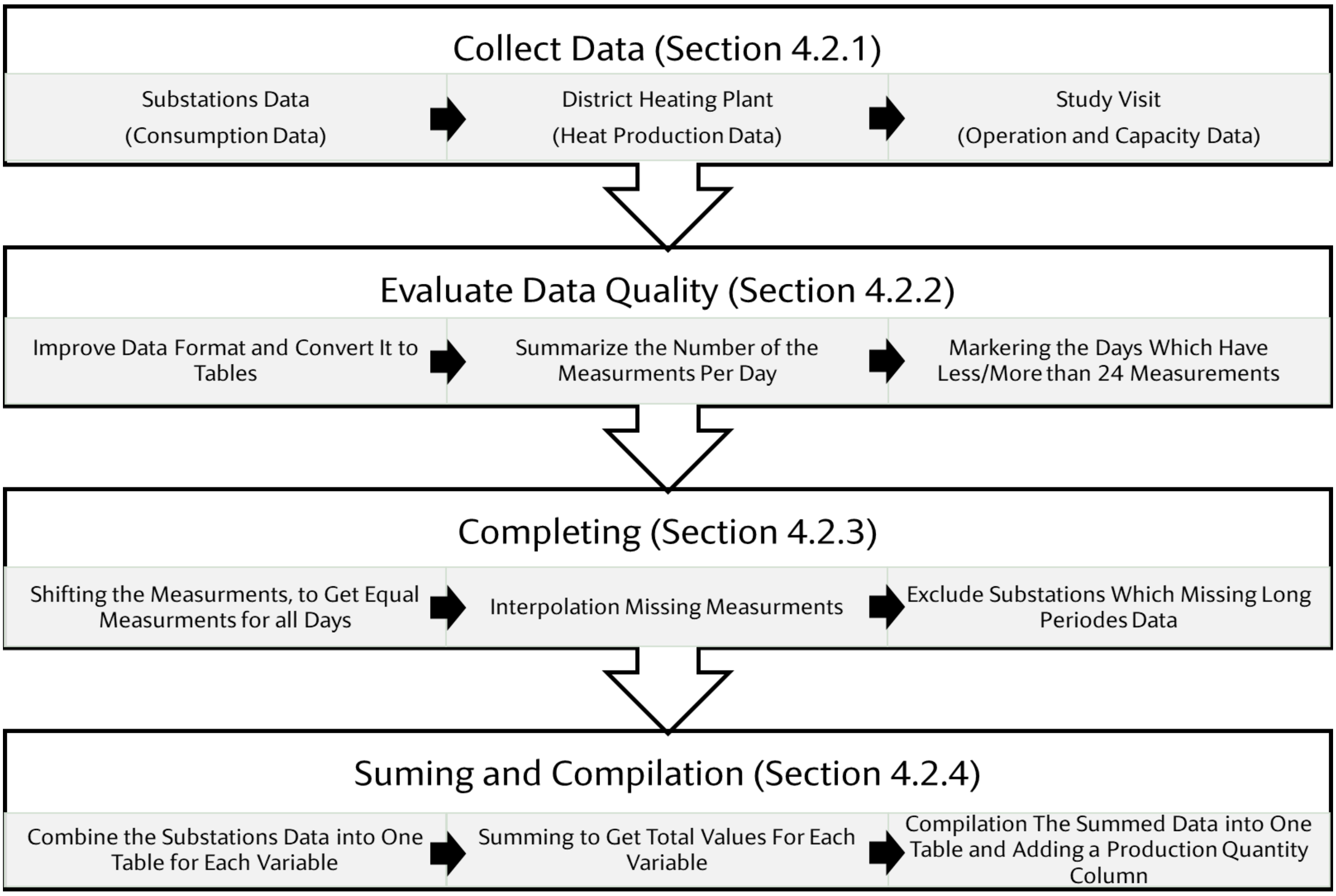



*Figure 4.1: Data Treatment Steps*

### 4.2.1 Data acquisition

To analyze the performance of the DH substations, data was collected from three sources. Firstly, the substation data provided consumption data for all 90 substations owned by Ludvikahem (see Figure 6.3). A total of 83 substation datasets were included in the analysis, while the remaining substations were excluded due to missing data for long periods (several weeks). In section 4.2.2 more details are explained. The measurements from the primary side of the substations were registered only, and data from the secondary side was not recorded, such as:

- Consumed volume in $m^3$
- Consumed energy in MWh
- Flow in $m^3/h$
- ST in °C
- RT in °C

The collected data and measurements for the substations were provided by Ludvikahem. The data for each substation was stored in a separate file, with varying numbers of rows and columns that differed in terms of the measurement processing time. Therefore, it was necessary to evaluate the quality of the data, organize it, and assess the possibility of completing any missing information before conducting any analysis operations, as shown in Figure 4.1.

There were two types of hourly collected data for substations: 'Consumed volume in $m^3$' and 'Consumed energy in MWh' were hourly integrated values. Thus, integrated data contains limited decimal places (1, 2, or 3 decimals for smaller values such as 0.001), which often results in similar integrated values, even when they should differ slightly.

On the other hand: 'Flow in $m^3/h$', 'ST in °C' and 'RT in °C' were instantaneous measured values. Thus, data is not integrated or averaged, just providing the conditions for a specific time point, leading to lower accuracy due to the variable load.

The heat rate at the measured time was not reflected in the instantaneous data. Similarly, the average temperatures and flow rates were not reflected in the hourly integrated data. Furthermore, the poor quality of the hourly integrated data, as depicted in Figure 4.2, reflects a low level of load variation and accuracy. Consequently, it is necessary for the heat rate to be calculated at each timestep when temperatures and flow are measured.

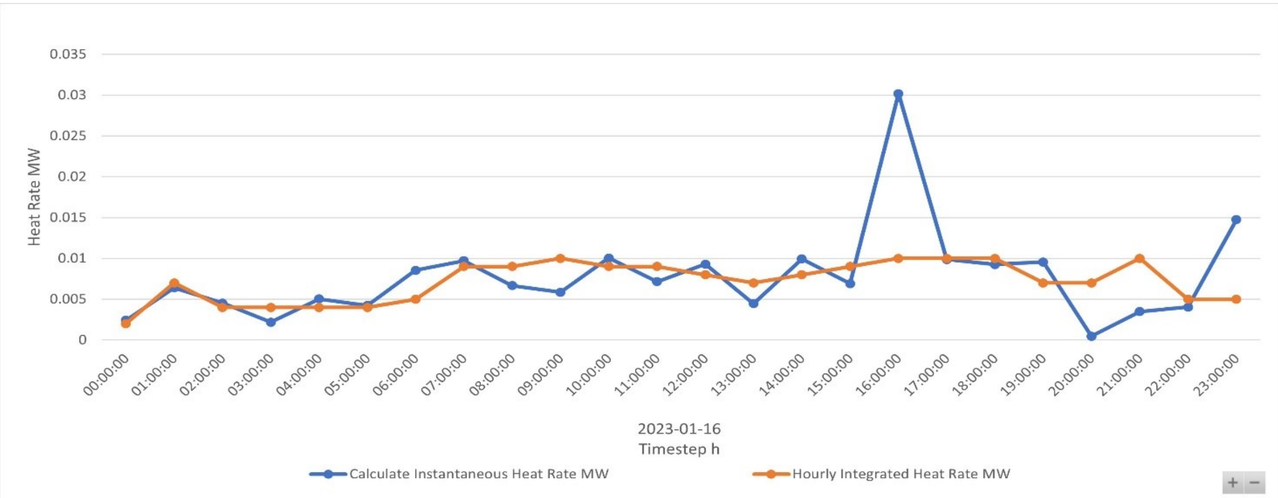



*Figure 4.2: Example of the Low Accuracy of the Measured Heat Rate Data as an Hourly Integrated Values*

Secondly, the DH plant data provided production data from two base boilers located at the Lyviksverket facility (LVC4). These boilers cover the heat demand of industrial customers, Ludvikahem buildings, and other private customers.

The DH production data collected by VB Energy was in a good format and complete datasets for each day. However, it lacked specific information regarding Ludvikahem's share of the total heat production. This makes it difficult to accurately determine the total energy supplied to the 90 substations. Furthermore, the temperatures were registered as hourly average values, which differed from the substation data where temperatures were registered as instantaneous values. Ludvikahem provided information regarding its buildings' share, which accounted for 45 % of VB energy total heat production.

The third source of data was obtained during study visits. A visit to the VB energy plant provided information about its production operation and capacity (see section 3.1). Additionally, a study visit to Ludvikahem's office offered insights into their management and control of the substations. It's worth mentioning that the monitoring was limited to primary side data only.

### 4.2.2 Data quality evaluation

The second stage to obtain good-quality data for the datasets of all 90 substations involved evaluating the completeness of the data timesteps. The measured data from each substation was provided in separate files, and the data format was improved and converted into tabular form using Excel and created own macros. It is important for the data to be treated as tables in order to facilitate content summarization using pivot tables. The macros are helpful in saving time and ensuring a consistent process for all the substations, thus ensuring a complete process for every dataset.

The collected data for the substations within the period from December 2022 to January 2023, with hourly measurements (readings) recorded. The total number of data readings would be 1488, based on 24 data readings per day. Each day's reading (measuring) began with the first reading at 00:00 and ended with the last reading (measuring) at 23:00. However, it is worth noting that the timing of the instantaneous readings was not perfectly hourly, and there were missing registered data readings sometimes.

Further, the hourly integrated readings consist of a limited range of decimals points, only 2-3 decimal places. Figure 4.3, shows an example of the data quantity evaluation results, in other words, indicates the data readings quantity for every day by using coded macros in three steps:

1- Improve the data format and convert it to tabular form. Adding heat rate column.
2- Create pivot tables to summarize the number of data readings every day.
3- Filtering and marking the data readings less than 24 and more than 24 per day.

| | |
|---|---|
| ⊞ 2023-01-11 | 23 |
| ⊞ 2023-01-12 | 24 |
| ⊞ 2023-01-13 | 24 |
| ⊞ 2023-01-14 | 22 |
| ⊞ 2023-01-15 | 23 |
| ⊞ 2023-01-16 | 24 |
| ⊞ 2023-01-17 | 24 |
| ⊞ 2023-01-18 | 24 |
| ⊞ 2023-01-19 | 24 |
| ⊞ 2023-01-20 | 24 |
| ⊞ 2023-01-21 | 25 |
| ⊞ 2023-01-22 | 23 |
| ⊞ 2023-01-23 | 24 |
| ⊞ 2023-01-24 | 24 |
| ⊞ 2023-01-25 | 24 |
| ⊞ 2023-01-26 | 23 |
| ⊞ 2023-01-27 | 25 |
| ⊞ 2023-01-28 | 22 |
| ⊞ 2023-01-29 | 24 |
| ⊞ 2023-01-30 | 24 |
| ⊞ 2023-01-31 | 24 |
| **Grand Total *** | **1476** |

*Figure 4.3: Example of Data Completeness Evaluation, Yellow refers to Missing Data Readings and Orange refers to Extra Data Readings at One Day Scale*

The substations have been categorized into five groups according to the extent of missing data, as presented in Table 4.3. The actions taken to address this issue and improve the data quality are clarified in Section 4.2.3.

*Table 4.3: Data Completeness Classification*

| Evaluation Result | Group Name | Number of Substations |
|---|---|---|
| Is missing 24-100 | Interpolate | 10 substations |
| Is missing 101-300 | Interpolate many | 9 substations |
| Is missing 301-500 | Missing | 2 substations |
| Is missing 501-1000 | Missing alot | 6 substations |
| Is missing over 1000 | Missing more than 1000 | 5 substations |

***Heat rate calculation***

The heat rate value describes the substation's performance response to the outdoor temperature, and also analyzes the interaction between other variables such as flow rate and return temperature. Adding new column by calculating the heat rate according to equation 8, the value considers an instantaneous value since ST and RT is an instantaneous data reading, not integrated. Specific heat capacity and density of water was considered as a constant value corresponding to the average temperature of the $\Delta T$ (50 °C), from Incropera and DeWitt (1996) [47], (attached in appendix 1).

$$P = \dot{V} * \rho * C_p * (T_s - T_r) \quad equation\, 8$$

Where:
$P$ = Heat rate (demand) [W]
$\dot{V}$ = Volume Flow [m$^3$/s]
$\rho$ = Water density [Kg/m$^3$]
$C_p$= Specific Heat Capacity [J/(Kg.K)]
$T_s$ = Supply Temperature [K, °C]
$T_r$ = Return Temperature [K, °C]

### 4.2.3 Data arrangement and completion

In order to accurately sum the measured values at the appropriate timesteps, is important to ensure completion of the datasets for all the substations. During the assessment of substation data, it became evident that the number of data points differed across days and reading intervals. This was primarily because the time intervals between data readings were not exactly an hour. Two situations were observed:

Firstly, there was a discrepancy in data readings between days, where a reading was recorded in the final minutes of the hour (e.g., 23:00), which should technically belong to the following day (00:00 o'clock) but was associated with the same day. Secondly, some days exhibited gaps in data readings at various timesteps, leading to incomplete data series.

These situations were handled differently. In the first situation, the registered data reading was shifted to the next day by advancing the hour by a few minutes. This adjustment ensured an equal number of data readings for the days that were interconnected.

In the second situation, the data was organized and completed with empty rows for each day to achieve the right total number of data readings, and the required timesteps were added. In this process, the integrated values of the consumed volume and energy had to be divided by the number of added rows after each addition. This step was necessary to maintain the accuracy of the integrated values after completing the missing data. Completion by interpolating the missing values.

Interpolation was made for the first two groups in Table 4.3 by using STATA software [48]. STATA interpolates quickly by importing the data as an unformatted excel file and then adds the whole new columns to the original tables, at this stage the datasets become complete.

The other three groups in Table 4.3 were 13 substations excluded and in lately stage used 6 data set of those excluded substations in the analyses because the data was completed at the chosen period, finally 83 of 90 substations were taken into account.

### 4.2.4 Data compilation

The compilation of the substations' data is important for assessing the performance of the DH network. In the assessment, any issues or inefficiencies within the network are identified, along with potential areas of shortage or improvements (see section 6.1.1).

The process of data compilation, involving three distinct data sources, has been finalized after implementing data quality enhancements (as explained in Section 4.2.3). The compiled dataset includes heat production data from VB Energy, consumption data for the 83 substations sourced from Ludvikahem, and real-time outdoor temperature data.

The heat production data for both base boilers were adjusted to 45% of their full heat production, representing the respective share of evaluated substations versus total heat production for whole the DH network. The hourly outdoor temperature observations for Ludvika were available as open-source data at the Swedish Meteorological and Hydrological Institute (SMHI) [49]. Consumption data were compiled in two steps. Firstly, the data from all 83 substations' datasets were gathered and organized into separate tables for each variable. Then, the values for each timestep (hour) were summed to obtain the total consumption value for each variable at every timestep. Secondly, the total values were consolidated into one table along with the heat production data and outdoor temperatures.

The calculation of supply and return temperatures takes into consideration the variation in flow rates. This process involves three steps:

1. Calculating the percentage of flow for each time step in each substation dataset.

$$Flow\ share\ \% = \frac{Flow\ rate\ at\ specific\ timestep}{Total\ Flow\ rate\ at\ the\ same\ timestep\ acroos\ all\ the\ substations} \times 100$$

2. Multiplying the temperature by the respective percentage for each time step in each substation dataset. This result specific temperature in each timestep for each substation.

$$Specific\ Temperature\ at\ specifik\ timestep\ ℃ = Flow\ share\ \% * Temperature\ ℃$$
$$\text{(both at the same timesetp and same substation dataset)}$$

3. Then summed across all substations for the same time step, thereby obtaining the total temperature for this specific time step encompassing all substations.

$$Total\ Temperature\ for\ that\ specific\ time\ °C = \sum_{Substation\ 1}^{substation\ 83} Specific\ Temperature\ at\ specific\ timestep$$

## 4.3 Substations performance analysis

The data from the substations are useful for assessing local performance. A substation with poor performance can have a negative impact on the entire system, leading to decreased efficiency when it returns a high temperature. It can also affect the flow balance in the network when there are increases or decreases in the pressure drop.

The performance of the substations is evaluated using instantaneous data, as the ST, RT, flow rate, and outdoor temperatures are measured instantaneously. The heat rate at each timestep is calculated to complement this data (see section 4.2.1).

### 4.3.1 Analyzing period and indicators

Choosing a specific period to evaluate the performance of substations in various heat demands aligns with the outdoor temperature variation and captures a wide range of fluctuations. This approach provides a comprehensive overview of substation efficiency in general. The chosen analysis period was limited to one week, from 21-01-2023 to 27-01-2023. This period was selected based on the lowest outdoor temperature recorded during the entire duration, which reached -15 °C on 22-01-2023. Additionally, data for 83 out of 90 substations was available within this timeframe.

Indicators play a vital role in assessing the performance of substations. By selecting indicators that are directly related to the research goal, it is possible to ensure that the analysis is focused, relevant, and aligns with the specified objectives. This alignment facilitates the formation of actionable insights and recommendations. For this evaluation, the key performance indicators (KPI) were interesting are:

1- Supply Temperature Max, Min, and Average.
2- Return Temperature Max, Min, and Average.
3- Cooling, calculated as a ratio of energy consumed to consumed volume.
4- The cooling average, calculated as a difference between supply and return temperature.

KPIs were calculated for each substation and summarized in one table (Table 5.1) and sorted from the best cooling indicator to the worst (see section 5.1).

### 4.3.2 Analyzing criteria

The temperature difference (ΔT) between the supply temperature and return temperature is considered the major key performance indicator (KPI) for comparison. For Ludvikahem, the acceptable range of ΔT is 42 °C for residences and 44 °C for activity locations. These values indicate the good performance of HEXes. In this analysis, ΔT values of 50 °C and above were considered acceptable performance, and the objective was to find better solutions for the substations operating near the limit.

### 4.3.3 Analyzing protocol

A protocol for analyzing data establishes appropriate guidelines, removes biases, and improves the dependability of the analysis. It is critical for ensuring consistency, repeatability, and proper documentation of analysis results. The protocol involves determining the optimal operational conditions and comparing the data (see section 5.2), as follows:

1- To visualize the relationship between variables and their response to outdoor temperature variation, a chart depicting the curves of heat rate, flow, RT, and outdoor temperature as instantaneous values was created. This chart offered a comprehensive overview of how these variables interacted with one another and responded to the changes in outdoor temperature. Aims to identify if there is any markable mismatch between variables to specify which component needs to look after for achieving a better heat exchange process.

2- The total values of the hourly integrated energy were compared with instantaneous heat rate, and the integrated volume was compared with instantaneous flow rate. The aim was to detect notable heat losses in the substations.

3- The flow required for the same average heat rate can be calculated by assuming ΔT to be 50 °C (as per equation 9). The calculated flow can then be compared with the actual average flow. This analysis aims to determine the deviation of flows from the optimal flow. It also helps identify potential errors in pump settings or sizing when supplying the heat exchanger with the appropriate water volume.

$$\dot{V} = \frac{P}{C_p * \rho * \Delta T} \qquad equation\ 9$$

Where:

$\dot{V}$ = Volume Flow [$m^3/s$]
$P$ = Average Heat rate [W]
$C_p$= Heat Capacity [J/(Kg.K)]
$\Delta T$ = Temperature difference between supply and return temperature assumed 50 [°C]

4- Determined the position of the substation on the district heating networks map. The benefits of this criterion include assessing whether the supply temperature is fair based on the distance from the heating source and identifying the nearest substations to analyze if there is a shortage in the area.

#### 4.3.4 Results handling

The substations to be analyzed are defined, and they are then classified into two groups based on the type of analyzed error: 'Management' errors, which occur due to incorrect settings or load determination, and 'Components' errors, which occur due to problems with components or sizing. Action proposals for the substations grouped based on the solution type (improving ideas) are discussed in the capital discussion (see section 6.1.2).

### 4.4 Load shifting simulation model and saving calculations

Regulating the heat demand is an important factor in the DH system to achieve the desired indoor climate comfort. The regulation process, as mentioned in section 2.2.2, involves multiple components that respond to the demand and determine the required flow and supply temperature. Regulation methods vary depending on the regulation devices and the managing strategy of the substations. Arce et al. [41] and Idowu et al. [43] studies have demonstrated that real-time control and accurate predictive methods are beneficial in optimizing the district heating (DH) network, as discussed in section 2.5.3.

Managing the regulation in a manner that satisfies the demand at the right time with the required heat rate reduces heat energy losses in underutilized resources, such as storing heat energy in the building's mass. Furthermore, it enhances the effectiveness of the DH system, reduces heat production, and increases overall system efficiency.

In this report, the examined managing strategy is based on real-time regulation that controls the indoor temperature setpoint based on the measured outdoor temperature. It involves lowering the indoor temperature setpoint during periods of low outdoor temperatures and thereafter raising it before and after that period to accumulate heat within the building structure. The objective is to decrease the heat rate requirements on colder days while still ensuring a comfortable indoor climate and optimizing the distribution of heat rate across different days.

#### 4.4.1 Simulation model

Simulating the management strategy requires using simulation programs such as IDA ICE or others. However, the lack of data regarding building structure and radiator sizing limits the capability to utilize these simulation programs. As a result, a simple simulator was created using Excel, this required a building model and a regulator model.

***The building model***

Excel was used to create a simple building model for simulating the managing strategy at one of the substation locations, specifically the building at 'Tre Krokars Gata 10, 771 34 Ludvika'.

This building is a six-floor apartment building with 34 residential apartments and a basement, with a heated area of 2439 m$^2$.

To calculate the heat rate demand required to maintain the desired indoor climate, the coefficient of heat transmission (U-value) and the heated area needs to be determined. However, the data necessary for calculating the U-value, such as the building's structure dimensions and insulation specifications, are missing. Similarly, the heated enveloping area is also not available.

Therefore, the annual consumption of energy for space heating and hot water was utilized to estimate the U-value. The required data was obtained from the online open database of the housing authority (Boverket), specifically the latest energy declaration for this building in 2020 [50]. To simplify the calculation, the UA-value was used instead of the U-value.

The UA-value was calculated based on the annual heat consumption and the number of heating degree hours (Gt) using equation 10. The heating degree hours for Ludvika were obtained from tables [51], which required the annual average temperature obtained from the Swedish Meteorological and Hydrological Institute (SMHI) website [49]. Additionally, the operation limit temperature (Tg), set at 17 °C according to the The Swedish National Board of Housing, Building and Planning (Boverket) standards [51], was taken into consideration.

$$E_h = UA * G_t \text{ [kWh]} \qquad equation\ 10$$

Where:
$E_h$= Heating energy demand [kWh]
$UA$ = Coefficient of Heat Transmission for all the Area [kW/°C]
$G_t$ = Heating degree hours [°C h]

The tap hot water share is estimated by considering the number of apartments and using a standard value provided by The Swedish Energy Agency [52]. The estimated value is approximately 2000 kWh per apartment per year.

$$E_{tw} = 2000\ kWh * 34\ Apartment$$

$$P_{tw} = \frac{(2000\ kWh * 34\ Apartment)}{8760\ h} = 7.8\ kW$$

Where:
$E_{tw}$= Tap hot-water energy demand [kWh]
$P_{tw}$= Tap hot-water heat demand [kW]

***The regulator model***

The load shifting approach requires a regulator model. A simple design of the regulator model involves taking input data, processing it according to the installed settings, and producing adjusted output data, as seen in Figure 4.4.

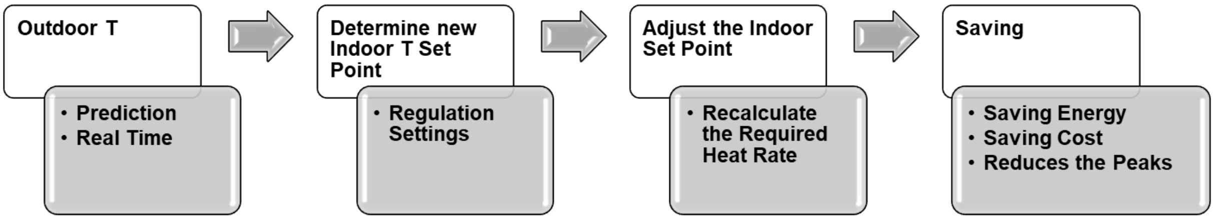



*Figure 4.4: The Regulation Diagram*

The input data utilized the measured outdoor temperature data for the Ludvika community during the period of December 2022 and January 2023. The processing of the input data involved creating a reference table that matched the desired indoor temperature with different outdoor temperature levels ranging from -18°C to 18°C as shown in Figure 4.5. The Excel MATCH function was used to define the indoor temperature based on the corresponding outdoor temperature level, which served as a regulating setting (see section 4.4.3). To ensure accurate matching, the outdoor temperature was rounded to the nearest integer.

INDEX($C:$C; MATCH(ROUND(K27, 0); $B:$B; 0))

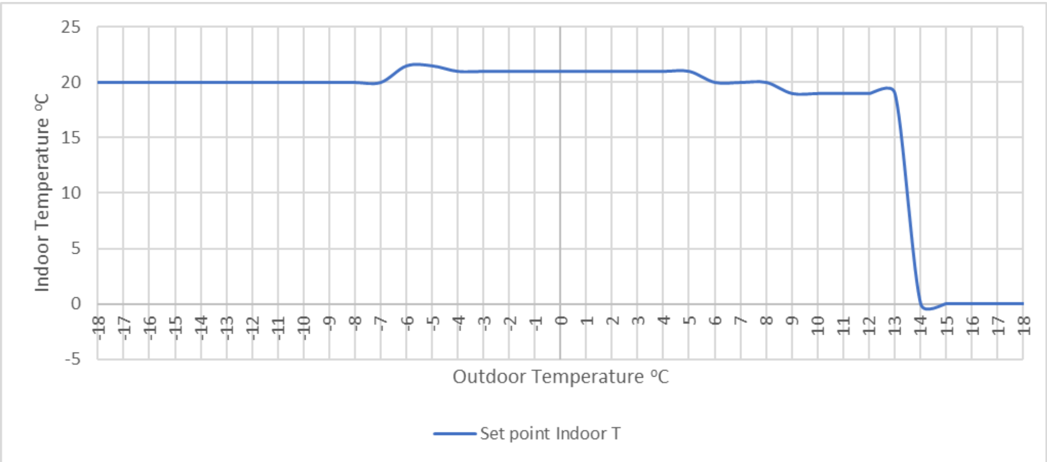



*Figure 4.5: Plot of the indoor temperature reference table in the load shifting approach.*

Thereafter, the required heat rate for space heating was calculated based on the matched indoor temperature and the defined outdoor temperature (this value can be measured using an outdoor temperature sensor or predicted data) (as per equation 11). The heat rate for tap hot water, which is also supplied through the district heating system, was added to the space heating heat rate for each hour throughout the entire period. Additionally, the same calculation was performed in another column, considering a fixed indoor temperature of 21 °C as the Ludvikahem standard (as per equation 11), in order to compare and evaluate the results.

$$P = UA * (Indoor\ T - Outdoor\ T) + P_{tw} \quad [kW] \quad equation\ 11$$

Where:
$P$ = Required Heat rate for Both Space Heating Circuit and Tap Hot Water circuit [W]
$UA$ = Coefficient of Heat Transmission for all the Area [kW/°C]
$Indoor\ T$ = Indoor Temperature [K, °C]
$Outdoor\ T$ = Outdoor Temperature [K, °C]
$P_{tw}$= Tap hot-water heat demand [kW], That assumed to 7.8 kW

The resulting output was an adjusted heat rate that was necessary to meet the indoor climate requirements, taking into account the accumulation of heat energy within the building's mass.

### 4.4.2 Regulating settings

The indoor temperature set point in the regulator settings at the apartments are based on the outdoor temperature, as shown in the Table 4.4 below:

*Table 4.4: Regulation Setting for The Strategy*

| | |
|---|---|
| Outdoor Temperature =< (-7 °C) | Indoor temperature set point (20 °C) According to VB energy at -8 °C using peak heating facilities. |
| Outdoor Temperature => (-6 °C) and =< (-5 °C) | Indoor temperature set point (21.5 °C) |
| Outdoor Temperature > (-4 °C) and < (5 °C) | Indoor temperature set point (21 °C) |
| Outdoor Temperature > (5 °C) and < (8 °C) | Indoor temperature set point (20 °C) |
| Outdoor Temperature > (8 °C) | Indoor temperature set point (19 °C) |
| Outdoor Temperature > (14 °C) | Space heating OFF. According to Ludvikahem control standards |

### 4.4.3 Energy cost saving calculations in the simulation

The following statistical data are evaluated:

1- The five highest daily average heat rate values were identified both before and after implementing the regulation strategy.

2- The saving potential in kW and percentage was calculated by determining the difference between the heat rate values before and after implementing the regulation strategy.

3- The statistics of the saving potential range at the lowest and highest outdoor temperatures were reviewed.

4- The cost saving calculation for the studied period was based on the VB energy tariffs and was calculated both before and after implementing the regulation strategy.

- Heat rate [kW] (Subscribed heat rate in kW, year) as:

(Subscribed Heat rate / 365) * Number of the period days (in our case 62 days) * Fees.

- Energy [MWh] as:

Summing up the heat rate within the period * Fees for MWh

- Flow [$m^3$] as:

Registered consumed volume (from raw data) * Saving potential * Fees for $m^{3.}$

5- The results were also visualized by showing the load shifting over the days in the graph (Figure 5.16) of 'Heat Rate with changed set point' and 'Heat Rate with fixed set point' over the simulated period. Furthermore, the load shifting throughout the hours was visualized in the graph (Figure 5.17) of 'Energy Saving Potential', 'Heat Rate with changed set point', and 'Heat Rate with fixed set point'.

## 4.5 Pricing model calculations

To assess the economic benefits of improving the DH efficiency through a better cooling process and implementing a load shifting strategy, a cost calculation provides valuable insights. The cost of DH is categorized into different energy using levels, with higher consumption levels resulting in lower costs. This is due to the high start and stop fees relative to smaller energy amounts. It is crucial to determine the annual energy usage by utilizing historical data or, for new subscriptions, by estimating an appropriate value. The total cost includes various components outlined in section 2.4 and is distributed based on their percentage share. Each pricing model follows its specific design.

### 4.5.1 Flow price

The flow component in the pricing model reflects the volume of water flowing through the HEX (Heat Exchanger). This component incentivizes customers to improve the efficiency of their substations. By enhancing the cooling process, the water flow through the HEX decreases, resulting in lower electricity consumption for pumps and reduced heat losses.

The flow component calculated included the water volume for the specified period, which can be monthly or yearly, and multiplied by the price of one cubic meter of water.

$$\text{Flow cost} = \text{Consumed Water Volume} * \text{Cost of each } m^3$$

### 4.5.2 Energy price

The energy component represents the largest portion of the DH cost and reflects the amount of energy consumed by the customers, measured in kilowatt hour or megawatt hour. The pricing is segmented into various seasons to accommodate fluctuations in production costs. During times of reduced heat demand, when economical fuel sources such as waste combustion suffice, this strategy comes into play to ensure fair cost for end-users. On the other hand, this pricing division encourages customers to conserve energy during seasons of higher prices.

The energy component is calculated by multiplying the energy consumption for each month by the corresponding monthly price. The sum of the monthly costs results in the annual energy cost.

$$\text{Energy cost} = \sum(\text{season price 1 [SEK]} * \text{season period 1 energy used [kWh]}) + (\text{season price 2 [SEK]} * \text{season period 2 energy used [kWh]}) + (\text{season price 3 [SEK]} * \text{season period 3 energy used [kWh]})$$

### 4.5.3 Heat rate price

The heat rate component refers to the heat rate demand of the buildings, to account the peak hours demand and its cost. The heat rate component incentivizes the customer to consider the load shifting and decreasing the peak hour loads.

In many cases, 'Fixed Price' and 'Heat Rate Fees' are combined by determining the yearly heat rate amount in kilowatts (kW) for each customer. This is referred to as 'Subscribed Heat Rate Calculations'.

The subscribed heat rate calculations methods used in this report include the P-signature method and the highest five values of the daily average heat rate (Max 5). The purpose of employing these methods is to assess their feasibility and determine the most suitable calculation method for district heating (DH) customers. These methods provide a comprehensive understanding of the heat rate requirements based on varying temperature conditions. Additionally, the Max 5 and P-signature methods are employed to capture the heat rate peaks as much as possible due to the high costs associated with heat rate peaks.

The hourly integrated heat rate values were summed up for each hour and then calculated the daily average by using a pivot table in Excel. Also, the outdoor temperature is calculated as the daily average temperature (see section 5.4).

***Max 5***

From the daily average heat rate within the entire period captured the highest values by using LARGE function in Excel. Then calculate the average of those highest five daily average heat rates. This is used as subscribed heat rate value.

$$\text{Subscribed Heat Rate} = \frac{\sum(\text{Heat Rate Highest 1+Highest 2+Highest 3+Highest 4+Highest 5})}{5} \text{ [kW]}$$

***P-signature***

The P-signature method considers the peak heat rate values at the lowest outdoor temperature. A scatterplot is created by plotting the daily average outdoor temperature against the daily average heat rate. Then established a linear equation that represents the relationship between these variables. The lowest daily outdoor temperature is then used as an input (X factor) in the equation to calculate the corresponding heat rate value, known as the P-signature, measured in kilowatts (kW) [53], see section 5.4. The P-signature value is used as the subscribed heat rate value.

***District heating fees in Ludvika (Calculation Example)***

To illustrate how the district heating cost is calculated from the fees and distributed between the different categories, for a building annually using 360 MWh heat energy and monthly used as shown in the Table 4.5 below, 16 000 $m^3$ per year, the DH fees are:

Subscribed Heat Rate 857 SEK/ kW, year.

Energy fees Dec-Mar 564 SEK/ MWh
April, Oct and Nov 350 SEK/ MWh
May-Sep 222 SEK/ MWh

Flow (Volume) fees 3.4 SEK/$m^3$

*Table 4.5: Monthly Energy Using (Assumed Value)*

| | | | | | |
|---|---|---|---|---|---|
| Jan | 99.2 | MWh | Jul | 20.8 | MWh |
| Feb | 84.8 | MWh | Aug | 27.2 | MWh |
| March | 76.8 | MWh | Sep | 27.2 | MWh |
| Apr | 52.8 | MWh | Oct | 60.8 | MWh |
| May | 36.8 | MWh | Nov | 60.8 | MWh |
| Jun | 20.8 | MWh | Dec | 84.8 | MWh |

DH cost Calculation

Heat Rate part:

$$\text{Subscribed Heat Rate (Max 5)} = \frac{\sum(266.8 + 260.9 + 260.1 + 256.6 + 252.7)\text{kW}}{5} \ [\text{kW}]$$

Subscribed Heat Rate = 259.4 kW per year

Defined subscribed heat rate amount per year (259.4 kW) * Cost of kW per year (857 SEK) = **222 310 SEK per year**

Subscribed Heat Rate (P-signature) = 273.4 kW per year (See figure 5.19 upper chart)

Defined subscribed heat rate amount per year (273.4 kW) * Cost of kW per year (857 SEK) = **234 304 SEK per year**

Energy part:

| | | | |
|---|---|---|---|
| Dec-Mar | 345.6 MWh | 564 SEK/MWH | 194 918.4 SEK |
| Apr, Oct, Nov | 174.4 MWh | 350 SEK/MWH | 61 040 SEK |
| May-Sep | 132.8 MWh | 222 SEK/MWH | 29 481.6 SEK |

**Total Energy cost per year 285 440 SEK**

Flow part:

Consumed Water Volume per year (16000 $m^3$) * Cost of $m^3$ (3.4 SEK) = **54 400 SEK per year**

**DH total costs per year (Max 5) = Sum of Heat Rate cost + Energy cost + Flow cost**
**= 222 310 + 285 440 + 54 400 = 562 150 SEK per year**

**DH total costs per year (P-sign) = Sum of Heat Rate cost + Energy cost + Flow cost**
**= 234 304 + 285 440 + 54 400 = 574 144 SEK per year**

# 5 Results

This chapter presents the results in three main sections. Firstly, the evaluation of substation performance and the classification of substations based on their performance. This is followed by an analysis of poorly performing substations. Secondly, the analysis focuses on the performance of the DH network and the impact of poorly performing substations on the entire network. Lastly, the chapter presents the results from the load shifting simulation, including energy savings and economic implications.

## 5.1 Substations performance analysis results

### 5.1.1 Performance classification results

The substation KPIs are summarized in Table 5.1, which highlights important indicators related to the cooling process. These include the maximum and minimum temperatures of the supply and return sides throughout the entire period. Additionally, the average supply and return temperatures provide a comprehensive indicator of the overall temperature level.

The cooling indicator reflects the amount of heat energy extracted from the water volume passing through the HEX. The average cooling provides an indication of the substation's thermal performance. It is calculated simply by taking the temperature difference between the supply and return sides (see section 4.3.1). So, the highest value corresponds to the greatest difference between the supply and return temperature, indicating that more heat energy has been extracted from the supplied water.

For classification purposes, the 'Average Cooling' serves as the rating scale. Substations are sorted in descending order based on their average cooling values. The highest values are colored in green, gradually transitioning to red for the lowest values, as demonstrated in Table 5.1.

According to Ludvikahem's evaluation of HEX performance (see section 4.3.2), an average cooling value of 50 °C and above is considered acceptable. Therefore, substations with values below 50 °C are deemed to be poorly performing substations marked within red rectangle in Table 5.1.

Twenty poorly performing substations, with an average cooling value below 50 °C, were identified. The performance of each of these substations has been thoroughly analyzed to uncover potential reasons for their inadequate performance. Detailed results of this analysis can be found in Section 5.1.2.

*Table 5.1: Summarized KPIs for the substations*

| Substations Info | | | | KPI | | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Adress | Category | Main use | Supply Temperature | | | Return Temperature | | | Cooling | Average Cooling | |
| | | | | Max | Min | Average | Max | Min | Average | | | |
| 2092 | TIMMERMANSVÄGEN 16 | Garage | Garage | 117.49 | 16.80 | 88.89 | 48.16 | 12.37 | 25.61 | 61.56 | 63.28 | |
| 2498 | HJORTRONGÅRDEN LUDVIKA | Bostadshus | Flerbostadshus | 110.44 | 83.56 | 95.70 | 43.81 | 25.14 | 35.43 | 61.80 | 60.27 | perid21-27Jan |
| 2321 | TRE KROKARS GATA 10, | Bostadshus | Flerbostadshus | 112.53 | 83.84 | 95.11 | 43.76 | 27.32 | 35.44 | 61.19 | 59.67 | |
| 2163 | KÖPMANSGATAN 13, LUDVIKA | Lokal | Kontor | 108.58 | 53.33 | 91.44 | 45.57 | 13.18 | 31.94 | 61.21 | 59.50 | |
| 2179 | KÖPMANSGATAN 20, LUDVIKA | Bostadshus | Flerbostadshus | 111.99 | 81.47 | 94.74 | 43.91 | 21.09 | 35.32 | 61.12 | 59.42 | |
| 2191 | KÖPMANSGATAN 4, LUDVIKA | Lokal | Teater | 111.17 | 82.72 | 94.23 | 40.24 | 26.30 | 34.95 | 60.59 | 59.29 | |
| 2011 | LJUNGHÄLLSVÄGEN 27, | Bostadshus | Flerbostadshus | 112.30 | 80.13 | 95.56 | 48.35 | 23.27 | 36.40 | 60.25 | 59.16 | |
| 2332 | BERGSGATAN 14, LUDVIKA | Bostadshus | Flerbostadshus | 112.22 | 74.22 | 94.65 | 48.79 | 27.20 | 35.72 | 60.09 | 58.93 | |
| 2036 | BISKOPSGÅRDEN, LUDVIKA | Bostadshus | Särskillt boende | 119.04 | 83.28 | 96.56 | 47.45 | 26.67 | 37.80 | 59.38 | 58.76 | perid21-27Jan |
| 2039 | HILLÄNGENS IDROTTSPLATS, | Lokal | Omklädningsrum | 105.09 | 47.30 | 81.78 | 67.73 | 18.15 | 23.55 | 64.42 | 58.23 | |
| 2461 | FREDSGATAN 28. KV. FREJA, | Bostadshus | Flerbostadshus | 111.72 | 84.00 | 95.18 | 42.76 | 29.00 | 37.05 | 60.45 | 58.13 | |
| 2106 | STADSHUSET, LUDVIKA | Lokal | Kontor | 109.50 | 81.92 | 93.64 | 47.57 | 9.64 | 35.57 | 61.27 | 58.07 | |
| 2351 | STIGBERGSGATAN 2, LUDVIKA | Bostadshus | Flerbostadshus | 111.25 | 82.89 | 94.10 | 44.07 | 22.35 | 36.16 | 59.32 | 57.94 | |
| 2018 | GRÅGÅSVÄGEN 6, LUDVIKA | Bostadshus | Flerbostadshus | 113.50 | 67.97 | 94.12 | 49.31 | 21.64 | 36.20 | 58.74 | 57.92 | |
| 2101 | STORGATAN 30, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 112.43 | 83.59 | 95.47 | 46.95 | 25.87 | 37.72 | 59.27 | 57.75 | |

*5.2: Continuation of Table 5.1*

| Substations Info | | | | KPI | | | | | | | | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Adress | Category | Main use | Supply Temperature | | | Return Temperature | | | Cooling | Average Cooling | |
| | | | | Max | Min | Average | Max | Min | Average | | | |
| 2402 | LORENSBERGA SKOLA, | Lokal | Skola | 111.62 | 62.81 | 93.59 | 50.41 | 28.57 | 36.92 | 57.92 | 56.66 | |
| 2001 | KÖPMANSGATAN 15, LUDVIKA | Bostadshus | Flerbostadshus | 111.85 | 66.21 | 95.11 | 44.95 | 27.47 | 38.59 | 57.83 | 56.52 | |
| 2454 | SOLSIDAN | Lokal | Förskola | 106.84 | 80.34 | 92.86 | 43.18 | 28.64 | 36.58 | 58.61 | 56.28 | perid21-27Jan |
| 2313 | BJÖRNBÄRSGÅRDEN 2, | Bostadshus | Flerbostadshus | 110.16 | 81.65 | 92.90 | 49.34 | 26.76 | 36.72 | 57.80 | 56.17 | |
| 2007 | KOLBOTTENVÄGEN 3, | Bostadshus | Flerbostadshus | 125.92 | 65.26 | 95.78 | 52.24 | 17.24 | 39.75 | 56.13 | 56.03 | |
| 2178 | ENGELBREKTSGATAN 22, | Bostadshus | Flerbostadshus | 111.42 | 82.50 | 94.17 | 48.27 | 21.27 | 38.16 | 57.51 | 56.01 | |
| 2470 | FREDSGATAN 30, KV. FREJA, | Bostadshus | Flerbostadshus | 112.59 | 67.95 | 95.02 | 58.43 | 28.68 | 39.51 | 57.37 | 55.51 | |
| 2331 | VINDELGATAN 14, LUDVIKA | Bostadshus | Flerbostadshus | 112.50 | 81.21 | 93.61 | 45.46 | 27.47 | 38.42 | 56.31 | 55.19 | |
| 2352 | TRE KROKARS GATA 12, | Bostadshus | Flerbostadshus | 113.05 | 83.92 | 96.37 | 48.34 | 15.77 | 41.30 | 56.65 | 55.06 | |
| 2304 | HÖGBERGSSKOLAN C, | Lokal | Skola | 111.95 | 57.30 | 94.40 | 55.12 | 28.33 | 39.42 | 56.60 | 54.98 | |
| 2508 | SLÅNBÄRSGÅRDEN 10, | Bostadshus | Flerbostadshus | 109.42 | 65.14 | 92.87 | 43.62 | 25.03 | 38.11 | 57.22 | 54.76 | |
| 2330 | VINDELGATAN 21, LUDVIKA | Bostadshus | Flerbostadshus | 112.94 | 83.59 | 94.04 | 44.09 | 30.13 | 39.33 | 58.18 | 54.71 | |
| 2227 | LUDVIKA GÅRDS FÖRSKOLA, | Lokal | Förskola | 107.81 | 79.12 | 91.17 | 40.72 | 23.35 | 36.48 | 56.24 | 54.69 | |
| 2010 | KVARNGATAN 5, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 116.93 | 64.63 | 94.30 | 47.04 | 25.52 | 39.65 | 54.96 | 54.65 | |
| 2353 | LINGONGÅRDEN 4, LUDVIKA | Bostadshus | Särskillt boende | 112.42 | 59.14 | 94.27 | 51.50 | 33.67 | 39.64 | 55.63 | 54.63 | |
| 2303 | HÖGBERGSSKOLAN A, | Lokal | Skola | 112.72 | 73.12 | 95.39 | 53.34 | 34.12 | 40.83 | 55.12 | 54.56 | |
| 2105 | KYRKSKOLAN, LUDVIKA | Lokal | Skola | 110.49 | 81.20 | 95.14 | 48.77 | 32.30 | 40.71 | 55.57 | 54.42 | |
| 2487 | GROTTVÄGEN 4, LUDVIKA | Bostadshus | Flerbostadshus | 108.78 | 58.62 | 90.61 | 44.17 | 18.08 | 36.28 | 55.88 | 54.33 | |
| 2002 | TIMMERMANSVÄGEN 12, | Bostadshus | Flerbostadshus | 123.22 | 64.24 | 94.09 | 52.19 | 25.50 | 39.93 | 54.22 | 54.16 | |
| 2505 | KRUSBÄRSGÅRDEN 2, | Bostadshus | Flerbostadshus | 110.84 | 69.93 | 93.67 | 46.78 | 26.40 | 39.83 | 56.25 | 53.84 | |
| 2506 | KRUSBÄRSGÅRDEN 3, | Bostadshus | Flerbostadshus | 110.84 | 69.93 | 93.67 | 46.78 | 26.40 | 39.83 | 56.25 | 53.84 | |
| 2431 | LÄRKVÄGEN 25, LUDVIKA | Lokal | Förskola | 104.62 | 78.85 | 90.09 | 44.36 | 17.75 | 36.37 | 55.27 | 53.72 | |
| 2507 | SLÅNBÄRSGÅRDEN 4, | Bostadshus | Flerbostadshus | 109.29 | 80.41 | 92.32 | 46.16 | 29.34 | 38.65 | 55.97 | 53.67 | |
| 2152 | VALLA, LUDVIKA XX22020 | Lokal | Kontor | 107.44 | 73.04 | 90.09 | 48.85 | 26.27 | 36.70 | 54.67 | 53.39 | |
| 2132 | KÖPMANSGATAN 26, LUDVIKA | Bostadshus | Flerbostadshus | 110.60 | 78.61 | 93.59 | 50.60 | 29.07 | 40.20 | 54.34 | 53.38 | |
| 2322 | PARKEN, LUDVIKA OBJ 330 | Bostadshus | Flerbostadshus | 107.81 | 80.75 | 91.42 | 49.15 | 27.74 | 38.07 | 54.23 | 53.36 | |
| 2348 | MAGNETBACKEN 5, LUDVIKA | Bostadshus | Flerbostadshus | 109.77 | 81.96 | 93.22 | 44.90 | 28.96 | 40.05 | 54.63 | 53.17 | |
| 2347 | TRE KROKARS GATA 8, | Bostadshus | Flerbostadshus | 110.88 | 82.21 | 93.98 | 54.52 | 27.13 | 41.04 | 55.09 | 52.94 | |
| 2346 | TRE KROKARS GATA 7, | Bostadshus | Flerbostadshus | 111.78 | 83.25 | 95.16 | 49.51 | 24.66 | 42.26 | 54.14 | 52.89 | |
| 2422 | BJÖRKVÄGEN 10, LUDVIKA | Bostadshus | Flerbostadshus | 109.87 | 53.33 | 92.98 | 49.47 | 31.07 | 40.10 | 53.78 | 52.88 | |
| 2025 | VASASKOLAN, LUDVIKA | Lokal | Skola | 111.47 | 55.18 | 94.70 | 50.84 | 33.08 | 42.07 | 53.59 | 52.62 | |
| 2413 | ÖSTANSBO SKOLA, LUDVIKA | Lokal | Skola | 109.64 | 60.18 | 91.92 | 57.36 | 29.11 | 39.59 | 53.82 | 52.33 | |
| 2003 | GRÅGÅSVÄGEN 19, LUDVIKA | Bostadshus | Flerbostadshus | 122.01 | 62.22 | 93.93 | 55.46 | 30.40 | 41.70 | 52.72 | 52.23 | |
| 2504 | KRUSBÄRSGÅRDEN 1 LUDVIKA | Bostadshus | Flerbostadshus | 109.82 | 68.31 | 93.64 | 50.11 | 28.94 | 41.66 | 56.76 | 51.98 | |
| 2120 | PRÄSTGÅRDSGATAN 13 , | Bostadshus | Flerbostadshus | 110.01 | 83.44 | 93.78 | 50.45 | 19.51 | 41.99 | 52.38 | 51.79 | |
| 2009 | FURUBORGSVÄGEN 9, | Bostadshus | Flerbostadshus | 123.03 | 66.35 | 94.91 | 55.74 | 34.23 | 43.19 | 52.01 | 51.72 | |
| 2000 | SOLVIKSSKOLAN | Lokal | Skola | 116.51 | 61.79 | 89.58 | 46.54 | 23.03 | 37.99 | 54.25 | 51.60 | |
| 2184 | KASTTJÄRNSGATAN 5, | Lokal | | 108.76 | 76.38 | 90.29 | 46.97 | 32.60 | 38.73 | 52.54 | 51.56 | |
| 2015 | INDUSTRIVÄGEN 6, LUDVIKA | Bostadshus | Flerbostadshus | 115.29 | 77.64 | 94.89 | 56.29 | 31.74 | 43.40 | 52.09 | 51.49 | |
| 2423 | SOLVÄGEN 1, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 106.11 | 79.07 | 91.02 | 43.26 | 34.71 | 39.55 | 52.24 | 51.46 | perid21-27Jan |
| 2125 | FOLKETS HUS, LUDVIKA | Lokal | Kontor | 109.72 | 72.44 | 94.01 | 56.87 | 34.60 | 42.66 | 52.18 | 51.35 | |
| 2113 | BRANDSTATION, LUDVIKA | Lokal | Brandstation | 109.93 | 82.93 | 93.63 | 51.71 | 18.38 | 42.28 | 52.51 | 51.35 | |
| 2151 | BJÖRKHAGA, LUDVIKA | Lokal | Kontor | 107.76 | 74.67 | 92.24 | 51.78 | 22.32 | 41.24 | 51.49 | 51.00 | |
| 2119 | STORGATAN 31, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 112.03 | 84.79 | 96.99 | 55.19 | 35.77 | 46.36 | 51.28 | 50.63 | perid21-27Jan |
| 2006 | KOLBOTTENVÄGEN 2, | Bostadshus | Flerbostadshus | 121.92 | 65.02 | 95.03 | 54.02 | 33.10 | 44.53 | 50.85 | 50.50 | |
| 2150 | ERIKSGATAN 17, LUDVIKA | Lokal | Kontor | 107.97 | 15.08 | 91.56 | 52.08 | 15.37 | 41.13 | 51.76 | 50.44 | |
| 2026 | MARNÄSLIDEN, LUDVIKA | Lokal | Kontor | 126.83 | 59.05 | 95.04 | 59.64 | 35.06 | 45.13 | 50.26 | 49.91 | |
| 2323 | HÖGBERGSGATAN 66, | Bostadshus | Flerbostadshus | 110.30 | 63.22 | 93.45 | 81.00 | 33.10 | 44.51 | 49.14 | 48.94 | |
| 2100 | TIMMERMANSVÄGEN 37, | Bostadshus | Särskillt boende | 106.87 | 63.69 | 85.08 | 40.29 | 16.38 | 36.32 | 50.43 | 48.75 | |
| 2315 | MAGNETEN FÖRSKOLA, | Lokal | Förskola | 104.75 | 77.00 | 88.99 | 51.86 | 25.46 | 40.80 | 51.73 | 48.19 | |
| 2462 | LORENSBERGA | Idrott | Sporthall | 110.85 | 58.03 | 89.21 | 54.78 | 19.62 | 41.49 | 53.68 | 47.71 | |
| 2412 | LORENSBERGA SKOLA, | Idrott | Sporthall | 106.76 | 76.67 | 89.54 | 50.77 | 14.89 | 41.94 | 49.06 | 47.60 | |
| 2195 | STATIONSHUSET ANNEX, | Lokal | Kontor | 101.59 | 71.91 | 82.89 | 42.27 | 30.57 | 36.01 | 47.94 | 46.88 | |
| 2131 | VASALUNDEN 3, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 110.99 | 55.14 | 94.03 | 63.54 | 39.18 | 47.57 | 46.81 | 46.47 | |
| 2154 | RESECENTER, LUDVIKA | Lokal | Kontor | 101.72 | 72.25 | 83.14 | 44.62 | 32.74 | 38.50 | 45.68 | 44.65 | |
| 2432 | GAMLA POSTEN, LUDVIKA | Lokal | Förskola | 101.71 | 70.63 | 85.60 | 46.21 | 30.10 | 41.07 | 45.77 | 44.53 | |
| 2457 | FÖRSKOLAN NOTGÅRDEN, | Lokal | Förskola | 101.59 | 74.70 | 87.56 | 56.59 | 33.96 | 43.64 | 45.15 | 43.92 | perid21-27Jan |
| 2035 | VÅRDSKOLAN, LUDVIKA | Lokal | Daglig verksamhet | 113.42 | 64.27 | 86.61 | 51.93 | 21.72 | 42.74 | 46.09 | 43.86 | |
| 2027 | SPORTHALLEN, LUDVIKA | Idrott | Simhall | 111.35 | 58.75 | 95.83 | 80.64 | 32.38 | 52.60 | 40.07 | 43.23 | |
| 2079 | HILLÄNGENS GAMLA | Lokal | Omklädningsrum | 102.26 | 73.06 | 84.56 | 52.13 | 32.22 | 42.58 | 42.73 | 41.98 | |
| 2130 | NORRA JÄRNVÄGSGATAN 4, | Bostadshus | Flerbostadshus | 111.54 | 78.55 | 94.79 | 69.13 | 41.45 | 53.62 | 41.01 | 41.17 | |
| 2082 | BISKOPSNÄSETS FÖRSKOLA, | Lokal | Förskola | 102.78 | 64.31 | 81.45 | 53.02 | 26.84 | 40.57 | 43.02 | 40.88 | |
| 2492 | GRÅGÅSVÄGEN 12, LUDVIKA, | Bostadshus | Särskillt boende | 91.00 | 68.24 | 77.07 | 53.62 | 17.65 | 39.20 | 41.26 | 37.87 | |
| 2190 | STORGATAN 37, LUDVIKA | Lokal | Affärsverksamhet | 106.67 | 77.94 | 89.04 | 66.42 | 43.60 | 51.68 | 37.89 | 37.36 | |
| 2301 | MARNÄSGATAN 36, LUDVIKA | Bostadshus | Flerbostadshus | 87.46 | 62.11 | 72.14 | 51.59 | 26.41 | 37.83 | 36.89 | 34.31 | |
| 2103 | STORGATAN 28, LUDVIKA OBJ | Bostadshus | Flerbostadshus | 111.48 | 54.46 | 94.87 | 106.65 | 30.10 | 76.62 | 27.43 | 18.25 | |
| 2300 | SOLVIKSSKOLAN | Lokal | Skola/OBS Returvärme | 49.91 | 31.72 | 39.61 | 45.02 | 24.53 | 34.25 | 7.43 | 5.36 | |
| 2226 | HILLÄNGENS | Idrott | Konstgräsplan | 90.47 | 46.04 | 48.81 | 55.32 | 12.25 | 45.53 | 65.28 | 3.28 | |
| 2176 | MARNÄSGATAN 40 | Lokal | Särskillt boende | | | | | | | | | Excluded |
| 2403 | GONÄSVÄGEN TEKN K, | Lokal | Kontor | | | | | | | | | Excluded |
| 2115 | KÖPMANSGATAN 3 A, | Bostadshus | Flerbostadshus | | | | | | | | | Excluded |
| 2116 | CARLAVÄGEN 2, LUDVIKA OBJ | Bostadshus | Flerbostadshus | | | | | | | | | Excluded |
| 2193 | VASAGATAN 4, LUDVIKA | Bostadshus | Flerbostadshus | | | | | | | | | Excluded |
| 2329 | VIDABLICKSVÄGEN 11, | Bostadshus | Flerbostadshus | | | | | | | | | Excluded |
| 2493 | KÖPMANSGATAN 9, LUDVIKA | Bostadshus | Flerbostadshus | | | | | | | | | Excluded |

### 5.1.2 The results of the analysis of the poorly performing substations

The following Figures (5.1 - 5.11) present the analysis of each poorly performing substation. Each figure displays a chart depicting various variables such as heat rate in MW, flow in $m^3/h$, outdoor temperature in °C, and return temperature in °C. The data is captured for the period from January 21st to January 27th, following the observations registered according to the analysis protocol (see section 4.3.3).

By analyzing these charts, specific characteristics of the problems associated with each substation can be identified. These problems can be classified into two groups:

Component Errors: Among the 20 substations analyzed, 8 of them exhibited technical issues related to the substation components. This could include mismatches between heat energy supply and demand, as well as issues with the control system, such as the RT being stuck at certain levels. In some cases, the flow did not interact properly with other variables.

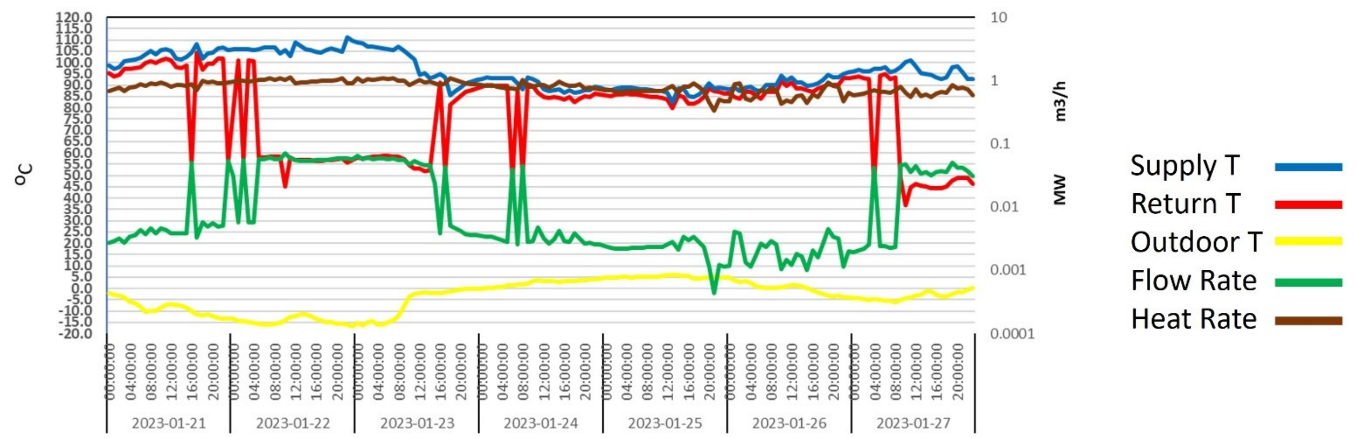
Management Errors: 8 out of 20 substations showed problems associated with management strategies that were not aligned with the specific activity profiles of the locations. Most of these substations were located in sports premises or preschools where demand varied significantly, leading to system instability. Flow oscillations also caused disruptions in the DH system. The remaining 4 substations, which exhibited low cooling performance, did not indicate any specific error indicators.

**Components Error Analyzed**

| Substation | ST | RT | Cooling |
|---|---|---|---|
| 2103 STORGATAN 28, LUDVIKA OBJ 295 Residential building Apartments | 83.14 | 76.62 | 18.25 |

**Observations**

- The heat rate curve is uneven and pointy a lot, but the flow curve is more smoothly.
- Morning and night times showed low heat exchange (high return temperature) but it has to be indoor temperature achieved in any case
- Integrated energy more than instantaneous heat rate about 8%, 10.6 MW.
- Integrated volume more than instantaneous flow about 1.5 %
- Calculated optimal flow less than average flow about 40%
- Other substations in the area also showed low cooling indicators

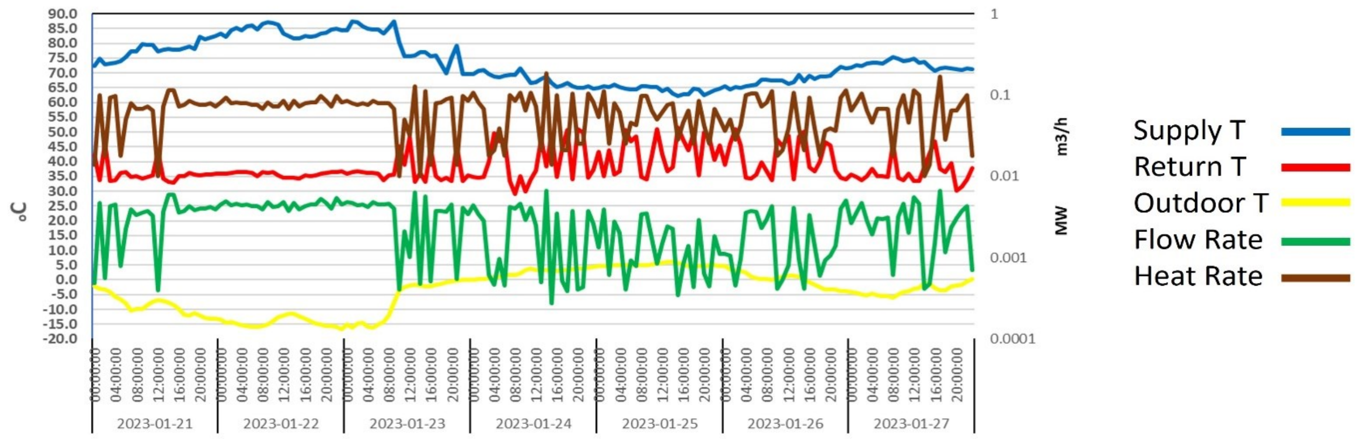



Characteristic of the problem: High thermal losses at the substation due to instantaneous peaks occurring within a span of less than an hour. Additionally, there is a lack of interaction between the flow and other variables, as the flow curve remains stable throughout the process.

*Figure 5.1: Storgatan 28 Performance Chart*

<table>
<tr><th colspan="4">Substation</th><th>ST</th><th>RT</th><th>Cooling</th></tr>
<tr><td>2301</td><td>MARNÄSGATAN 36, LUDVIKA</td><td>Residential building</td><td>Apartments</td><td>72.14</td><td>37.83</td><td>34.31</td></tr>
<tr><td>Observations</td><td colspan="6">

- The heat rate and flow curves are uneven and pointy a lot.
- At low outdoor temperature (less than -5) the curves become smoothly than higher temperatures
- Integrated energy close to the instantaneous heat rate about 0.02% over
- Integrated volume very close to the instantaneous flow
- Calculated optimal flow less than average flow about 30%
- Another substation in the area excluded because of data missing

</td></tr>
<tr><td colspan="7">
</td></tr>
<tr><td colspan="7">Characteristic of problem: ST does not decrease at the appropriate time, resulting in an unstable heat exchange process. In other words, there is a mismatch between the substation temperature and the heat demand, causing instability in the heat exchange operations.</td></tr>
<tr><td>2190</td><td>STORGATAN 37, LUDVIKA</td><td>Place</td><td>Business Activity</td><td>89.04</td><td>51.68</td><td>37.36</td></tr>
<tr><td>Observations</td><td colspan="6">

- The heat rate and flow curves are relatively smooth but oscillation all the time.
- At positive outdoor temperatures deltaT decrease less than 30 °C, (control valve opens more than should)
- Integrated energy very close to the instantaneous heat rate about 0.02% over
- Integrated volume very close to the instantaneous flow
- Calculated optimal flow less than average flow about 25%
- Other substations in the area also showed low cooling indicators

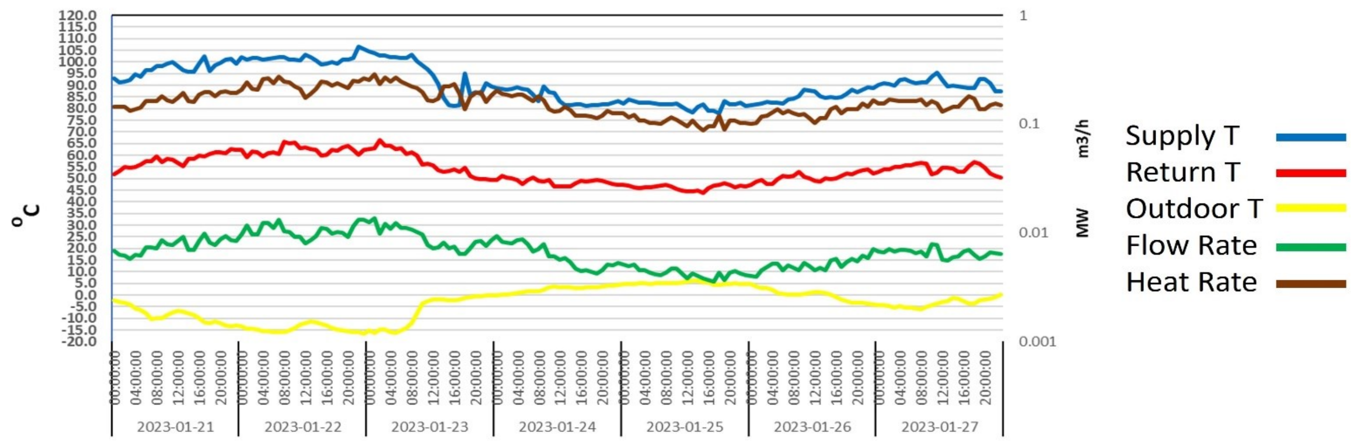
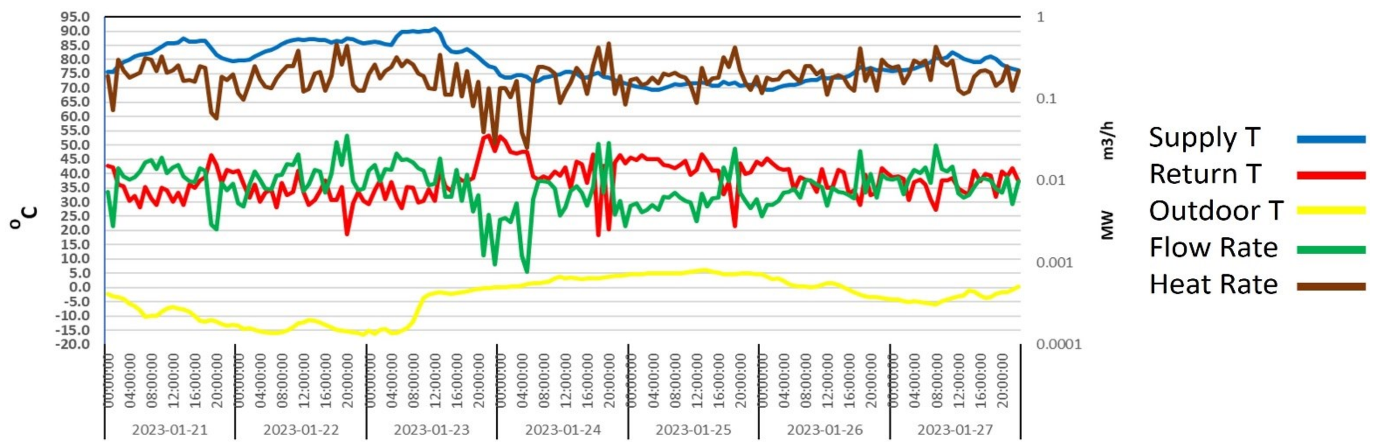
</td></tr>
<tr><td colspan="7">
</td></tr>
<tr><td colspan="7">Characteristic of problem: In general, the heat exchange capacity was not fully utilized. Even at positive outdoor temperatures, the ST remained high while the heat demand was low.</td></tr>
</table>

*Figure 5.2: Performance Chart, Up) Marnäsgatan 36 a residential building. Down) Storgatan 37 a business location*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2492 | GRÅGÅSVÄGEN 12, LUDVIKA, | Residential building | Special Residential | 77.07 | 39.20 | 37.87 |

**Observations**

- The heat rate and flow curves are pointy a lot and oscillation all the time.
- Return Temperature variation about 10 °C in period of one hour
- Integrated energy very close to the instantaneous heat rate
- Integrated volume very close to the instantaneous flow
- Calculated optimal flow less than average flow about 19%
- Other substations in the area showed good cooling indicators

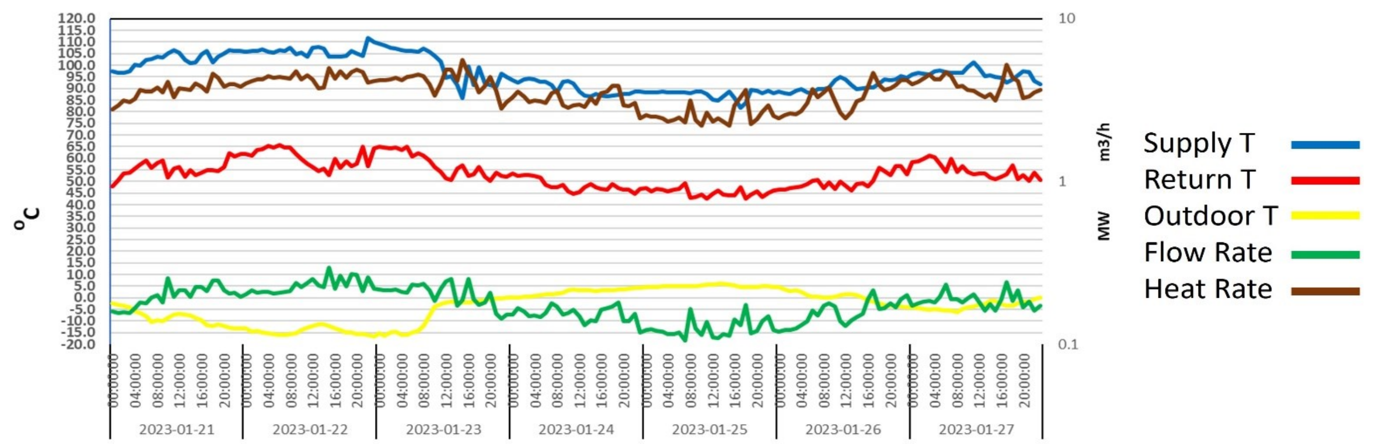



Characteristic of problem: The network is not stable at all, and the ST control is not smooth enough and leads to a high oscillation rate.

| | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2130 | NORRA JÄRNVÄGSGATAN 4 | Residential building | Apartments | 94.79 | 53.62 | 41.17 |

**Observations**

- The heat rate and flow curves are relatively pointy in a low level (oscillation value 0.08MW).
- The return Temperature unstable oscillate a lot.
- Integrated energy close to the instantaneous heat rate.
- Integrated volume close to the instantaneous flow
- Calculated optimal flow less than average flow about 10%
- Another substation in the area showed cooling indicators at the limits.



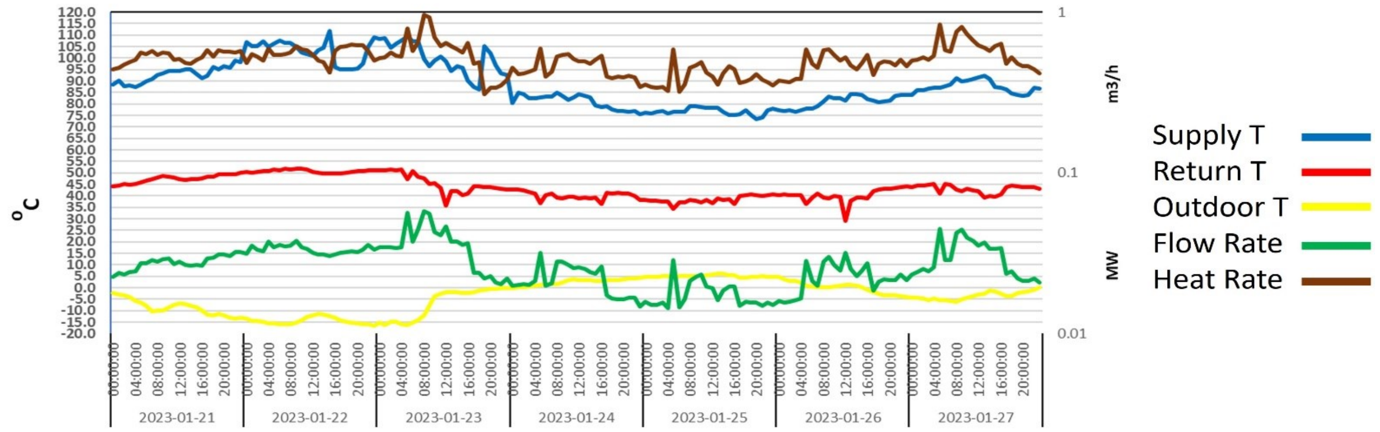

Characteristic of problem: The RT of the system is unstable and does not respond appropriately to changes in flow and heat rate. This indicates a lack of effective control and regulation.

*Figure 5.3: Performance Chart, Up) Grågåsvägen 12 a residential building. Down) Norra Järnvägsgatan 4 a residential building*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2035 | VÅRDSKOLAN, LUDVIKA | Place | Daily activities | 86.61 | 42.74 | 43.86 |

**Observations**

- The heat rate and flow curves are relatively smooth, pointy between 04 and 06 o'clock daily
- Integrated energy higher than the instantaneous heat rate about 1 MW
- Integrated volume close to the instantaneous flow
- Calculated optimal flow less than average flow about 9%
- Another substation in the area showed good cooling indicators.

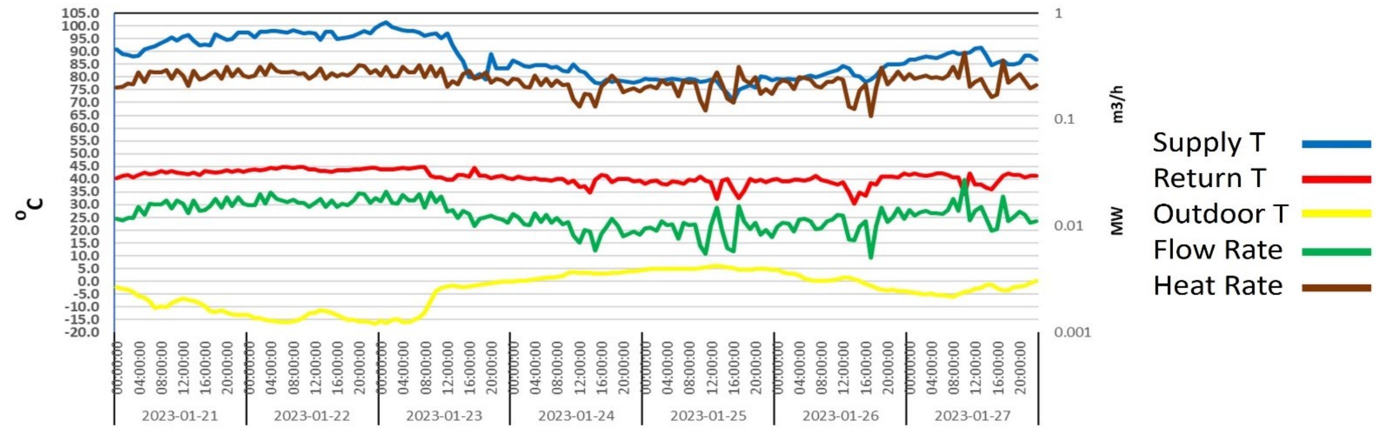



Characteristic of problem: The RT gets stuck at certain levels, indicating a lack of smooth and continuous control. These issues contribute to the high thermal losses observed in the system.

| | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2432 | GAMLA POSTEN, LUDVIKA GÅRD | Place | Preschool | 85.60 | 41.07 | 44.53 |

**Observations**

- The heat rate and flow curves are relatively pointy in a low level (oscillation value 0.08MW).
- The return Temperature unstable oscillate a lot
- Integrated energy close to the instantaneous heat rate
- Integrated volume close to the instantaneous flow
- Calculated optimal flow less than average flow about 10%
- Another substation in the area showed cooling indicators at the limits.



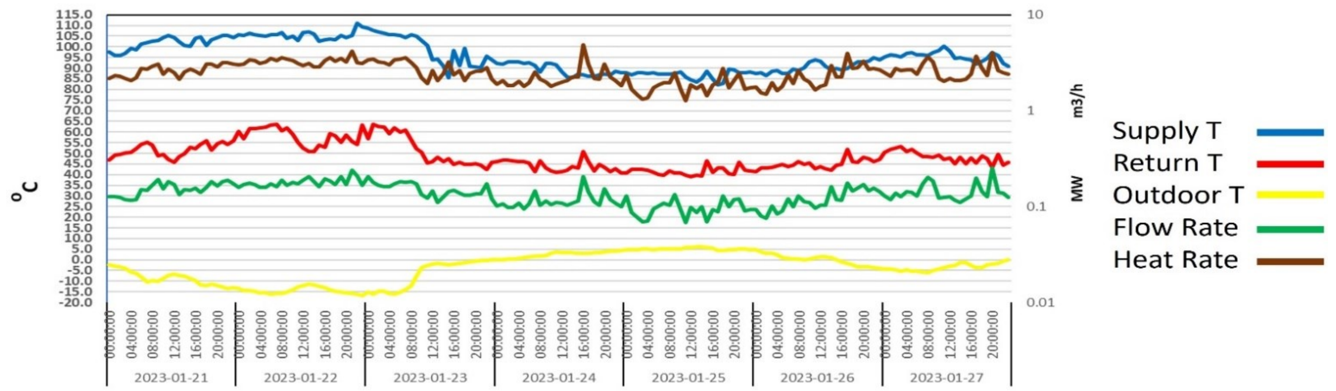

Characteristic of problem: The system unstable. The hot water demand affecting the network.

*Figure 5.4: Performance Chart, Up) Vårdskolan Education location. Down) Ludvika Gård a Preschool*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2131 | VASALUNDEN 3 | Residential building | Apartments | 94.03 | 47.57 | 46.47 |

**Observations**

- The heat rate and flow curves are pointy a lot and oscillation all the time.
- The RT at low outdoor temperature high (increase) at the same time heat rate doesn't increase a lot.
- Integrated energy close to the instantaneous heat rate, less about 0.2%.
- Integrated volume close to the instantaneous flow, higher about 0.5 %.
- Calculated optimal flow less than average flow about 8%.
- Other substations in the area showed cooling indicators at the limit.




Characteristic of problem: When the ST increases in response to the outdoor temperature, the RT remains elevated. This mismatch between the supply and demand indicates that the heat energy supplied by the system does not align properly with the heat demand.

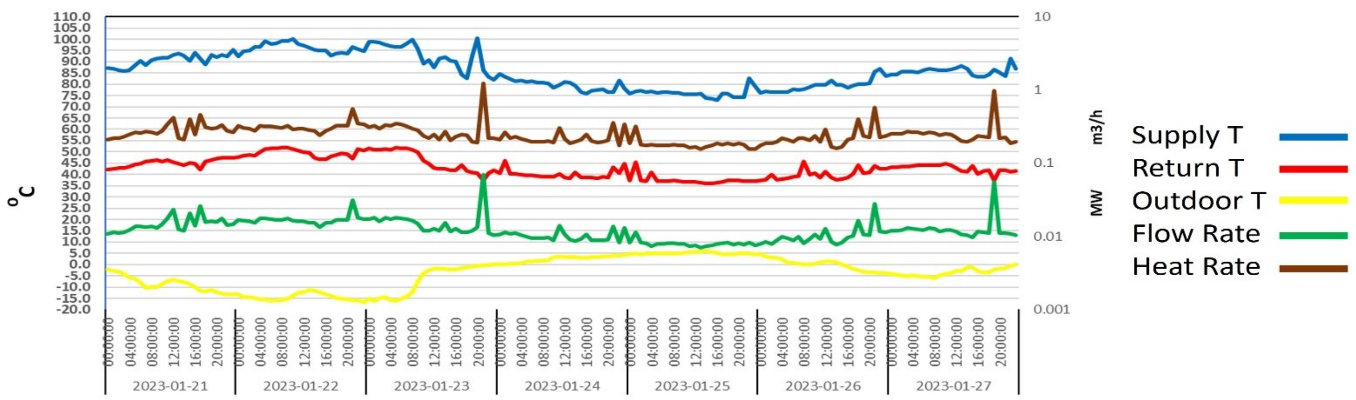
*Figure 5.5: Performance Chart, Vasalunden 3 a residential building*

**Management Error Analyzed**

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2079 | HILLÄNGENS GAMLA | Place | Dressing Rooms | 84.56 | 42.58 | 41.98 |

**Observations**

- The heat rate and flow curves are relatively smooth but pointy when using based on the local activities.
- The return Temperature high because of low heat rate required.
- Integrated energy close to the instantaneous heat rate.
- Integrated volume close to the instantaneous flow.
- Calculated optimal flow less than average flow about 14%.
- Another substation in the area is showed low cooling indicators.



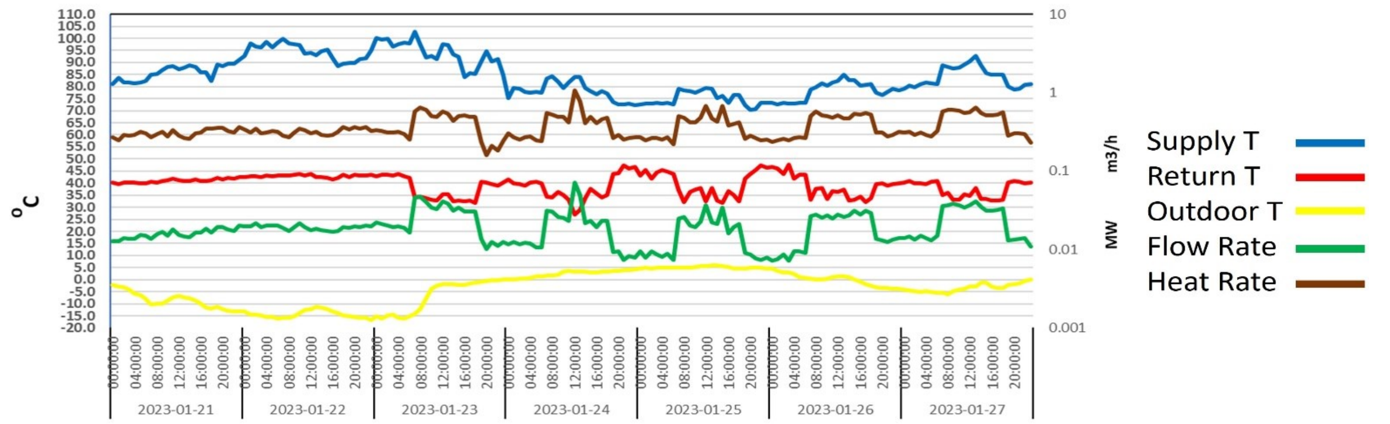

Characteristic of problem: In this location, the dominant heat energy demand is for tap hot water due to the nature of the activities taking place. The heat rate demand for space heating is relatively low, with significant variations observed between different days.

*Figure 5.6: Performance Chart of Hillängens Gamla a Sport Dressing Room*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2082 | BISKOPSNÄSETS FÖRSKOLA | Place | Preschool | 81.45 | 40.57 | 40.88 |

**Observations**

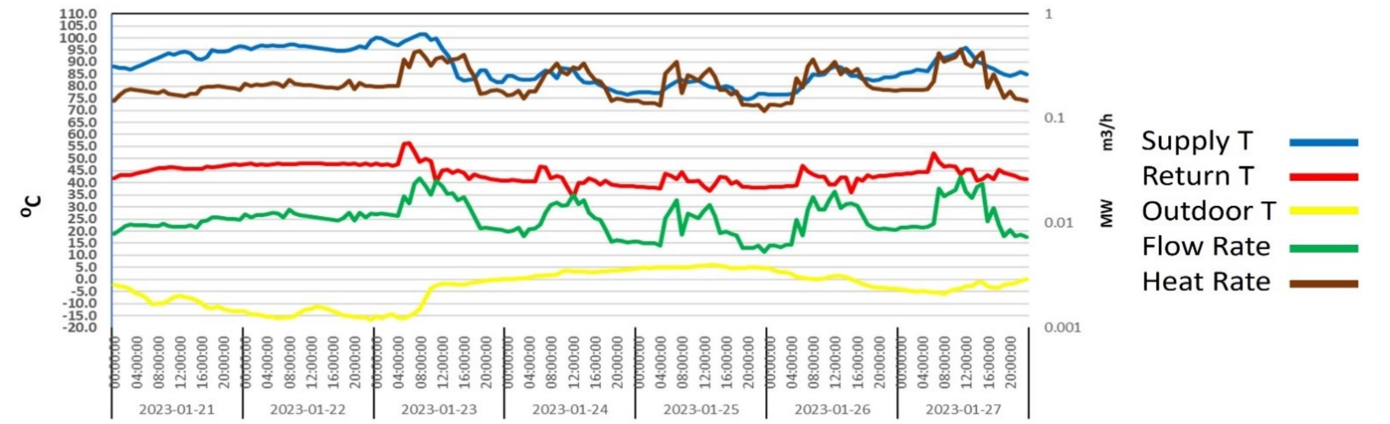
- The heat rate and flow curves are relatively smooth.
- During evenings and night low heat rate required based on the local activities type (Preschool).
- Integrated energy close to the instantaneous heat rate.
- Integrated volume close to the instantaneous flow.
- Calculated optimal flow less than average flow about 17%.
- Other substations in the area showed cooling indicators at the limits (Special Residence).




| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2457 | FÖRSKOLAN NOTGÅRDEN | Place | Preschool | 87.56 | 43.64 | 43.92 |

**Observations**

- The heat rate and flow curves are relatively smooth.
- During evenings and nights low heat rate required based on the local activities type (Preschool).
- Integrated energy close to the instantaneous heat rate.
- Integrated volume close to the instantaneous flow about.
- Calculated optimal flow less than average flow about 11%.
- Another substation in the area showed good cooling indicators.



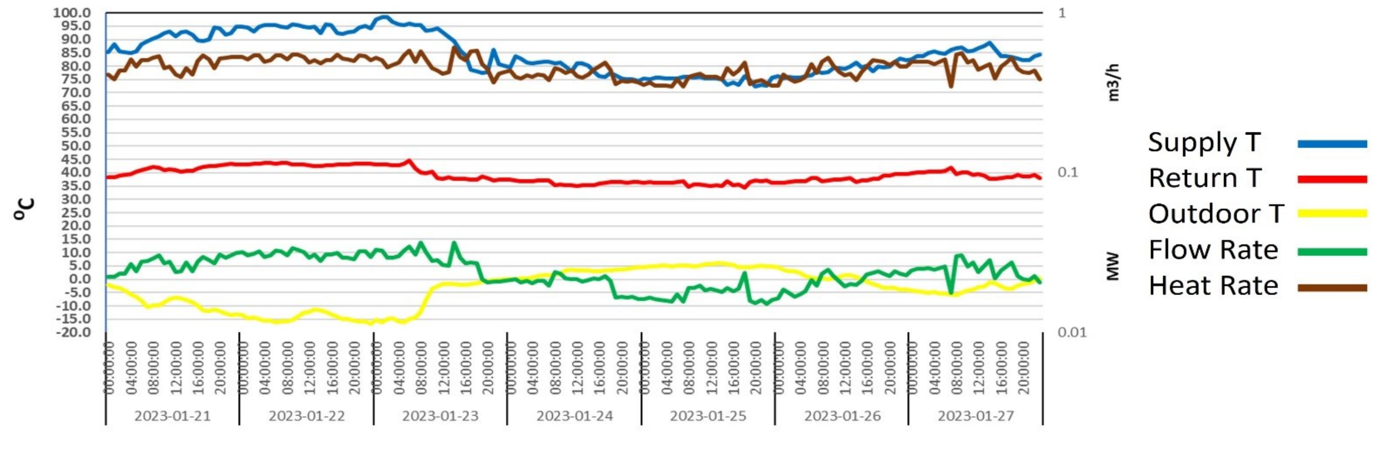

Characteristic of problem: There is a significant variation in demand between day and night at the two Preschools. This variation in demand can impact the overall efficiency and stability of the district heating system in these specific locations.

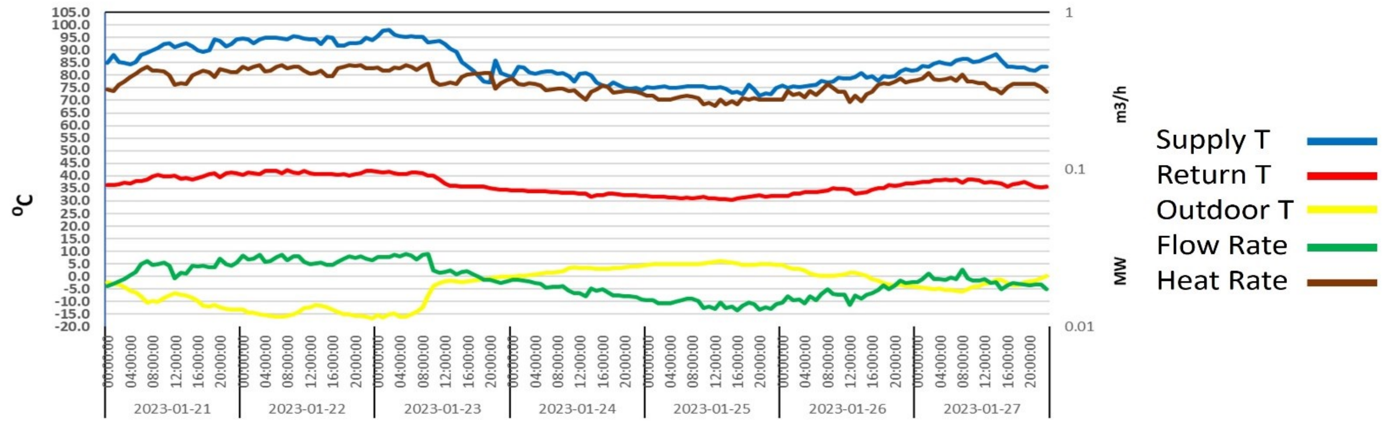
*Figure 5.7: Performance Chart, Up) Biskopsnäsets Preschool. Down) Notgården a Preschool*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2154 | RESECENTER, LUDVIKA | Place | Daily Activity | 83.14 | 38.50 | 44.65 |
| 2195 | STATIONSHUSET ANNEX | Place | Office | 82.89 | 36.01 | 46.88 |

**Observations**

- The heat rate, flow and return temperature curves are smooth and stable.
- Integrated energy very close to the instantaneous heat rate
- Integrated volume very close to the instantaneous flow
- Calculated optimal flow less than average flow about 6%
- Another substation in the area showed good cooling indicators.



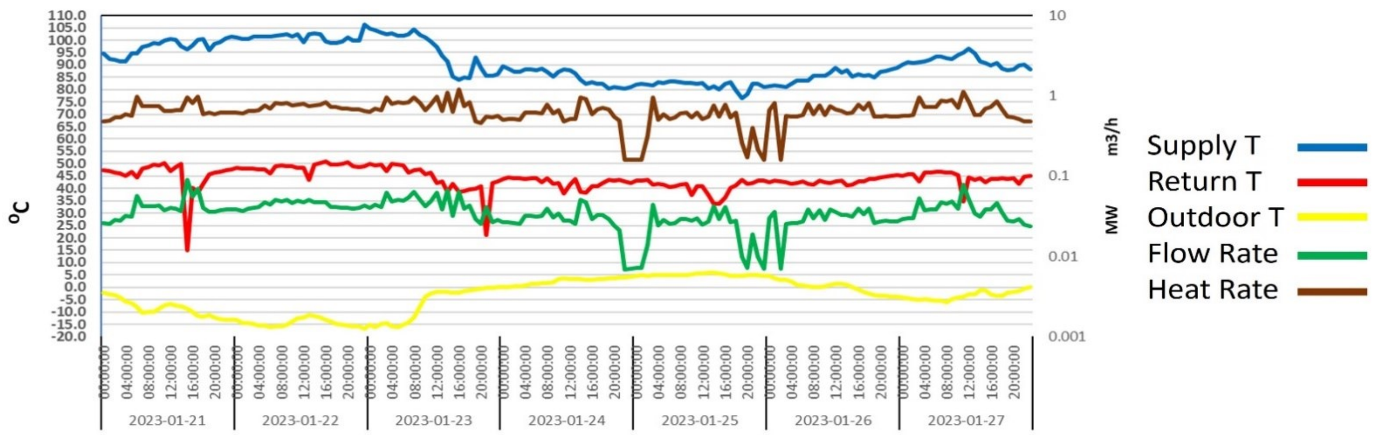

Characteristic of problem: No problem identified, the cooling process around the limited. So, improving the performance recommended.

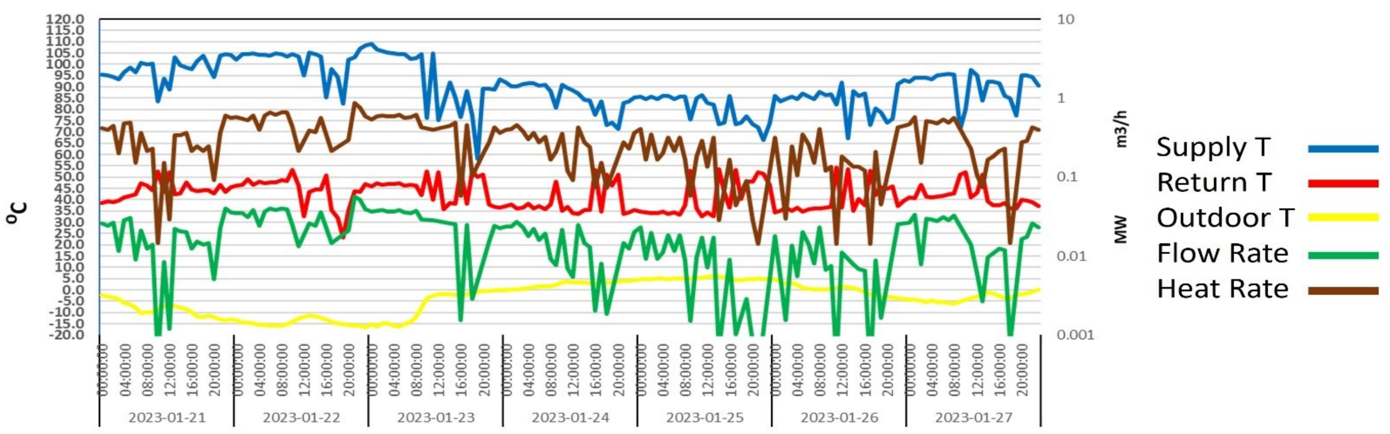
*Figure 5.8: Performance Chart, Up) Resecenter a dalily activity location. Down) Stationshuset Office*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2412 | LORENSBERGA SKOLA, GYMNASTIKHALL | Sport | Sports hall | 89.54 | 41.94 | 47.60 |
| 2462 | LORENSBERGA RACKETHALLEN | Sport | Sports hall | 89.21 | 41.49 | 47.71 |

**Observations**

- The heat rate and flow curves are pointy a lot and oscillation all the time.
- In the afternoon the curves drop a lot.
- Integrated energy less than the instantaneous heat rate about 1.5%.
- Integrated volume higher of the instantaneous flow about 0.5 %.
- Calculated optimal flow less than average flow about 6%.
- Another substation in the area showed good cooling indicators



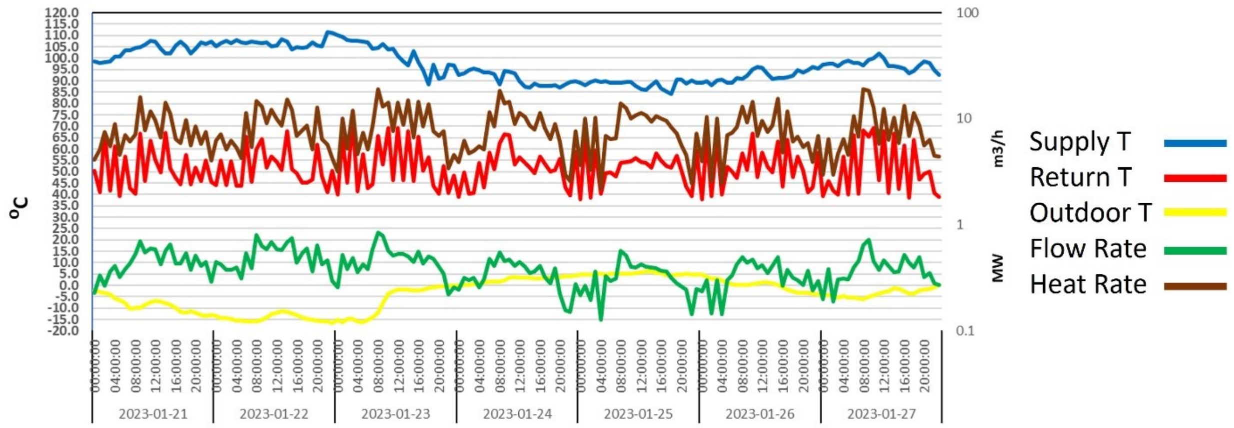

Characteristic of problem: The return temperature curve does not align with the heat rate and flow curves, indicating a lack of synchronization between these variables. This inconsistency suggests that the heat demand and flow fluctuate significantly, leading to instability in the system.

*Figure 5.9: Performance Chart, Up) Gymnastikhall. Down) Rackethallen. Sport Activity locations*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2027 | SPORTHALLEN, LUDVIKA | Sport | Swimming pool | 95.83 | 52.60 | 43.23 |

**Observations**

- The heat rate and flow curves are very sharp and the flow curve pointy alot.
- The return Temperature curve oscillate all the time and very sharp.
- Integrated energy close to the instantaneous heat rate.
- Integrated volume close to the instantaneous flow.
- Calculated optimal flow less than average flow about 26%.
- Another substation in the area showed good cooling indicators.




Characteristic of problem: The RT exhibits sharp and sudden changes, which are not strongly influenced by the outdoor temperature. The oscillation in flow further disrupts the stability and performance of the system, leading to inefficiencies in heat transfer and overall system operation.

*Figure 5.10: Performance Chart of Public Swimming Pool*

| Substation | | | | ST | RT | Cooling |
|---|---|---|---|---|---|---|
| 2315 | MAGNETEN FÖRSKOLA | Place | Preschool | 88.99 | 40.80 | 48.19 |
| 2100 | TIMMERMANSVÄGEN 37 | Residential building | Special Residence | 85.08 | 36.32 | 48.75 |
| 2323 | HÖGBERGSGATAN 66 | Residential building | Apartments | 93.45 | 44.51 | 48.94 |
| 2026 | MARNÄSLIDEN | Place | Office | 95.04 | 45.13 | 49.91 |

**Observations**

- The heat rate, flow and return temperature curves are smooth.
- The curves stable, peaks in specific times based on the local activities.
- Integrated energy very close to the instantaneous heat rate.
- Integrated volume very close to the instantaneous flow.
- Calculated optimal flow less than average flow about 6%.

Characteristic of problem: In these last 4 substations didn't find any errors indicators

*Figure 5.11: Performance Observations of Substations indicates as working at the limits.*

## 5.2 The DH network performance

The figure (Figure 5.12) visualizes the total heat rate consumed by the substations and the hourly average heat rate data supplied to the district heating (DH) network from the accumulator tank. Which adjusted to 45 % of the total heat production to match the DH share (see section 4.2.1). The accumulator tank is fed by both base boilers to manage heat demand variations and temperature differences between the industrial network and the DH network.

Comparing the total heat rate consumed by the substations with the hourly average heat rate data supplied to the DH network. Comparison provides insights into the overall performance of the system and highlights areas for improvement. Additionally, it indicates potential energy losses or inefficiencies in the system.

The main results indicate that the data obtained from the substations exhibit similar patterns and fluctuations to the supplied heat rate data. It also points out that the load shifting strategies are primarily limited to the effect of the accumulator tank.

The assessment of network losses is relatively less accurate due to the exclusion of certain substations with missing data. Furthermore, the heat production data provided for the substations lacks the necessary level of detail regarding their share of the total heat production, as explained in sections 4.2.1 and 4.2.2. Figure 5.12 displays certain phenomena of mismatching between the substations' consumption and the supplied heat energy, which are further discussed in section 6.1.1.

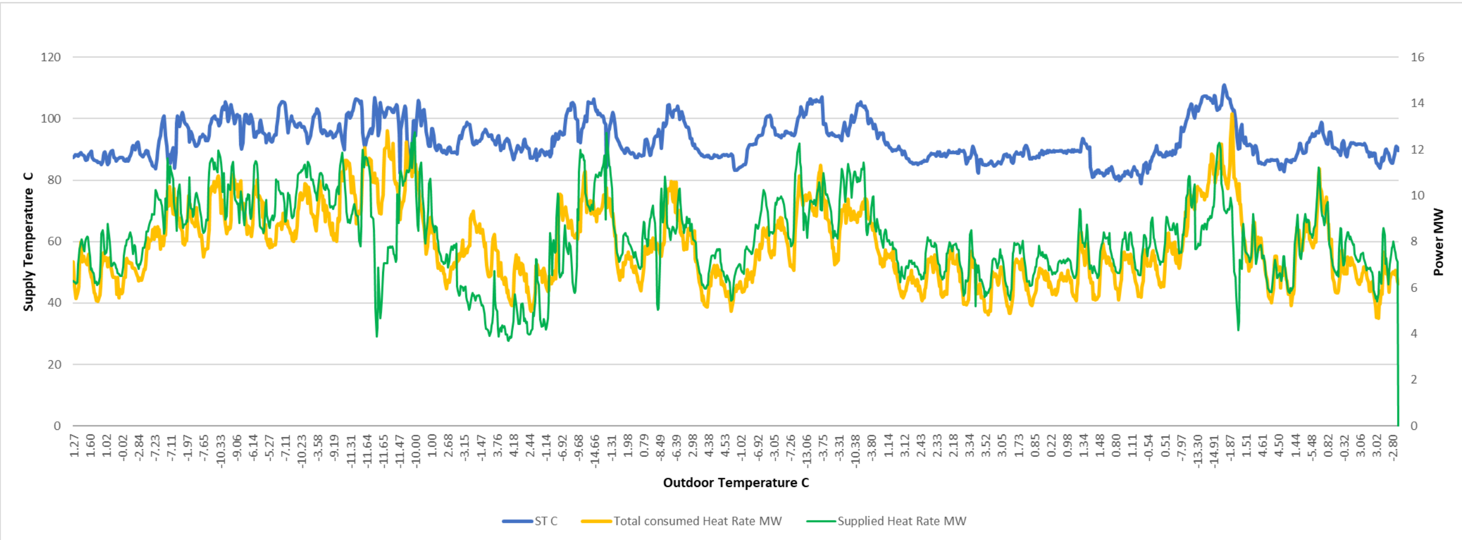



*Figure 5.12: Graf of Supplied and Consumed Heat Rate*

The instantaneous variables, measured at specific time points, were aggregated to obtain a total value for each timestep across all the included substations (see section 4.2.4). These aggregated values were then visualized in a chart to assess the peak load profile, as shown in Figure 5.13.

The observations from Figure 5.13 highlight the dynamic nature of the heat demand and the corresponding fluctuations in temperature within the district heating system. The instantaneous measurements of variables from all substations reveal a decrease in heat demand during the night compared to the morning and afternoon peaks. There is a notable variation in the ST compared to the RT, and RT increases as the heat demand rises. Additionally, the heat rate exhibits a smooth response to changes in the outdoor temperature.

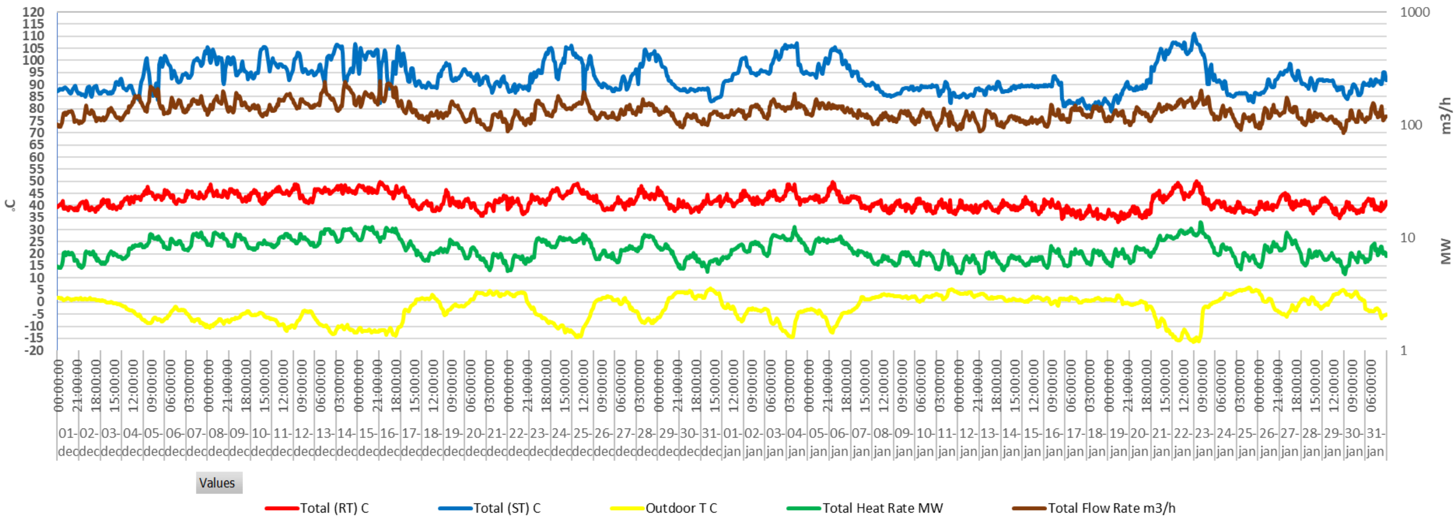



*Figure 5.13: Total Instantaneous Values for All the Included Substations in Period Dec 2022 - Jan 2023*

The return temperature of the substations was compared under two different situations: one where all poorly performing substations were included. Another where those substations were excluded from the analysis, which were 19 substations of 83, for the entire available data period.

The purpose of this comparison was to evaluate the impact of the poorly performing substations on the overall DH network. By visualizing the return temperature in both situations, it was possible to assess how the poorly performing substations affected the overall system performance as shown in Figure 5.14.

Figure 5.14 indicates the impact of the poorly performing substations that exhibit higher return temperatures relative to the substations classified as having good cooling performance.
These poorly performing substations have a negative impact on the system stability, resulting in an increase in the return temperature level of approximately 2 °C. At one of the substations, specifically 'Storgatan 28', cooling process issues resulted in a significant decrease in the RT at a certain point the RT of this substation decreased by half. In Figure 5.14, it can be observed by the point marked at 6.2 MW. This instability in the substation's performance had a notable impact on the return temperature behavior. Some comparison results summarized in Table 5.3 below:

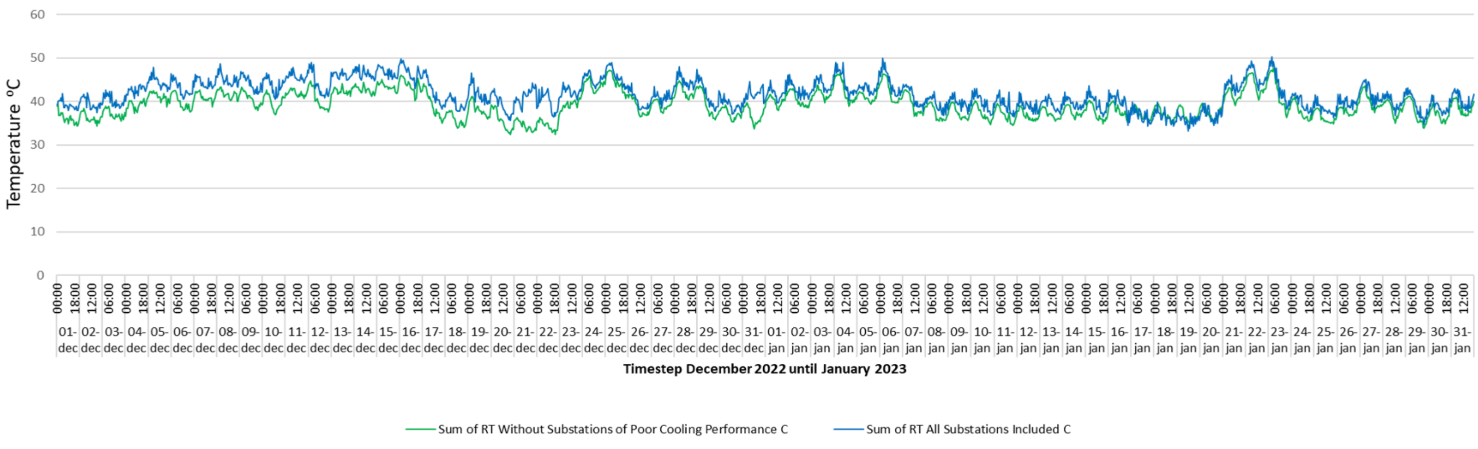



*Figure 5.14: A comparison of the return temperature was conducted between situations where all poorly performing substations were included and excluded. The comparison was performed over the period from December 2022 until January 2023, considering changes in heat demand based on the outdoor temperature.*

*Table 5.3: Summarized results of comparison between situations where all poorly performing substations were included and excluded.*

| | **All substations** | **Poorly performing substations were excluded** |
|---|---|---|
| **Average flow rate** | 133 m3/h | 113 m3/h |
| **Average ST** | 93 °C | 92 °C |
| **Average RT** | 41.5 °C | 39 °C |
| **ΔT (ST-RT)** | 51.5 °C | 53 °C |

## 5.3 Load shifting simulation and saving calculations

This simulation aimed to evaluate the potential benefits and energy savings that could be achieved through load shifting strategies within the district heating system.

The simulation involved shifting the heat demand from peak periods to off-peak periods by utilizing real-time regulation techniques (as described in section 4.4) and leveraging the thermal storage capabilities of the building materials. The objective was to optimize energy usage and reduce peak load requirements by redistributing the heat demand throughout the day.

Application of the model to the chosen building because it shows high KPIs and good cooling efficiency. But the energy declaration for this building didn't match the heat rate and energy values with the collected raw data (see section 4.4.1). Those values in the declaration showed lower energy consumption than raw data give, therefore the UA-vale was adjusted to match the calculations between the model and the raw data, see Figure 5.15. Correction is done by multiple UA with 3.3543 as a correction factor.

| Raw data Max 5 | Model Max 5 |
|---|---|
| 266.78 | 278.24 |
| 260.87 | 259.40 |
| 260.09 | 258.89 |
| 256.63 | 252.25 |
| 252.66 | 248.45 |
| Average | Average |
| 259.4 | 259.45 |

*Figure 5.15: Adjusting the heat rate in kW of the raw data to match the simulation model data.*

In this section, the load shifting simulation and saving calculations were performed and the results are visualized in Figure 5.16 which indicates the load shifting between the days showing the absence of significant shifts in the heat demand peaks. Results in Figure 5.17 show the shifting of heat demand peaks in relation to the outdoor temperature, offering a clearer and more detailed representation of the load shifting patterns throughout the hours.

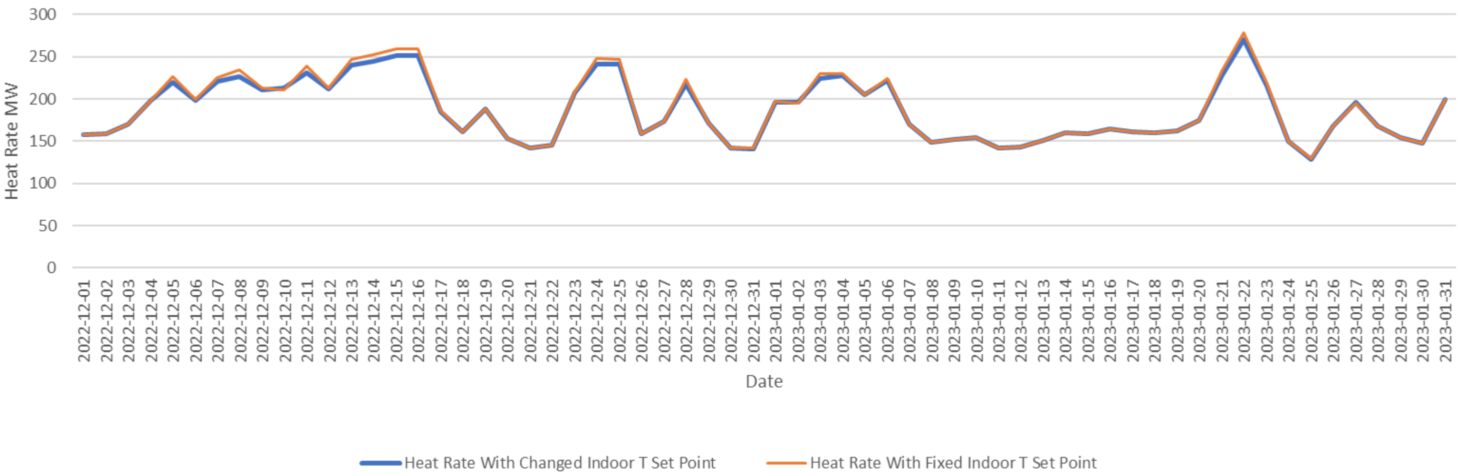



*Figure 5.16: Load shifting simulation result of the Heat Rate over the days, done by calculating the daily average heat rate in tow situations fixed and changed indoor temperature set-point.*

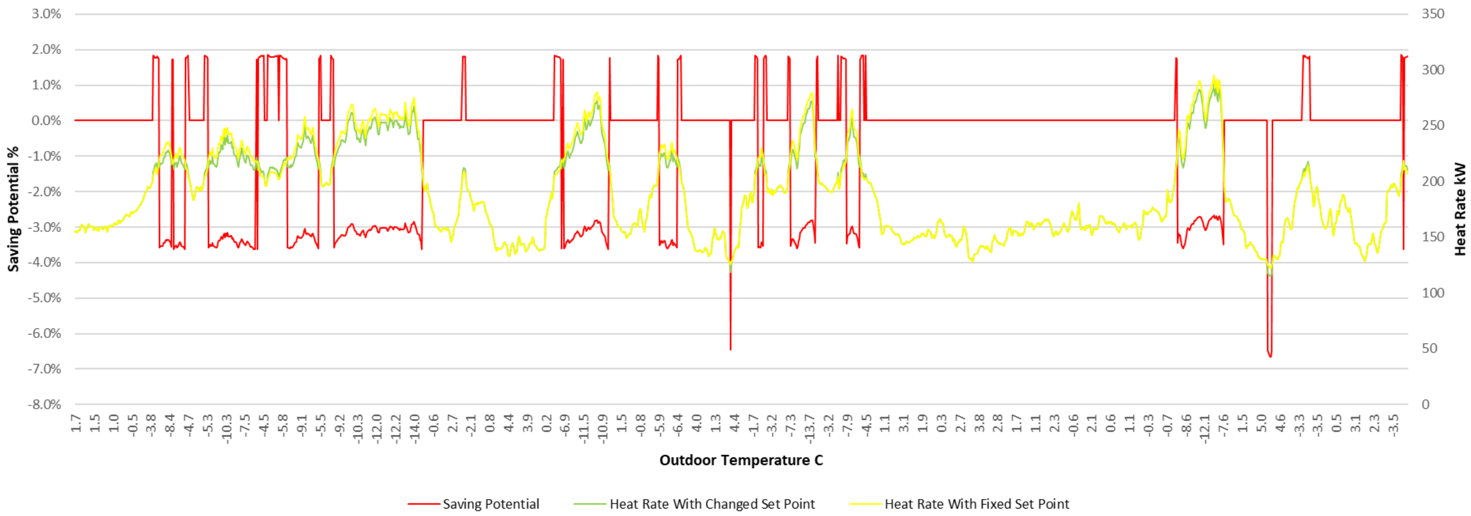



*Figure 5.17: Load shifting strategy savings related to the outdoor temperature throughout the simulated period from December 2022 to January 2023, on an hourly basis.*

Figure 5.18 displays the savings calculations of the load shifting simulation carried out to determine the reduction achieved in the highest five values of the daily average heat rate by redistributing the heat demand through indoor temperature regulation. By analyzing the output data and comparing the two scenarios (with and without indoor temperature regulation), it becomes possible to assess the extent of energy savings achieved through load shifting and indoor temperature regulation. Additionally, the corresponding cost savings can also be evaluated. These calculations and analyses are described in detail in section 4.4.4 of the report.

**Input Data** Data collected from the last energy declaration in 2019, downloaded from Boverket database online.
Tre Krokars Gata 10, 771 34 Ludvika - Year of construction: 1957
Six-floor apartment building with 34 residential apartments, and basement.
Energy performance, primary energy number (primärenergital): 130 kWh/m² och år

| Tap Hot Water | Space Heating | Temperate floor area | DIT | DVUT | Outdoor air flow | UA-value |
|---|---|---|---|---|---|---|
| kWh, year | kWh, year | $m^2$ | °C | °C | l/s | $W/m^2$ K |
| 60975 | 250000 | 2439 | 21 | -17.7 | 0.35 | 7.64 |

Indoor T [C] 21 Standard
Outdoor T [C] The outdoor temperature in the calculations took a real registration temperature for Ludvika for the period Dec 2022 until January 2023

**Output Data Calculations**

**Heat Rate Savings**

| Max 5 Heat Rate Values | |
|---|---|
| Changed set-point | Fixed set-point |
| 270.6kW | 278.2kW |
| 251.8kW | 259.4kW |
| 251.3kW | 258.9kW |
| 244.6kW | 252.3kW |
| 240.8kW | 248.4kW |
| Average | Average |
| 251.8kW | 259.4kW |

**Energy Savings**

| | |
|---|---|
| Dec-Jan | 2584.86kWh |
| | -0.9% |

**Savings Observations Statistic**

| Outdoor T Range | Max | Min |
|---|---|---|
| (-18) to ( -7) | -3.6% | -2.7% |
| (-6) to ( +5) | 1.9% | 1.7% |
| (+6) to ( +8) | -6.7% | -6.5% |

| | |
|---|---|
| When outdoor T under (-8 C) | -3.1% |
| When outdoor T over (+6 C) | -6.6% |
| Average of max 5 heat rate values | -3.03% |

**Coast Savings** (Subscribed Heat Rate Average of max 5)

| | After Regulation | Befor Regulation |
|---|---|---|
| Heat Rate | 26 038 kr | 27 667 kr |
| Energy | 135 569 kr | 136 831 kr |
| Flow | 13 838 kr | 13 964 kr |
| Total | 175 446 kr | 178 462 kr |

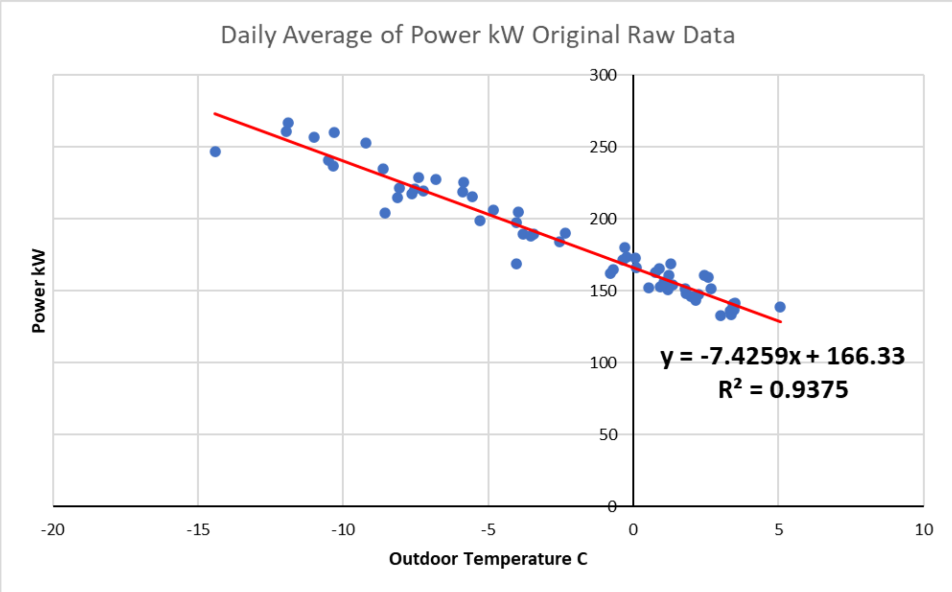
*Figure 5.18: Presenting the results of the savings calculations achieved by load shifting simulation. The upper part of the results presents the input data utilized in the simulation model in Excel, while the lower part presents the calculations performed on the output data.*

## 5.4 Pricing model calculations

The pricing model calculations in this study focused on comparing different methods for calculating the subscribed heat rate, as described in section 4.5.3.

In this analysis, data from December 2022 to January 2023 was utilized to calculate the subscribed heat rate in kilowatts (kW). Two situations were considered, utilizing the simulation data before and after the regulation of the heat rate demand. The results enable a comparison of the feasibility and effectiveness of different calculation methods aims to lower the subscribed heat rate value; methods are described detailed in section 4.5.3. It was observed that the daily average heat rate of the highest five values (Max 5) resulted in a lower subscribed heat rate value in both situations, as presented in Figure 5.19.

| Model Before Regulation | |
|---|---|
| P-sign | Max 5 C |
| Y= -7.4259*X+166.33 | 266.8 |
| Lowest Daily Average T | 260.9 |
| -14.2 °C | 260.1 |
| | 256.6 |
| | 252.7 |
| | Average |
| 273.4 kW | 259.4 kW |




| Model After Regulation | |
|---|---|
| P-sign | Max 5 |
| Y= -7.1522*X+167.7 | 270.6 |
| Lowest Daily Average T | 251.8 |
| -14.2 °C | 251.3 |
| | 244.6 |
| | 240.8 |
| | Average |
| 270.8 kW | 251.8 kW |

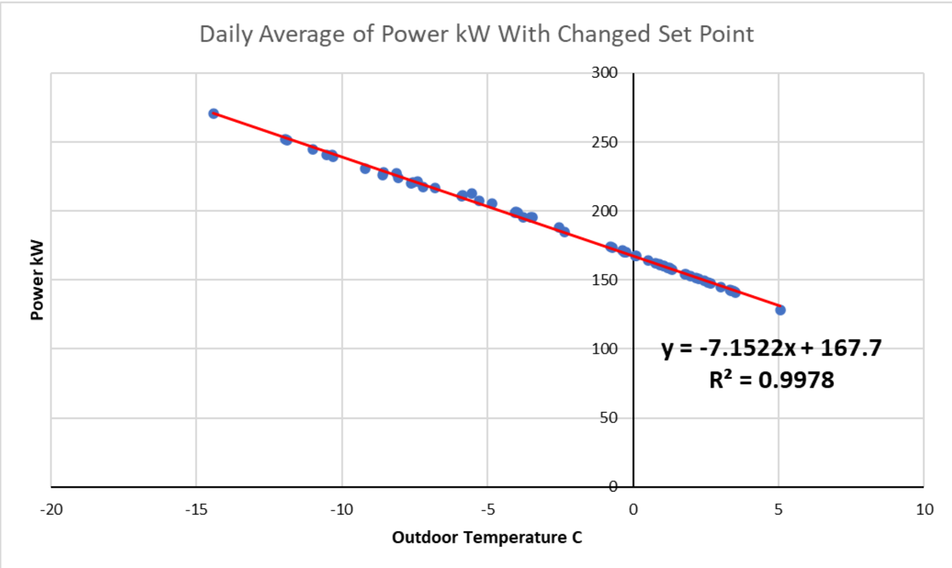



*Figure 5.19: Scatterplot for the heat rate and outdoor temperature. Up for on Substation Before Simulation, Down After Simulation for the same Substation.*

# 6 Discussion

## 6.1 Result discussion

### 6.1.1 Substations performance analysis

To identify the problems related to low cooling efficiency at the substations, as indicated in the performance classification results in section 5.1.1 (Table 5.1) showing low average cooling KPI, further actions need to be taken. It is necessary to visit the locations and conduct measurements to gain a comprehensive understanding of the situation, allowing for the proposal of effective action plans for the case study company. The available data does not provide a complete description of the problem due to missing secondary side data.

The substations map reveals that a majority of the substations with low cooling KPI are situated at the end of the distribution line (Figure 6.1).

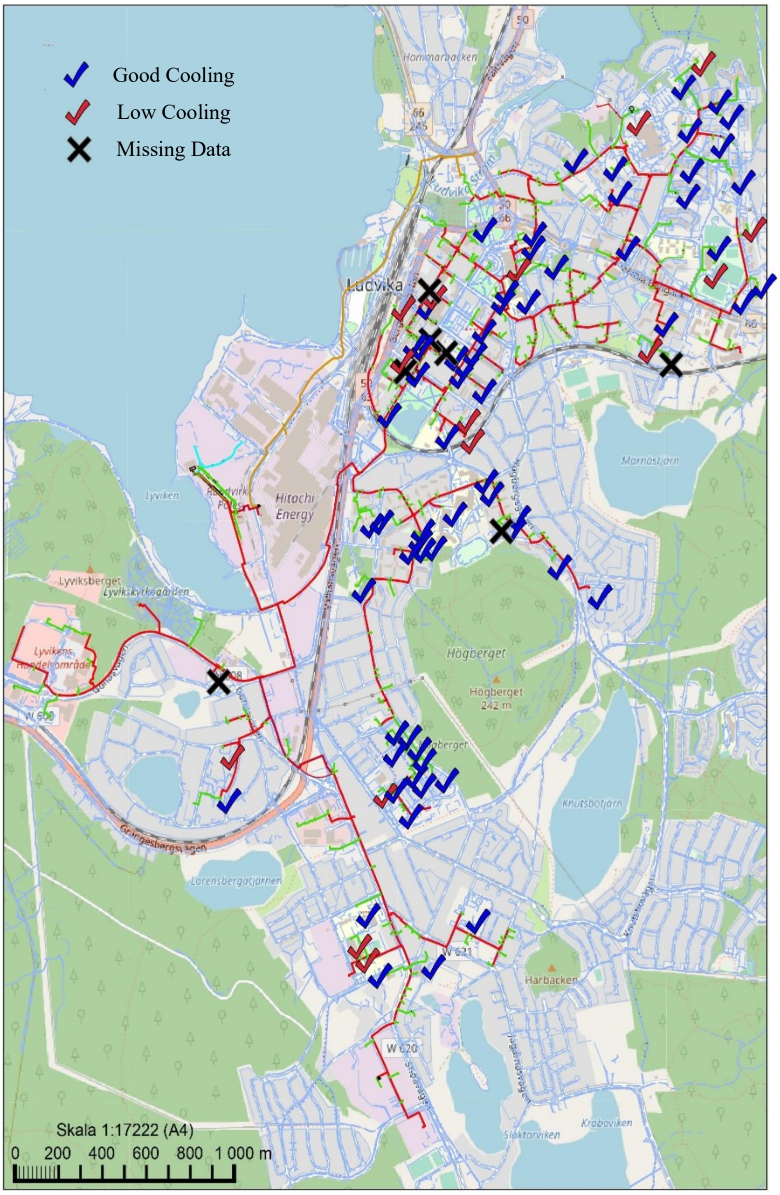



*Figure 6.1: Map of the Substations*

For the poorly performing substations, the average return temperature is 50°C when the supply temperature is above 90°C, and 40°C when the supply temperature is below 90°C.

One possible reason for the high return temperature is the presence of oversized branch pipes. Oversized branch pipes result in reduced velocity, leading to higher heat losses and reduced heat exchange efficiency.

The reduction in differential pressure in the branch pipes as the distance from the main pump increases affects the control valve equally. The flow rate is proportional to the differential pressure across the control valve.

In most of the substations indicating a low cooling KPI, the ST drops to around 85°C, as observed in Table 5.1. Additionally, the scenario of oversized pipes results in reduced velocity through the control valve, leading to lower flow and decreased efficiency in the heat exchange process, eventually resulting in higher return temperature.

The size of the HEXes also impacts the cooling process, as described in equation 3, where the heat exchanging area is proportional to the heat demand. However, the lack of thermal data on the secondary side makes it challenging to assess the correlation between HEX size and heat demand accurately according to equations 4 or 5.

Another possible reason is the presence of drag reduction additives (surfactant solutions) that dampen turbulence in the channels of the plate heat exchangers at lower flow velocities. This, in turn, reduces heat transfer [43].

The poorly performing substations should be inspected by staff equipped with measurement equipment to evaluate the temperatures over the HEXes. Additionally, other components such as control valves, regulation devices, and sensors need to be inspected to assess their condition and functionality. Based on the evaluation results, the components can be classified into categories indicating their level of quality or validity.

It is also important to check the adjusting settings of these components to ensure they are within the appropriate range and to examine the validity of their operation.

Theoretically, based on the analyzing criteria results and a recommendation from the Swedish Energy Agency as defined in the report '*Profits with reduced return temperatures in district heating systems*' [53], a main problem can be identified see Table 6.1 below. Insufficient data quality and availability affect the certainty levels of the main problems.

*Table 6.1: Theoretically Identifying Substations Problem*

| **Checking** | **Action** | **Substation** |
|---|---|---|
| Check the control valve condition and age.<br>When the flow is constant and does not vary according to the heat demand. The valve may be stuck in one position or do not close completely which causes a flow even when is no heat demand, so no cooling action and results in excess temp on the load side and in the return pipe. | Change the control valve if there any seen damages or leaking. | 2103 STORGATAN 28<br>2190 STORGATAN 37<br>2035 VÅRDSKOLAN<br>(Section 5.1.2) |
| Check the sizing of the control valves by measuring the differential pressure at the supply side of the substation.<br>It is possible that the control valves are oversized, causing them to operate close to the closed position. Fluctuations in the return temperature (RT) can be an indication of this issue. | Consider replacing the control valves with a more suitable size | 2103 STORGATAN 28<br>2190 STORGATAN 37<br>2035 VÅRDSKOLAN<br>(Section 5.1.2) |

| Checking | Action | Substation |
|---|---|---|
| Measure the temperature over the HEX and check with the manufacturer data if the kA- value is out of the operation range.<br>HEX can be dirty or undersized which needs high flow to satisfy the heat demand.<br>Oversized HEX leads to bad regulation. | Cleaning the HEX or change it. | 2130 NORRA JÄRNVÄGSGATAN 4<br>2131 VASALUNDEN 3<br>(Section 5.1.2) |
| Check regulator setting, wrong setting, or wrong heat curve implemented leads to fluctuation in the secondary ST. | Reinstall the setting or change it if any damages observed. | 2432 GAMLA POSTEN, LUDVIKA GÅRD<br>(Section 5.1.2) |
| Checking the hot water circulation (VVC, HWC) flow settings, higher HWC losses lead to higher RT.<br><br>Measure the pressure drops over the HEX, if the pressure drops high indicate a bad situation of HEX or a problem with the pump's setting or pump situation. | Adjust the pump setting.<br>Clean the Hex or change it. | 2301 MARNÄSGATAN 36<br>2492 GRÅGÅSVÄGEN 12<br>(Section 5.1.2) |
| Test the temperature sensors by using multimeters or compare a secondary temperature to the corresponding primary side.<br>If it is lower on the secondary side that is mean one of them is damaged**[20]**. That result in regulation errors. | Change the sensor. | |

Some poorly performing substations can be experiencing issues with their management strategies, as detailed in section 5.1.2 and depicted in Figures 5.6 to 5.11. The low cooling efficiency indicates high variations in the demand side between day and night, particularly observed in sports facilities and preschools. The diversity of consumption time and the ability of buildings to store heat energy can enhance the effectiveness of the system, as mentioned in the literature review (section 2.5.3).

Table 6.2 and 6.3 below provides some recommendations for improving the substation cooling performance. However, the economic evaluation of these recommendations is not discussed in detail as it requires more extensive data for simulation and to accurately assess the energy savings and efficiency benefits associated with such projects.

*Table 6.2: Improvement recommendations for locations with high variations in hot water demand*

| **Action** | **Substation (Section 5.1.2)** |
|---|---|
| Install accumulator tank for tap hot water. Another recommendation is to install solar collectors with accumulator tanks. | 2079 HILLÄNGENS GAMLA omk.<br>2412 LORENSBERGA GYMNASTIKHALL<br>2462 LORENSBERGA RACKETHALLEN<br>2082 BISKOPSNÄSETS FÖRSKOLA<br>2457 FÖRSKOLAN NOTGÅRDEN |

Since in these premises, the hot water demand is dominant and the heat rate peaks at certain times, while being very low during other times, recommendations include storing heat energy in an accumulator tank to smooth out changes in the DH demand or shift load to a different time [54]. Another suggestion is to produce heat and store it in the tank using solar collectors when sunlight is available. Solar heating can cover approx. 50 % of the annual need for heat for domestic hot water in solar heating systems [55]. These approaches help avoid costs associated with unit start-ups, shutdowns, and load changes. The capacity for heat storage is limited by the size of the tank and the speed at which hot water can be pumped in or out of the tank. The accumulator tank is connected between the load and the DH network to prioritize the utilization of stored heat energy.

*Table 6.3: Improvement recommendations for locations need increase the heat exchange rate.*

| **Action** | **Substation (Section 5.1.2)** |
|---|---|
| Using 2-steps coupling for HEX by adding additionally HEX (se section 2.3) | 2027 SPORTHALLEN, SWIMINGPOOL |
| Increase the radiator size or decrease the indoor temperature set point. | 2154 RESECENTER, LUDVIKA<br>2195 STATIONSHUSET ANNEX |
| This action aims to increase the heat exchange and improve the cooling process at this premises. | |

### 6.1.2 The DH network performance

The performance of the DH network is influenced by various factors, which will be discussed in this section. Starting by analyzing the overall network performance and how it differs from individual substation performance. Additionally, exploring the impact of poorly performing substations on the entire network.

Generally, the consumption is lower than the supply due to heat losses within the network and substations. Furthermore, in the studied DH network, data for the consumption of 13 substations are missing (see section 4.2.3). Figure 6.2 displays the heat energy supply and consumption for all included substations detecting discrepancies at different times and days.

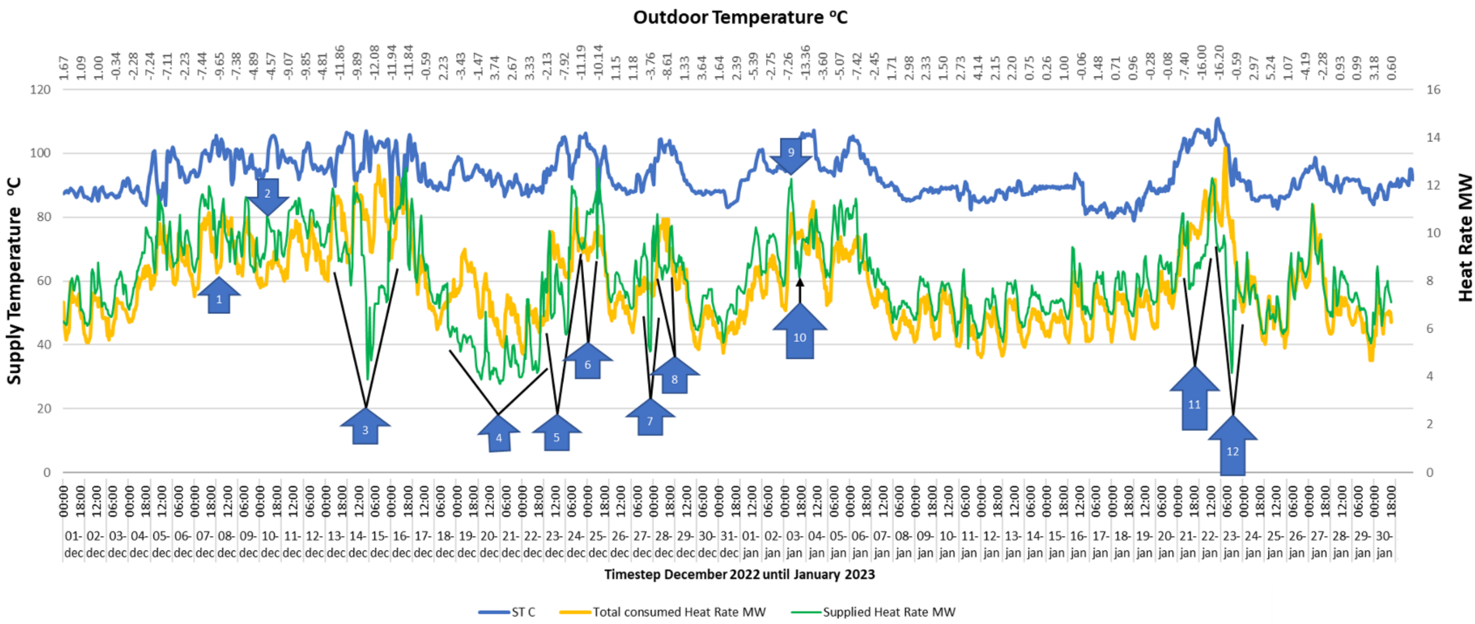



*Figure 6.2: The hourly integrated supplied and consumed heat rate for all the substations with mismatching marks*

At certain outdoor temperatures, the heat rate consumed exceeds the supplied heat, while at other times, the supplied heat rate far exceeds the consumption (see Figure 6.2). These mismatching phenomena can be classified into three main reasons:

- At outdoor temperatures below -8 °C, the peak heating facilities are utilized to meet the demand, as indicated by signs number 3, 5, 10, and 11. This demand exceeds the capacity of both base boilers.

- The DH system employs heat storage mechanisms within the network, as evidenced by various points on the graph. The distribution network dynamically adjusts by using an accumulator tank to balance the heat rate within the network. The accumulator tank controls the feeding of heat energy directly into the distribution network, as shown in Figure 3.1.

  The network charges with heating energy to store it before outdoor temperatures decrease, as observed at sign number 7, when the outdoor temperature is -0.85 °C, the network is charged with heating energy. As the outdoor temperature drops to around -5 °C, the heat energy supply decreases, and the stored heat energy within the network is utilized. Additionally observed in signs 2 and 9. When outdoor temperatures are around -5 °C, the network is charged in preparation for the upcoming -9 °C temperatures.

Conversely, there are instances when the network releases accumulated heating energy within the network after a decrease in outdoor temperature (discharging from network to load without increasing the production), as seen in signs number 6, 8, and 12, resulting in higher consumption than supply.

- Base boilers may not be operational due to cleaning or maintenance, as indicated by sign number 4. During this period, the outdoor temperature is relatively high compared to the rest of the period. According to information from VB Energy's operating technician, when maintenance or cleaning operations are planned, both base boilers at LVC 4 plant are switched off, and the peak heating facilities are utilized (see section 3.1). As a result, the production from these base boilers is lower than the supply, and it is likely that at least one of them is switched off.

The instantaneous measurements of variables from all substations indicate a decrease in demand during the night compared to the morning and afternoon peaks (see Figure 5.13 upper graph). This is attributed to Ludvikahem's strategy of shutting off ventilation systems and associated heating in public facilities buildings during the night, which includes a total of 37 substations of 90.

Furthermore, the peaks in the overall network graph appear smoother compared to individual substation graphs. This can be attributed to energy storage mechanisms within the network and the use of an accumulator tank to balance heat production and demand (see Figure 3.1). These mechanisms contribute to the smooth flow of heating energy throughout the network as shown in Figure 6.3.

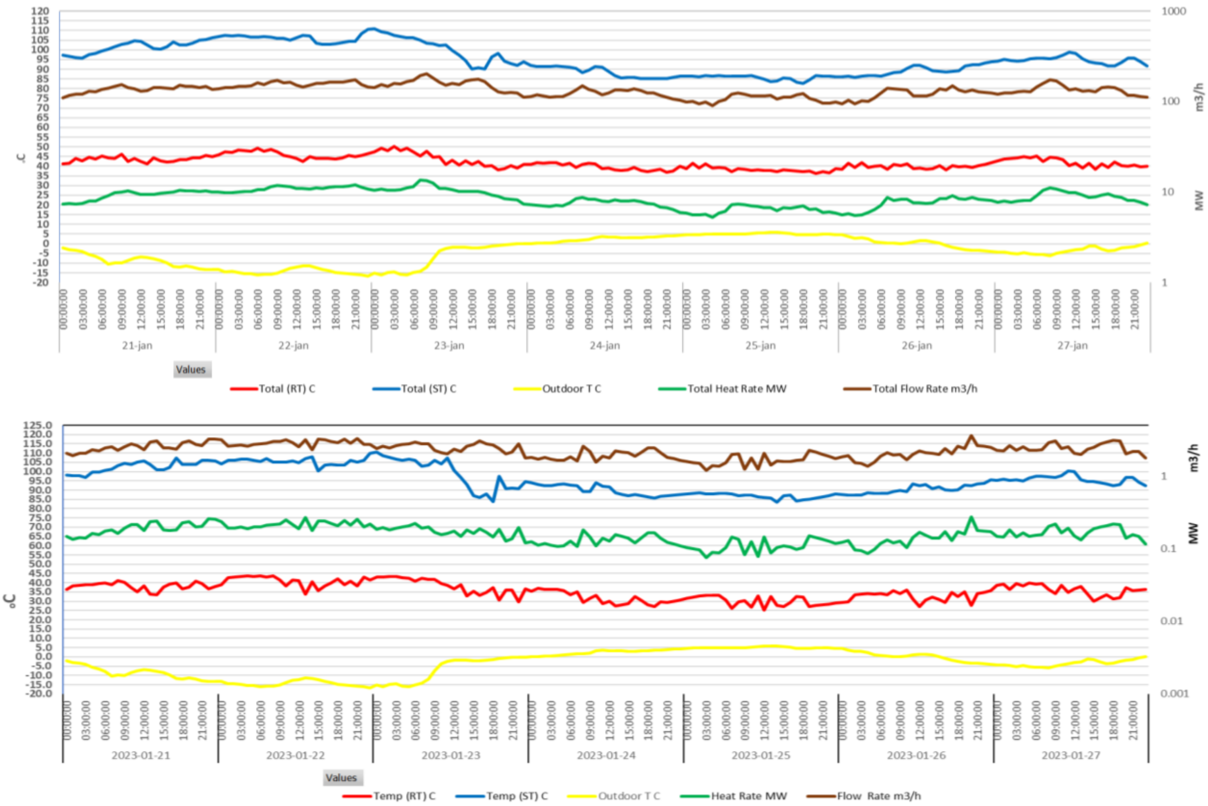



*Figure 6.3: Up) Total DH Variables, Down) Single Substation Variables*

Substations with poor cooling performance, characterized by low average cooling indicators, negatively affect the stability of the entire system by causing fluctuations in the RT level within the network, as shown in Figure 6.4. These fluctuations, in turn, require variations in the flow rate and ST to meet the heat demand.

The data shows that in situation one (with all 83 substations included), the average flow rate is approximately 133 m3/h. Whereas in situation two (with 19 substations with poor performance excluded), the average flow rate decreases to 113 m3/h. The higher flow rate in situation one is caused by variations in the RT when the ST is predetermined by the heating plant. To maintain balance in the network, adjustments in the flow rate are necessary to manage the oscillation of the RT.

Furthermore, the ST level indicates a decrease of around 1 °C from the main boilers to the substations. Also, the RT level shows a decrease of around 2.5 °C in situation two from the substations. As a result, situation two demonstrates improved temperature levels in the network, with lower ST, RT, and a higher temperature difference (network's ΔT) between them. This leads to a more stable and efficient district heating network, see Table 5.3.

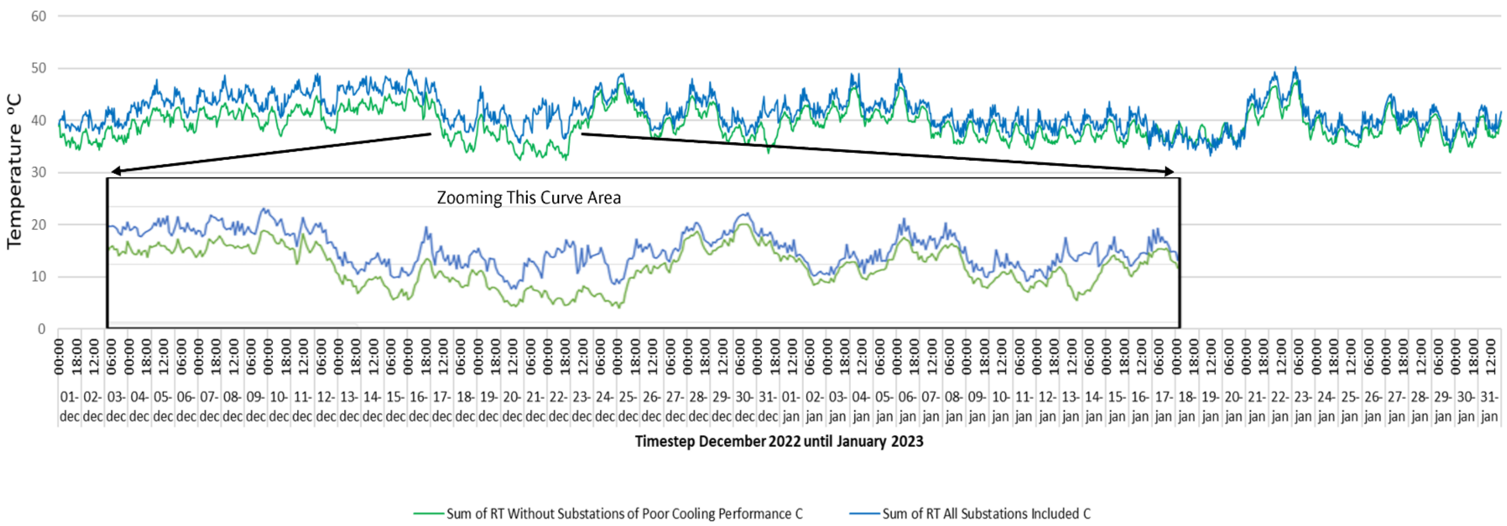



*Figure 6.4: Clarifying the Impact of the Poorly Performing Substation*

### 6.1.3 Calculated savings with load shifting

The results and findings of the load shifting simulation, along with the calculated energy and cost savings, are presented in section 5.3. These findings offer valuable insights into the potential benefits and feasibility of implementing load shifting strategies within the district heating system.

The main goal of load shifting is to reduce the heat rate requirements by redistributing heat energy according to the outdoor temperature by a specific strategy. This involves lowering the indoor temperature setpoint to 20 °C to reduce heat rate peaks. Prior to this, the indoor temperature setpoint is increased to 21.5 °C to accumulate heat energy within the buildings, which compensates for the subsequent reduction in heat energy. This compensation process ensures thermal comfort even during colder outdoor temperatures (-8°C and below). Additionally, this approach can result in an overall increase in total heat energy while maintaining a lower heat rate demand.

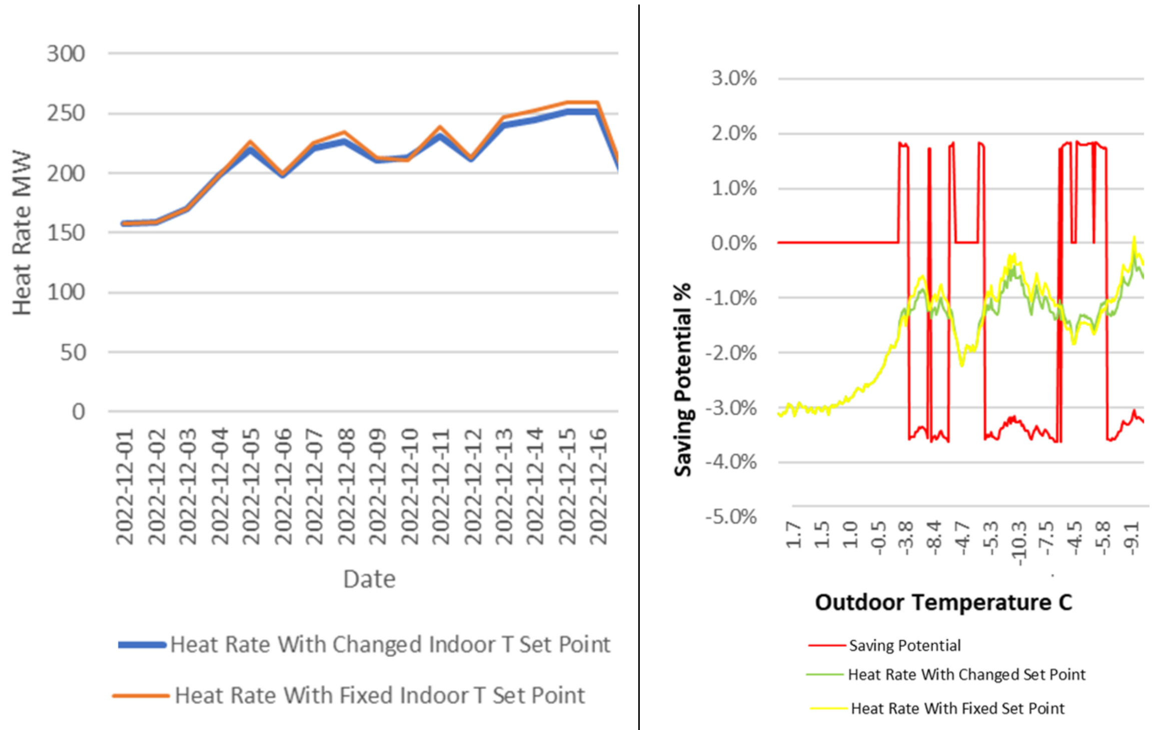
The statistics regarding saving potential fall within an acceptable range, and the heat rate curve becomes broader and flatter. This is shown in Figure 6.5.B, where the green curve extends and gradually decreases.

Based on the results, the load shifting strategy aimed at shifting the load between days showed a low level of enhancement, but it resulted in smoother load shifting between hours, as shown in Figure 6.5. The reduction in the heat rate peak levels was notable, with a 3% decrease, leading to savings in the subscribed heat rate of approximately 7 kW. The loss in thermal comfort was not far from the operative temperature standards according to *ASHRAE 55–2017*, which is 20.5 °C (PMV-PPD method at conditions of 1.0 clo, 0.1 m/s airspeed) [56] [57].

The cost savings amounted to about 3000 SEK over two months for a single building. Assuming this level of saving for one building over a year, the total savings for all substations would be around 270,000 SEK. It is important to note that the heat rate peak savings in other seasons may not be at the same percentage since outdoor temperatures do not drop significantly below -7 °C.

The energy usage savings achieved were approximately 0.9%, regard to a reduction of the indoor temperature and consequently, lower heat demand. These savings are expected to be even more significant during periods of higher outdoor temperatures in low heat demand seasons because they prevent unrequired heating energy, which otherwise represents heat losses. It is expected that there is still energy consumption saving potential between +8 °C and +5 °C, as observed in Figure 5.18. When the outdoor temperature is over 5 °C, the energy saving potential is 6.6%. This presents an opportunity to take advantage of lower energy prices or higher availability of renewable energy sources during those times.

Housing company 'Stockholmhem' calculated energy savings of 6-7% by installing temperature sensors in the apartments and connecting them to a central regulation and monitoring system to adjust the heat rate as needed [58]. Zhang et al. [59]proposed a control approach for the indoor thermal environment, considering real-time thermal feeling to meet thermal comfort requirements. Experimental results showed a 10% savings in daily energy consumption. Hoyt et al. [60] studied the reduction of the heating set point from 21 to 20 °C and found that it could save 34% of heating energy in simulations data for both new and retrofit buildings throughout the year.




*A) Daily load shifting* *B) Hourly load Shifting*

*Figure 6.5: Load shifting simulation results comparison between daily and hourly load shifting. Cutting off parts of Figures 5.16 and 5.17 for a clearer view*

The model of real-time regulation could be improved by accurately considering heat storing capabilities, which involves storing time to get a larger amount of heat energy in the buildings' construction to facilitate better load shifting between days. In this case, it is necessary to incorporate a time constant representing the storing ability of the building construction. This variable would enhance the regulation of the indoor temperature increasing's period (charging time) and prevent the loss of stored energy over time while discharging.

Research has highlighted that a longer loading time (duration) increases the storage/release depth until it reaches 100 % saturation level. Therefore, accurate forecasting of this time helps prevent losses and potentially decreases heat demand, by reducing time with indoor temperatures above the desired set point temperature [34].

Although the improvement may be marginal, it can be combined with other heat-storing possibilities, such as monitoring the heat energy stored in the network by measuring the supply temperature level and determining the required heat rate accordingly. This allows for adjusting the heat demand to a lower level when the network and buildings have a high state of charge.

Real-time regulation helps optimize customer consumption, which serves the suppliers in maintaining an efficient district heating system. Studies have shown that real-time control leads to the optimization of the DH network when implemented in the DH system control [41]. Additionally, customers' flexibility in consumption brings environmental and economic benefits to the entire system.

Heat storage is a vital component of the DH system. Studies have indicated that heat storage helps meet peak load demands. Proper utilization of the building's thermal mass for heat storage can reduce the heating rate peaks by approximately 12% in cold zones when utilized accurately [61].

The use of a constant model with predictive control (MPC) may lead to errors if it fails to account for the adaptability of different building materials and unexpected weather changes, as well as the risk of compromising thermal comfort.

The incorporation of adaptive MPC helps in stabilizing the network by smoothing the curves. Adaptive MPC adapting the prediction model for operating conditions at runtime within a certain time interval [62]. These features enable a smooth adjustment in the indoor temperature set point and accurate determination of the heat demand. Research has shown that adopting adaptive MPC to control indoor temperature while considering indoor thermal comfort in buildings resulted in energy savings of approximately 10% compared to conventional control systems (such as thermostats) [63].

Furthermore, the use of adaptive MPC in DH pump regulation contributes to faster network stabilization compared to conventional methods. This demonstrates the effectiveness of adaptive MPC in optimizing energy usage and enhancing the overall performance of the district heating system [24].

Adaptive MPC not only improves energy consumption but also enhances production schemes, especially when combined with forecasting heat demand over a sufficient timeframe, such as a 24-hour forecast. This can be achieved by performing online estimation of weather forecasting and incorporating thermal comfort biases to ensure the effective delivery of the required demand.

To establish such a system, it's necessary to install temperature sensors within the building's individual apartments. These sensors should be linked to additional regulating devices located within the apartments. Subsequently, establish a connection between the secondary regulator and the internet, as well as a weather forecasting service. This connection aids in computing the heat demand for a specific time interval. The collected data should then be transmitted to central monitoring and control units, which will adjust the heat demand accordingly. An alternative method involves sending signals to the substation regulator to modify the flow rate. Alternatively, for high-level demand-side control, an automated adjustment of the radiator system can be implemented. This would necessitate connections to the radiators themselves. These measures would facilitate real-time data collection and analysis, thereby allowing for more precise predictions and enhanced control over the district heating system.

This improvement in control efficiency contributes to the overall stability and performance of the district heating system, leading to cost savings for customers and promoting sustainable energy practices. Summarized benefits of the management strategy simulation:

1- Reduces peak heat demand on the highest days, leading to lower subscribed heat rate. Saving in the energy usage.
2- Decreases the cost of heat rate share, and energy use.
3- Reduces the need for peak heating facilities, resulting in decreased production requirements and fuel consumption.

### 6.1.4 District heating pricing model

The pricing model components help incentivize customers to use energy more effectively, promoting a more sustainable society. Understanding the division of the price model and the factors that affect it leads to fairer costs for customers.

Cost reduction, especially in energy and flow components, depends on energy usage and substation performance. Better performance leads to a lower water volume passing through the HEXes, resulting in reduced flow, lower electricity consumption for pumps, and decreased thermal losses in the system.

The cost of heat rate depends on strategies for managing peak hours and utilizing heat storage capabilities. The calculation method also plays a role in determining fair costs for both suppliers and end-users.

The most well-known methods for calculating the heat rate involve taking the average of the highest five or three peak heat rate days from the previous year. These methods are commonly used by the study case companies. Another popular approach is to select the highest daily average heat rate measured during the previous year as the subscribed heat rate value.

The categorical number method calculation relies on dividing the yearly energy consumption by a number that represents the utilizing hours of the location, as mentioned in section 2.4. The categorical number can vary based on the local type and activities. However, one drawback of this method is that it ignores the heat rate peaks, which can lead to less accuracy in capturing the highest energy demands during peak periods. As a result, it may not fully account for the impact of peak heat rate values on the overall cost estimation. [53].

The P-signature method is based on the linear relation between daily average heat rate and the outdoor temperature within the winter season for the previous season. Calculation mathematically by obtaining a linear equation from scatterplot, and find the lowest outdoor temperature then calculate the subscribed heat rate value corresponding to the linear equation [53]. The chosen outdoor temperature as a reference for the entire year plays a critical role in this method. By selecting the lowest daily average outdoor temperature, it represents the highest peak heat rate value, even if it occurred within a very short period.

The results showed that the Max5 method was more feasible for the end-users than the P-signature method and ensured fairness for both suppliers and end-users. This is because Max5 captures the highest five heat rate peaks and takes into account the duration period when calculating the average, whereas P-signature only captures the highest heat rate peak as a subscribed value.

## 6.2 Method applicability/sources of error

The DH performance assessment and identification of the factors affecting the system efficiency can be better investigated initially. This will enable a more accurate definition of the required data for this study.

The method could be improved by incorporating a practical inspection visit to substations and conducting measurements, such as measuring pressure drops over the HEX, checking the control valve situation and settings, and assessing the actual performance of the HEX using manufacturer data. This practical aspect would help narrow the scope of the study and provide insights into the reasons for low-performing substations located at the end of the DH distribution network. Additionally, it would assist in defining a more effective analyzing protocol for the low-performing substations.

Data quality introduces uncertainty in the results due to several factors. Some substations have missing data, and the production data source and consumption data source do not complement each other fully. Additionally, the instantaneous measured values of flow, ST, and RT for specific time points result in low accuracy due to demand variations.

Furthermore, the simplified load shifting simulation model overlooks other influential factors such as radiator size or air velocity (the ventilation system), which can impact the results.

Both the heat rate and density of water used in the calculations for substation data completion and simulation model rely on constant values corresponding to the average temperature of ΔT (50 °C), as mentioned in section 4.2.2. However, in reality, these values vary with water temperature, leading to potential errors in the calculations.

## 6.3 Applicability of the study

The study emphasized the significance of the cooling process in substations as an important factor in increasing the overall efficiency of the DH system. Improving the cooling process of low performance substations can in this case result in a decrease of about 2 °C in the return temperature.

Furthermore, the study identified which substations have an impact on the DH network but did not pinpoint the exact problems. It highlighted the importance of conducting periodic inspections and documenting the substation performance to enable follow-up assessments.

The load shifting approach demonstrated that enhancing regulation and managing strategies to meet thermal comfort requirements leads to more efficient energy consumption and cost savings for both heat suppliers and end-users.

Additionally, the study highlighted the importance of choosing an appropriate subscribed heat rate calculation method to determine fair costs for both heat suppliers and end-users.

The study serves as a valuable inspection guide for assessing substation performance and offers improvement proposals to enhance the effectiveness of substations, contributing to a more sustainable district heating system from an environmental protection perspective.

Regarding heat demand management, the study provides a simplified simulation model that aids decision-makers in identifying factors influencing energy savings. It also assists in selecting suitable regulation devices that not only achieve savings but also facilitate load shifting of heat demand. This approach aims to reduce heat costs while ensuring efficient energy usage and promoting a more sustainable district heating system. In this context, the *Ngenic* smart heat control system fulfills these criteria, which can give incentive to invest in the demand-side control strategy.

## 6.4 Future work

As this thesis has explored and presented various aspects of the DH systems and substation performance, it is evident that there are still numerous opportunities for further research and development in this field. The findings and conclusions drawn from this study have laid the foundation for future work that could lead to significant advancements in the efficiency, sustainability, and overall performance of DH systems.

This section outlines potential areas for future research and improvement, aiming to address existing challenges. The identified areas of future work are as follows:

1- Advanced Control Strategies: Further investigation into the development of advanced control strategies is essential to achieve higher levels of system flexibility and energy optimization, such as:

- Predictive Control: Using predictive algorithms and real-time weather forecasts to anticipate changes in heat demand and optimize heat generation accordingly.
- Load Shifting: Shifting heat demand from peak periods to off-peak hours through automated control mechanisms, ensuring a more even distribution of heat consumption and minimizing peak load requirements.

2- Substations located at the end of pipelines tend to exhibit lower performance compared to those situated closer to the central heating plant. Further analysis of the relationship between poorly performing substations and their location at the end of pipelines is an important phenomenon to identify.

# 7 Conclusions

Through accurate data analysis and in-depth assessments, the study has uncovered significant factors that influence the overall effectiveness of district heating. It highlights the importance of assessing the cooling process performance of the substation and identifies areas for developing and implementing control strategies. So, district heating systems can achieve higher consumption efficiency, reduce energy wastage, and provide customers with more flexible and sustainable heating demand.

The main findings of the study are as follows:

- Substation Performance Evaluation: The evaluation of the substation performance revealed and located the poorly performing substations that contribute to inefficiencies in the DH network. Critical factors such as cooling processes and heat exchange efficiency of the substations had significantly impacted the DH efficiency.

- Routine Control and Inspection: Substations require routine control, inspection, and thorough documentation of these assessment actions to ensure optimal performance and efficiency.

- Optimizing Heat Demand: Improving certain substations experiencing high variations in demand between day and night, depending on the activity type at these premises, is necessary to decrease heat demand requirements and enhance overall system efficiency.

- Real-Time Regulation and Load Shifting: The development of real-time regulation and load shifting strategies is essential for optimizing customer consumption and maintaining an efficient district heating system, benefiting both suppliers and consumers.

# 8 References


[1] H. Li and N. Nord, "Transition to the 4th generation district heating - possibilities, bottlenecks, and challenges," *Energy Procedia,* vol. 149, pp. 483-498, 2018/09/01/ 2018, doi: https://doi.org/10.1016/j.egypro.2018.08.213.

[2] S. Frederiksen and S. Werner, *District heating and cooling* (no. Book, Whole). Lund: Studentlitteratur AB (in English), 2013.

[3] H. Lund, B. Möller, B. V. Mathiesen, and A. Dyrelund, "The role of district heating in future renewable energy systems," *Energy,* vol. 35, no. 3, pp. 1381-1390, 2010/03/01/ 2010, doi: https://doi.org/10.1016/j.energy.2009.11.023.

[4] B. Rezaie and M. A. Rosen, "District heating and cooling: Review of technology and potential enhancements," *Applied Energy,* vol. 93, pp. 2-10, 2012/05/01/ 2012, doi: https://doi.org/10.1016/j.apenergy.2011.04.020.

[5] Anders Lindén, Kristofer Eriksson, and B. Sjöholm, "Metoder för att sänka effektbehovet vid fjärrvärme," Svenska Fjärrvärme AB, Rapport 2009:41, 2009, issue ISBN 978-91-7381-056-2. [Online]. Available: https://energiforskmedia.blob.core.windows.net/media/1231/metoder-att-saenka-effektbehovet-fjaerrsynsrapport-2009-41.pdf

[6] A. Marwan and N. Eema, "Project Report Within Course Sustainable Energy Systems (10 Credits), Dalarna University," in *Fjärrvärmesystem Optimering, För ett mer hållbart fjärrvärmesystem*, ed, 2023.

[7] A. Marwan and N. Eema, "Project Report Within Course Research Method (2.5 credits), Dalarna University," in *Fjärrvärmesystem Optimering, För ett mer hållbart fjärrvärmesystem*, ed, 2023.

[8] H. Ritchie. How have the world's energy sources changed over the last two centuries? [Online] Available: https://ourworldindata.org/global-energy-200-years

[9] D. Ürge-Vorsatz, L. F. Cabeza, S. Serrano, C. Barreneche, and K. Petrichenko, "Heating and cooling energy trends and drivers in buildings," *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 85-98, 2015/01/01/ 2015, doi: https://doi.org/10.1016/j.rser.2014.08.039.

[10] UN-DESA, "The Sustainable Development Goals Report 2022," United Nations publication issued by the Department of Economic and Social Affairs (DESA), http://www.un.org/publications, E.22.I.2, July 2022. [Online]. Available: https://unstats.un.org/sdgs/report/2022/

[11] C. Susanne and B. Carl, "Fjärrvärmen och miljön," Svenska Fjärrvärme AB, 2021. [Online]. Available: https://www.arvidsjaur.se/globalassets/fjarrvarmen_och_miljon.pdf

[12] R. Eva, "Article "Fjärrvärmens miljönytta"." [Online]. Available: https://www.energiforetagen.se/energifakta/fjarrvarme/fjarrvarmens-miljopaverkan/fjarrvarmens-miljonytta/

[13] M. Tunzi, R. Boukhanouf, H. Li, S. Svendsen, and A. Ianakiev, "Improving thermal performance of an existing UK district heat network: A case for temperature optimization," *Energy and Buildings,* vol. 158, pp. 1576-1585, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.enbuild.2017.11.049.

[14] D. Chinese, A. Meneghetti, and G. Nardin, "Waste-to-energy based greenhouse heating: exploring viability conditions through optimisation models," *Renewable Energy,* vol. 30, no. 10, pp. 1573-1586, 2005/08/01/ 2005, doi: https://doi.org/10.1016/j.renene.2004.11.008.

[15] H. Li and S. Svendsen, "Energy and exergy analysis of low temperature district heating network," *Energy,* vol. 45, no. 1, pp. 237-246, 2012/09/01/ 2012, doi: https://doi.org/10.1016/j.energy.2012.03.056.
[16] R. E. Klaassen and M. K. Patel, "District heating in the Netherlands today: A techno-economic assessment for NGCC-CHP (Natural Gas Combined Cycle combined heat and power)," *Energy,* vol. 54, pp. 63-73, 2013/06/01/ 2013, doi: https://doi.org/10.1016/j.energy.2013.02.034.
[17] A. Helge and W. Sven, "Framtida fjärrvärmeteknik," Energiforsk AB, 2017:419, August 2017 2017. [Online]. Available: https://energiforsk.se/program/futureheat/rapporter/framtida-fjarrvarmeteknik-2017-419/
[18] G. K. Pavlov and B. W. Olesen, "Building Thermal Energy Storage - Concepts and Applications," in *12th International Conference on Air Distribution in Rooms*, Trondheim, Norway, 19 June 2011 through 22 June 2011 2011. [Online]. Available: https://orbit.dtu.dk/en/publications/building-thermal-energy-storage-concepts-and-applications. [Online]. Available: https://orbit.dtu.dk/en/publications/building-thermal-energy-storage-concepts-and-applications
[19] X. Sheng and L. Duanmu, "Energy saving factors affecting analysis on district heating system with distributed variable frequency speed pumps," *Applied Thermal Engineering,* vol. 121, pp. 779-790, 2017/07/05/ 2017, doi: https://doi.org/10.1016/j.applthermaleng.2017.04.079.
[20] K. Nilsson, "Avkylningens ekonomiska inverkan på lönsamheten vid byte av fjärrvärmekundcentral," Civilingenjörsnivå, Civilingenjör Lunds Universitet - Lunds Tekniska Högskola, 0282-1990, 2015.
[21] P. Lauenburg and J. Wollerstrand, "Adaptive control of radiator systems for a lowest possible district heating return temperature," *Energy and Buildings,* vol. 72, pp. 132-140, 2014/04/01/ 2014, doi: https://doi.org/10.1016/j.enbuild.2013.12.011.
[22] S. Chicherin, A. Zhuikov, M. Kolosov, L. Junussova, M. Aliyarova, and A. Yelemanova, "Temperature and flow rates dynamics in a district heating (DH) network fed by a combined heat-and-power (CHP) plant," *Energy Reports,* vol. 7, pp. 327-333, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.egyr.2021.08.139.
[23] F. M. L. Di Lascio, A. Menapace, and M. Righetti, "Joint and conditional dependence modelling of peak district heating demand and outdoor temperature: a copula-based approach," (in English), *Statistical methods & applications,* vol. 29, no. 2, pp. 373-395, 2020, doi: 10.1007/s10260-019-00488-4.
[24] W. Birk, K. T. Atta, and F. Udén, "Improving District Heating System Operation through Control Configuration Selection and Adaptive Control," in *2019 18th European Control Conference (ECC)*, 25-28 June 2019 2019, pp. 2944-2949, doi: 10.23919/ECC.2019.8795742.
[25] Swedish-District-Heating-Association's-Substations-Group, *District Heating Substations "Design and Installation"* (Technical Regulations). www.svenskfjarrvarme.se: Energiföretagen Sverige – Swedenergy – AB, 2016.
[26] https://www.pngwing.com/en/free-png-bjaef/download (accessed.
[27] C. Johansson, F. Wernstedt, and P. Davidsson, "Deployment of agent based load control in district heating systems," in *First International Workshop on AgentTechnologies for Energy Systems, Canada*, 2010: Citeseer.
[28] Swedish-District-Heating-Association's-Substations-Group, *Värmemätare 'tekniska branschkrav och råd om mätarhantering'* (Technical Regulations). www.svenskfjarrvarme.se: Energiföretagen Sverige – Swedenergy – AB, 2008.

[29] S. Daniel, R. Bo, and G. Anders, *Lilla Prismodellboken* (Fjärrvärmens Affärsmodeller). www.fjarrvarmensaffarsmodeller.se: PR-Offset, Mölndal, 2012.
[30] J. Hellström, "Prisbildning på Svenska fjärrvärmemarknaden," Energimarknadsinspektionen. Hellström är professor vid Handelshögskolan vid Umeå Universitet., 2019.
[31] European-Parliament, "The promotion of cogeneration based on a useful heat demand in the internal energy market," in "European Parliament and of the Council, and amending Directive 92/42/EEC. L52/50.," Official Journal of the European Union, 2004. [Online]. Available: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:052:0050:0060:EN:PDF
[32] D. Bauer, R. Marx, J. Nubicker-Lux, F. Ochs, W. Heidemann, and H. Müller-Steinhagen, "German central solar heating plants with seasonal heat storage," *Solar Energy,* vol. 84, no. 4, pp. 612-623, 2010/04/01/ 2010, doi: https://doi.org/10.1016/j.solener.2009.05.013.
[33] M. Liu, S. Wang, Y. Zhao, H. Tang, and J. Yan, "Heat–power decoupling technologies for coal-fired CHP plants: Operation flexibility and thermodynamic performance," *Energy,* vol. 188, p. 116074, 2019/12/01/ 2019, doi: https://doi.org/10.1016/j.energy.2019.116074.
[34] X. Gou, Q. Chen, and K.-L. He, "Real-time quantification for dynamic heat storage characteristic of district heating system and its application in dispatch of integrated energy system," *Energy,* vol. 259, p. 124960, 2022/11/15/ 2022, doi: https://doi.org/10.1016/j.energy.2022.124960.
[35] W. Janusz and L. Patrick, "Adaptiv styrning av radiatorkretsar," Svensk Fjärrvärme AB, 2011. [Online]. Available: https://www.yumpu.com/sv/document/view/20278487/adaptiv-styrning-av-radiatorkretsarpdf-svensk-fjarrvarme
[36] H. Gadd and S. Werner, "Achieving low return temperatures from district heating substations," *Applied Energy,* vol. 136, pp. 59-67, 2014/12/31/ 2014, doi: https://doi.org/10.1016/j.apenergy.2014.09.022.
[37] T. Laajalehto, M. Kuosa, T. Mäkilä, M. Lampinen, and R. Lahdelma, "Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network," *Applied Thermal Engineering,* vol. 69, no. 1, pp. 86-95, 2014/08/01/ 2014, doi: https://doi.org/10.1016/j.applthermaleng.2014.04.041.
[38] C. Weissmann, T. Hong, and C.-A. Graubner, "Analysis of heating load diversity in German residential districts and implications for the application in district heating systems," *Energy and Buildings,* vol. 139, pp. 302-313, 2017/03/15/ 2017, doi: https://doi.org/10.1016/j.enbuild.2016.12.096.
[39] R. Wiltshire, *Advanced district heating and cooling (DHC) systems* (no. Book, Whole). Amsterdam: Elsevier (in English), 2016.
[40] N. Mirl, F. Schmid, and K. Spindler, "Reduction of the return temperature in district heating systems with an ammonia-water absorption heat pump," *Case Studies in Thermal Engineering,* vol. 12, pp. 817-822, 2018/09/01/ 2018, doi: https://doi.org/10.1016/j.csite.2018.10.010.
[41] I. del Hoyo Arce, S. Herrero López, S. López Perez, M. Rämä, K. Klobut, and J. A. Febres, "Models for fast modelling of district heating and cooling networks," *Renewable and Sustainable Energy Reviews,* vol. 82, pp. 1863-1873, 2018/02/01/ 2018, doi: https://doi.org/10.1016/j.rser.2017.06.109.
[42] J. Dancker and M. Wolter, "Improved quasi-steady-state power flow calculation for district heating systems: A coupled Newton-Raphson approach," *Applied Energy,* vol.

295, p. 116930, 2021/08/01/ 2021, doi: https://doi.org/10.1016/j.apenergy.2021.116930.
[43] S. Idowu, S. Saguna, C. Åhlund, and O. Schelén, "Applied machine learning: Forecasting heat load in district heating system," *Energy and Buildings,* vol. 133, pp. 478-488, 2016/12/01/ 2016, doi: https://doi.org/10.1016/j.enbuild.2016.09.068.
[44] A. Grant, *Doing Excellent Social Research with Documents : Practical Examples and Guidance for Qualitative Researchers (Edition 1)*, 1 ed. (no. Book, Whole). Milton: Routledge (in English U6 - eBook), 2018.
[45] E. Johansson, "Litteratursökning med exempel på sökdokumentation," ed. Umeå: Umeå universitet, 2015, p. 6.
[46] G. A. Bowen, "Document Analysis as a Qualitative Research Method," *Qualitative Research Journal,* vol. 9, no. 2, pp. 27-40, 2009, doi: 10.3316/QRJ0902027.
[47] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*. Wiley, 1996.
[48] *STATA 14*.
[49] SMHI. Ladda ner meteorologiska observationer [Online] Available: https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=airtemperatureInstant,stations=core
[50] Boverket. Sök och hämta energideklaration [Online] Available: https://www.boverket.se/sv/energideklaration/sok-energideklaration/
[51] C. Warfvinge and M. Dahlblom, *Projektering av VVS-installationer*, 1. uppl. ed. (no. Book, Whole). Lund: Studentlitteratur (in Swedish), 2010.
[52] *Vattenanvändning i hushåll*, ISSN 1403-1892, Energimyndighet, Online @www.energimyndigheten.se, 2012 2012. [Online]. Available: https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=104368
[53] L. Karin, E. Saga, and Anthesis, "Vinster med sänkta returtemperaturer i fjärrvärmesystem," Energimyndigheten, www.bebostad.se, 2019.
[54] B. K. Funkqvist, "Modellering och driftoptimering av laststyrning i fjärrvärmesystem," Civilingenjörsnivå, Civilingenjör Lunds Universitet - Lunds Tekniska Högskola, 0282-1990, 2020.
[55] E. Kjellsson, "Solvärme i bostäder med analys av kombinationen solfångare och bergvärmepump," Civilingenjörsnivå, Civilingenjör Byggnadsfysik LTH, Lunds Tekniska Högskola, 91-88722-32-5, 2004. [Online]. Available: https://portal.research.lu.se/sv/publications/solv%C3%A4rme-i-bost%C3%A4der-med-analys-av-kombinationen-solf%C3%A5ngare-och-be
[56] Z. Wang and T. Hong, "Learning occupants' indoor comfort temperature through a Bayesian inference approach for office buildings in United States," *Renewable and Sustainable Energy Reviews,* vol. 119, p. 109593, 2020/03/01/ 2020, doi: https://doi.org/10.1016/j.rser.2019.109593.
[57] ASHRAE-Standard, "Thermal environmental conditions for human occupancy," *ANSI/ASHRAE, 55-2017,* vol. 5, 1992.
[58] H. Anna, "Article "Storsatsning på sensorer ska minska energianvändning"." [Online]. Available: https://byggkoll.byggtjanst.se/artiklar/2023/februari/storsatsning-pa-sensorer-ska-minska-energianvandning/
[59] W. Li, J. Zhang, T. Zhao, and J. Ren, "Experimental study of an indoor temperature fuzzy control method for thermal comfort and energy saving using wristband device," *Building and Environment,* vol. 187, p. 107432, 2021/01/01/ 2021, doi: https://doi.org/10.1016/j.buildenv.2020.107432.

[60] T. Hoyt, E. Arens, and H. Zhang, "Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings," *Building and Environment,* vol. 88, pp. 89-96, 2015/06/01/ 2015, doi: https://doi.org/10.1016/j.buildenv.2014.09.010.

[61] Y. Ding, Y. Lyu, S. Lu, and R. Wang, "Load shifting potential assessment of building thermal storage performance for building design," *Energy,* vol. 243, p. 123036, 2022/03/15/ 2022, doi: https://doi.org/10.1016/j.energy.2021.123036.

[62] The-MathWorks-Inc., "Adaptive MPC Controller " in *MATLAB (R2023a)*, ed: The MathWorks Inc., 2023.

[63] S. Yang, M. P. Wan, W. Chen, B. F. Ng, and D. Zhai, "An adaptive robust model predictive control for indoor climate optimization and uncertainties handling in buildings," *Building and Environment,* vol. 163, p. 106326, 2019/10/01/ 2019, doi: https://doi.org/10.1016/j.buildenv.2019.106326.

# Appendices

Appendix 1 – Water Density and Specific Heat Capacity Graphs from Incropera and DeWitt (1996).

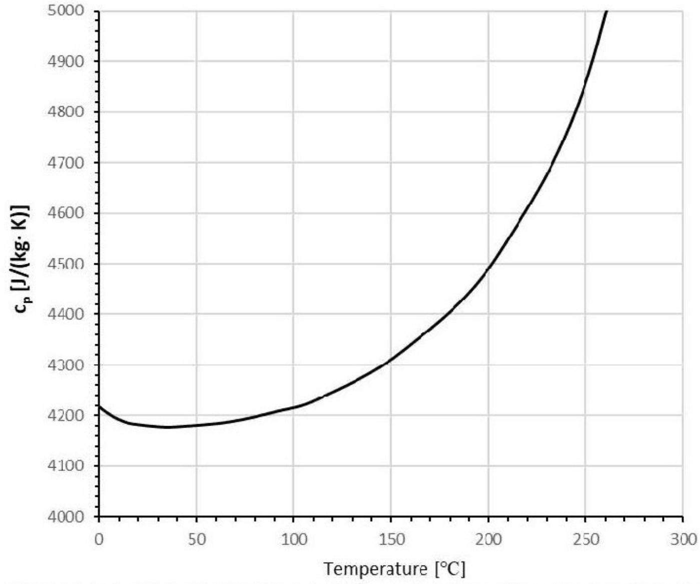



Figure 4. Specific heat capacity of water as a function of temperature from Incropera and DeWitt (1996).

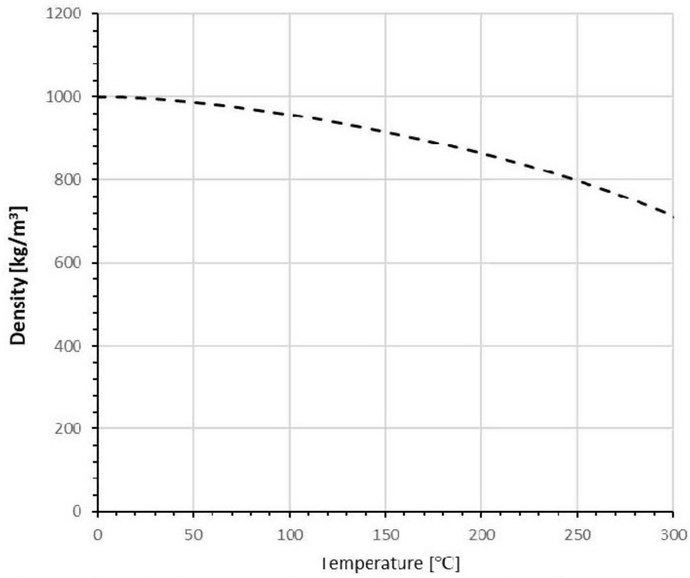



Figure 5. Density of water as a function of temperature from Incropera and DeWitt (1996).