UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Escuela Técnica Superior de Ingeniería Industrial

Development and numerical analysis of two different advanced control strategies for a cold district heating network.

Trabajo Fin de Máster

Máster Universitario en Ingeniería Industrial-Màster Universitari en Enginyeria Industrial

AUTOR: Ros Martín, Alberto

Tutores: Bracho León, Gabriela Cristina; Karunvigal, Rahul, Müller, Dirk

CURSO ACADÉMICO: 2023/2024

MA 552

Master’s Thesis

Development and numerical analysis of two different advanced control strategies for a cold district heating network

Aachen, November 2023

Alberto Ros
Matriculation number: 449439

Supervisors:
Rahul Mohandasan Karuvingal
Univ.-Prof. Dr.-Ing. Dirk Müller

The present work was submitted to the:
E.ON Energy Research Center | ERC
Institute for Energy Efficient Buildings and Indoor Climate | EBC
Mathieustrasse 10, 52074 Aachen, Germany

Abstract

Over the last few years, the world's awareness of environmental issues and pollution has been increasing, to the point of developing new sustainable development and energy-saving techniques to reduce the impact of greenhouse gases and CO2 footprint. One of these techniques is the cold heating networks, particularly the 5th generation, which is the latest development. Some of the main improvements of this technology is to be able to use waste heat from different buildings and industries in the same area to heat or cool the water supply of different buildings or to use low-temperature networks to have the lowest heat demand in the water transport process. This system, being more complex than those previously developed, such as the 4th generation. It requires advanced control systems in order to make the whole system works efficiently by meeting energy demand of each building. This project is based on determining advanced control systems that are best suitable to install in a residential neighbourhood under construction.

First of all a literature review has been carried out on 5th generation district heating and cooling, where different possible control strategies to control the different variables involved in the network, such as temperature, pressure and mass flow have been determined and also compared with the 4th generation district heating. Secondly, possible configurations of advanced control strategies based on the literature review have been established. Out of these configurations two different control strategies, that are best suited for the given district, have been identified. These configurations integrate commercially available elements, including sensors, with a clear determination of their intended measurements and strategic placement. Two different thermo-hydraulic simulations have been carried out in Modelica for the construction phase one of the district. It includes four multifamily buildings and a centralized supply station. Thirdly and finally these two selected configurations have been analysed based on the simulations results. Detailed analysis based on the key parameters derived from the thermo-hydraulic simulations have been carried out and conclusions regarding the operation of the system, its robustness and design have been drawn.

The main objective of this thesis is not the optimization of the implemented control system but rather to draw conclusions about the relationship of the implemented control blocks and the variables to be controlled, as well as to identify possible improvement opportunities for future designs.

Zusammenfassung

In den letzten Jahren ist das Bewusstsein für Umweltfragen und Umweltverschmutzung weltweit gestiegen und hat zur Entwicklung neuer nachhaltiger Entwicklungs- und Energiespartechniken geführt, um die Auswirkungen von Treibhausgasen und den CO2-Fußabdruck zu verringern. Eine dieser Techniken sind die kalten Heiznetze, insbesondere die 5. Generation, die die neueste Entwicklung darstellt. Einige der wichtigsten Verbesserungen dieser Technologie bestehen darin, dass die Abwärme verschiedener Gebäude und Industrien im selben Gebiet zum Heizen oder Kühlen der Wasserversorgung verschiedener Gebäude genutzt werden kann oder dass Niedertemperaturnetze verwendet werden, um den geringsten Wärmebedarf beim Wassertransport zu haben. den geringsten Wärmebedarf im Wassertransportprozess zu haben. Dieses System ist komplexer als die zuvor entwickelten Systeme, wie das der 4. Es erfordert fortschrittliche Kontrollsysteme, damit das gesamte System effizient arbeitet und den Energiebedarf der einzelnen Gebäude deckt. Dieses Projekt basiert auf der Bestimmung fortschrittlicher Kontrollsysteme, die sich am besten für die Installation in einem im Bau befindlichen Wohnviertel eignen.

Zunächst wurde eine Literaturrecherche über Fernwärme und -kühlung der 5. Generation durchgeführt, bei der verschiedene mögliche Regelungsstrategien zur Steuerung der verschiedenen am Netz beteiligten Variablen wie Temperatur, Druck und Massenstrom ermittelt und auch mit der mit der Fernwärme der 4. Generation verglichen. Zweitens wurden auf der Grundlage der Literaturrecherche mögliche Konfigurationen für fortschrittliche Regelungsstrategien festgelegt. Aus diesen Konfigurationen wurden zwei verschiedene Regelungsstrategien ermittelt, die für das jeweilige Gebiet am besten geeignet sind. In diese Konfigurationen wurden handelsübliche Elemente, einschließlich Sensoren, integriert, wobei die beabsichtigten Messungen und die strategische Platzierung klar festgelegt wurden. Zwei verschiedene thermohydraulische Simulationen wurden in Modelica für die erste Bauphase des Viertels durchgeführt. Sie umfasst vier Mehrfamilienhäuser und eine zentrale Versorgungsstation. Drittens und letztens wurden diese beiden ausgewählten Konfigurationen auf der Grundlage der Simulationsergebnisse analysiert. Auf der Grundlage der aus den thermohydraulischen Simulationen abgeleiteten Schlüsselparameter wurden detaillierte Analysen durchgeführt und Schlussfolgerungen in Bezug auf den Betrieb des Systems, seine Robustheit und Auslegung gezogen.

Das Hauptziel dieser Arbeit ist nicht die Optimierung des implementierten Regelsystems, sondern vielmehr Rückschlüsse auf den Zusammenhang zwischen den implementierten Regelblöcken und den zu regelnden Größen zu ziehen, sowie mögliche Verbesserungsmöglichkeiten für zukünftige Entwürfe aufzuzeigen.

Table of Contents

Nomenclature

Symbols and units

Symbol	Meaning	Unit
c_p	Specific heat capacity at constant pressure	J/(kgK)
C	Heat capacity	$\mathrm{W\,kg^{-1}}$
E	Energy	J
$\dot{m}$	Mass flow	$\mathrm{kg\,s^{-1}}$
p	Pressure	Pa
$\dot{Q}$	Heat flow	W
T	Temperature	K
t	Time	s
h	Heat transfer coefficient	$\mathrm{W/(m^2K)}$
V	Volume	$\mathrm{m^3}$

Greek formula symbols

Symbol	Meaning	Unit
Δt	Temperature difference	K

Indices and abbreviations

Symbol	Meaning
CHP	Combined Heat Power
MSL	Modelica Standard Library
PCM	Phase change material
TES	Thermal energy storage
ATES	Aquifer thermal energy storage
BTES	Barehole thermal energy storage

Continued on next page

Indices and abbreviations

Symbol	Meaning
STES	Seasonal hermal energy storage
DHW	Domestic hot water
eff	Effective
1GDH	First Generation District Heating
2GDH	Second Generation District Heating
3GDH	Third Generation District Heating
4GDH	Forth Generation District Heating
5HDHC	Fifth Generation District Heating and Cooling
TS	Temperature sensor
FRS	Flow rate sensor
BTS	Bottom temperature sensor
TTS	Top temperature sensor
RTD	Resistance temperature detector
L	Litres

List of Figures

List of Tables

1 Introduction

When the first major international environmental conference was held in Stockholm in 1972 [1], the world began to become aware of the impact of human beings on the environment, and thus of the possible repercussions.

Since then, the environmental issue has been brought into the public spotlight and has become increasingly important over the years, leading to the development of new technologies and technologies that are more and more environmentally friendly, such as the generation of both thermal and electrical energy through renewable energies, the use of electric cars, and smaller-scale actions such as recycling.

In recent years, pollution and concern for preserving the environment has been on the rise, and with it the reduction of man's impact on it. This has led the world to wage a war against the pollution generated by the human race over the last few years, trying to fix the problem we ourselves created.

In 2015 the United Nations General Assembly established Agenda 2030 as a sustainable development action plan with 169 targets covering the three dimensions of sustainability: economic, social and environmental [2]. This action plan is composed of 17 Sustainable Development Goals (SDGs) that aim to eradicate poverty, protect the planet and improve the lives and prospects of all people, everywhere.

Another important environmental agreement is the Paris Agreement, which was adopted in December 2015 at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris, France. The main objective of the Paris Agreement is to combat climate change and limit the global temperature increase to levels below 2 degrees Celsius above pre-industrial levels, and to make efforts to limit the temperature increase to 1.5 degrees Celsius [3].

One of the most widely used processes in recent years to meet the goals of both the 2030 Agenda and the Paris Agreement is decarbonisation, which is a process that seeks to reduce or eliminate the emission of greenhouse gases, especially carbon dioxide, in energy production and consumption. In order to carry out this decarbonisation, some measures have been implemented over the years, such as: increasing the energy efficiency of the technologies used, the implementation of renewable energies, the substitution of fossil fuels by electric energy, reforestation or sustainable mobility.

The aim of this thesis is to develop control systems to regulate the operation of a low-temperature grid in order to harness the energy from the grid.

1.1 What is district and heating and cooling

District Heating and cooling are systems for distributing heat or cold generated in a centralized location through a system of insulated pipes for residential, commercial, or industrial heating and cooling requirements. These systems are also known as district energy systems or teleheating [4][5]. Heating and district cooling function similarly to district heating, but instead of supplying hot water, they supply chilled water to buildings that require cooling. [4][6].

District heating and cooling (DHC) is a system for distributing heat or cold generated in a centralized location through a system of insulated pipes for residential, commercial, or industrial heating and cooling requirements. DHC systems can provide space heating, space cooling, process heating, process cooling, and/or domestic hot water through a central piping network [7]. DHC systems use a central plant to produce steam, hot water, or chilled water distributed through a network of pipes to a group of buildings [8]. DHC is a modern, efficient way to air condition a network of buildings in cities or campuses, and it creates an economy of scale that drives efficiency, balances electric loads, and reduces fuel costs[9][10].

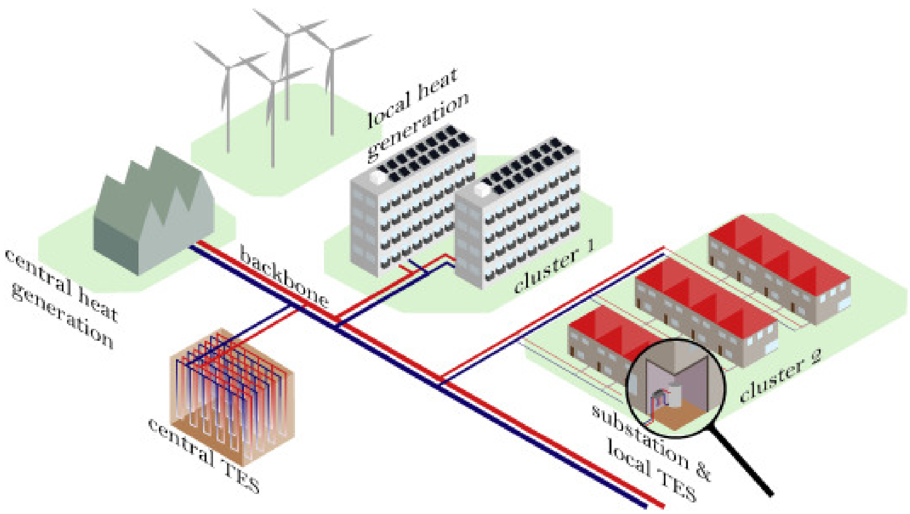

Figure 1.1: Example of District heating and cooling[11]

The 5th generation of district heating and cooling (5GDHC) is a fundamentally new concept based on a decentralized network allowing direct energy flows among and within buildings, not requiring a central heat plant[10]. Its key features are a low energy grid utilizing low temperature heat sources, closed thermal energy loops ensuring hot and cold exchange among clusters of buildings, and integration and synergy between thermal and electricity grids[10].

1.2 The evolution of District Heating and Cooling (DHC) over the years and its classification

District heating has a history dating back to Roman times, with the use of hypocausts - hot-air furnaces which were adapted to warm multiple buildings in close proximity [12]. For instance, the three temples at Carnutum (Vienna) were heated using this technology. During the Renaissance, the hypocaust and other Roman advancements were reintroduced and served as a foundation for further improvements.

The first modern district heating system was implemented in Lockport, New York in 1877, where steam was delivered to two stores and a number of houses[13].

In the 1930s, the United States saw the implementation of its first district cooling system in downtown Denver, Colorado [13]. This system involved distributing ice produced in a central plant to buildings via a network of pipes. Notably, the country's first large-scale district cooling system was established in 1955 in downtown Houston, Texas [14], utilizing chilled water from a central plant that was also distributed through a network of pipes to buildings. This was the first generation of district heating and cooling (1GDH).

This type of technology has been evolving over the years until today, where fourth-generation systems (4GDH) are already established and fifth-generation (5GDHC) systems are starting to be implemented.

The district heating and cooling systems go from the first generation (1GDH) to the fifth generation (5GDHC) whose features will be explained in the following paragraphs.

1.2.1 Classification of different generations of the district heating and cooling networks

First generation (1GDH: 1880s – 1930s): District heating systems were first established in the USA with steam as the primary energy carrier. The aim was to replace individual heating, which was considered to be extremely harmful at the time. However, the high temperature of the steam (over 200°C) caused critical explosions that led to the deaths of numerous pedestrians. Additionally, operating conditions often resulted in corrosion in the return network, causing rapid flow drop and decreasing overall efficiency. Though some cities were able to convert these systems, only New York and Paris still use them today.

Second generation (2GDH: 1930s – 1980s): Due to safety concerns, hot water exceeding 100°C is now used instead of steam as an energy source in some applications.

These systems were first developed in the Soviet Union and employed components like water pipes in concrete ducts, large tube and shell heat exchangers, and heavy valves due to the high temperatures involved. The main objective of district heating is to enhance fuel efficiency and provide better household comfort through the use of combined heat and power (CHP).

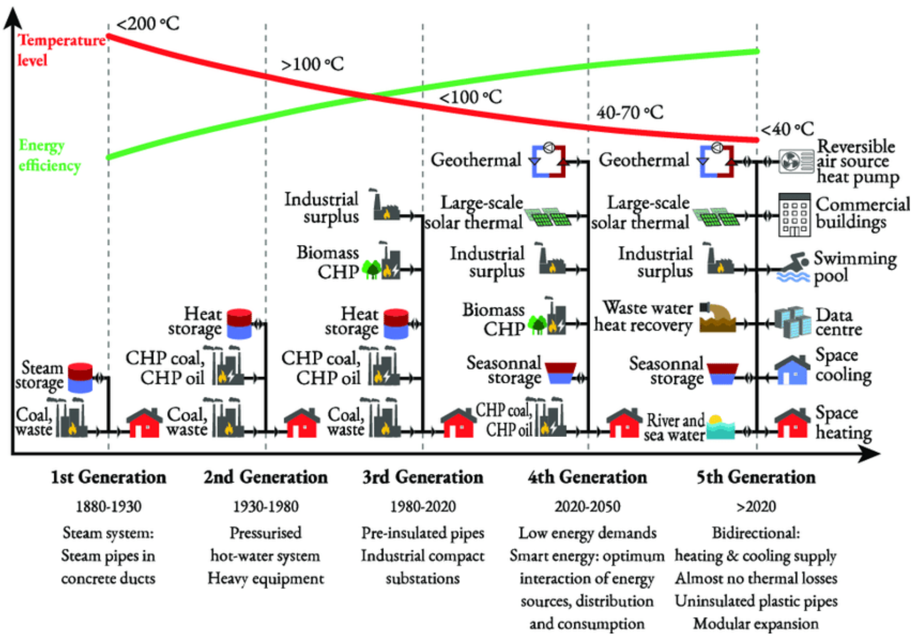

Figure 1.2: Evolution of the different generations of DHC over the years [15]

Third generation (3GDH: 1970s – 2020s): The production process in question follows a traditional centralized approach, where pressurized water acts as the primary energy carrier. However, the process has undergone changes, and now the supply temperature is less than 100°C, while the return temperature ranges between 40-50°C.

The technology for underground district heating systems has been rapidly advancing in Northern Europe, with Denmark and Sweden at the forefront. The components are usually prefabricated and the pipes are pre-insulated, before being directly buried in the ground. Centralized thermal storage for heat is also involved in the process, as well as a plate steel heat exchanger in the substation.

The third generation of technology is currently the most widely used worldwide, not only in Europe but also in China, Korea, Canada, and the USA. Although policies and regulations may vary from country to country, the primary use of the 3rd generation is to ensure a secure supply amidst oil crises and the increasing demand for efficient use of CHP.

Fourth generation (4GDH: 2020s – 2050): The future of district heating is heading towards the concept of a smart thermal grid. This means that the infrastructure network will need to evolve towards a low-temperature network, supplying heat at 50-60°C and returning at around 25-15°C. The aim is to increase the overall efficiency. This will also allow for a higher level of renewable integration, as well as the opportunity to increase the use of assembly-oriented components and more flexible pipe materials, making the system more adaptable.

The residential sector is currently integrating advanced cooling systems, including centralized cooling storage and smart digital tools. This integration will enable a comprehensive view of heating and cooling demands. The new concept also allows for more flexibility in integrating decentralized energy production sites. However, this will not affect the traditional role of final consumers. Furthermore, these technologies will enhance the optimization of operation and maintenance processes, thereby improving the overall efficiency of the system.

Fifth generation (5GDHC: >2020): In the coming years, we can expect significant changes in both the network and consumer behavior. The heating and cooling network will likely undergo a transformation, moving away from traditional topologies and towards a decentralized model. This new model will involve plants of varying sizes and technologies, primarily heat pumps, which will supply heat via ultra-low temperature headers in the network.

The supply temperature in a 5GDHC system will be kept below 45°C, while the return temperature should be around 25-15°C. Some smaller systems may also include ambient loops. 5GDHC systems are typically composed of un-insulated plastic pipework which results in minimal heat losses and longer pipe runs. Such systems often incorporate seasonal thermal storage to balance the spine temperatures and may also include short-term localized thermal storage.

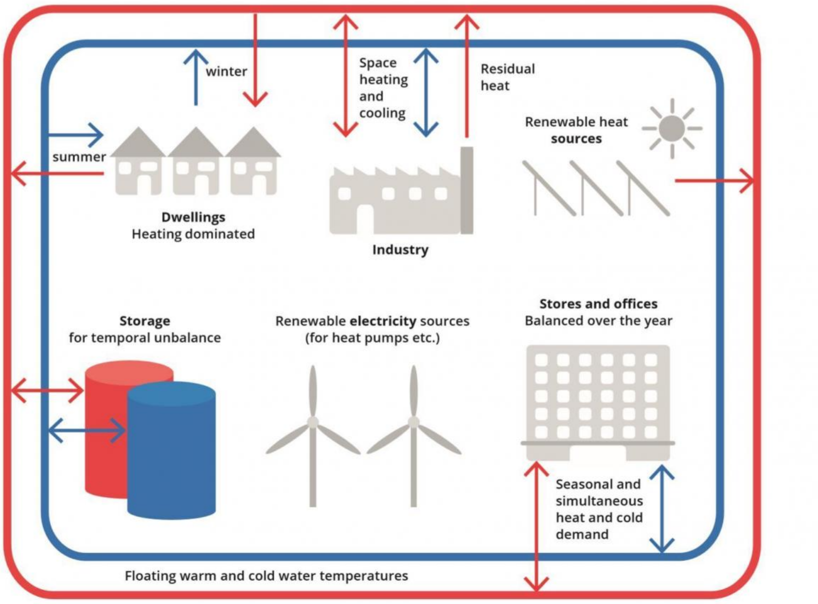

Figure 1.3: 5GDHC example[4]

This technology comes with a built-in cooling system that allows for the exchange of heating or cooling between buildings. Unlike other systems, this network can easily expand as the city grows and can integrate battery storage systems, which improves overall efficiency and helps manage demand while ensuring high use of renewable energy. It is an ideal solution for both heating and cooling needs.

2 Research of DHC control straregies

In this chapter, various control techniques for district heating and cooling will be explored. Control strategies play a crucial role in ensuring the efficient and reliable operation of these systems. They help to keep costs down, promote sustainability, and enhance user satisfaction. By enabling district heating and cooling systems to adapt to changing conditions, control strategies maximize energy utilization and minimize environmental impacts.

2.1 What are the different control strategies in conventional (3rd, and 4th gen)DHC?

2.1.1 Tempertature control

Temperature control is an important aspect of 4th Generation District Heating and Cooling (4GDHC) systems [16]. The control of temperature in 4GDHC systems is typically achieved by using temperature sensors and flow controllers to regulate the temperature of the water or other fluids that circulate within the system. Having precise control over the temperature of the heating or cooling supply can greatly enhance the efficiency of the entire system. Sometimes, 4GDHC systems employ centralized control methods that allow for the transfer of low-temperature energy between buildings. This kind of energy is sourced from low-temperature heat found in the environment or waste heat and can be utilized for both heating and cooling. Overall, temperature control is a crucial factor in the success of 4GDHC systems, as it ensures that the heating or cooling supply is delivered to buildings at the appropriate temperature to meet their needs. Proper temperature control, which refers to the ability to manage the temperature of the system effectively to provide efficient heating and cooling, in 4GDHC is crucial to ensure the efficient and reliable operation of the system. The following are some best practices for temperature control in 4GDHC:

1. Low-temperature supply: 4GDHC systems typically use low-temperature heat sources, so the supply temperature should be kept as low as possible for reducing heat losses while still meeting the heating and cooling demand.

2. Centralized control strategy: A centralized control room should be set up to monitor and control the temperature of the heat transfer fluid. Advanced control algorithms such as model-based predictive control (MPC) can be used to adjust the flow rate and

temperature of the heat transfer fluid in real-time to maintain a constant supply temperature.

3. Thermal energy storage: One useful application of Thermal Energy Storage (TES) is its ability to store excess heat or cold, which can then be released during times of high demand. This process helps to even out peak loads and increase the overall efficiency of the system.

4. Decentralized control: Decentralized control strategies can be employed by installing local controllers at each building or substation to control the supply temperature to the building. This can allow for more precise temperature control and improve the system's overall efficiency.

5. Hydronic balancing: It ensures that the flow of water in the system is distributed evenly throughout the network so that all units receive the same amount of water flow and operate at a consistent temperature. This control can help ensure that each building receives the proper supply temperature, which can improve the system's overall efficiency.

2.1.2 Load management

Load management control is a method used to regulate the heating and cooling supply to buildings based on their specific needs. Its objective is to optimize the use of energy supply, lessen energy consumption and enhance the overall effectiveness of the system. Load management can be achieved through various strategies such as the use of a centralized control system, decentralized control systems and thermal energy storage (TES) [17][18].

1. A centralized control system can monitor and adjust the flow rate and temperature of the heat transfer fluid in real time to meet the changing demand for heating and cooling. These systems involve a centralized control centre that monitors the demand for heat or cooling throughout the network and adjusts the production and distribution accordingly. In the case of load management, the control centre can adjust the production and distribution of heat or cooling to match the current demand, in order to avoid overloading the network.

2. In 4GDHC networks, decentralized control systems usually incorporate smart grids and control mechanisms that enable real-time optimization of the network. This type of control can also be installed at each building or substation to control the supply temperature to the building.

These systems can monitor the demand for heat or cooling and adjust production and distribution accordingly. This can help to minimize energy waste and improve the efficiency of the system. One example is the use of heat pumps, that can be installed in buildings throughout the network, allowing them to produce heat or cooling on a local level. A smart control system can then monitor the demand and adjust production accordingly.

3. Thermal Energy Storage (TES) can help to flatten out peak loads by storing excess heat or coolness during periods of low demand and releasing it during periods of high demand. Demand-side management can also help to reduce peak demand for heating and cooling by adjusting the temperature settings of the building or delaying non-critical tasks, like laundry, to off-peak hours when energy demand is lower. Other load management strategies include hydronic balancing and thermal storage integration.

2.1.3 Storage management

Thermal energy storage can be used in to store excess heat or cold during periods of low demand, and then release the stored energy during periods of high demand [19]. This can help to reduce the amount of energy required to meet peak demand and can improve the overall efficiency of the system. Peak demand refers to the period when there is a high demand for heating or cooling within the district heating and cooling network. This is often a short-term period of intense energy usage, and it can put a strain on the energy system and increase the risk of power outages or other issues [20]. Some types of energy storage are:

1. Thermal Energy Storage (TES): TES systems store excess thermal energy in the form of hot or cold water, which can be used later to meet heating or cooling demands. TES can be achieved through different methods such as sensible heat storage (using the temperature difference) or latent heat storage (using phase change materials).

2. Aquifer Thermal Energy Storage (ATES): ATES utilizes underground aquifers, which are natural underground layers of permeable rock or sediment that can contain or transmit groundwater, to store thermal energy. Groundwater within an aquifer can flow through fractures in rocks or permeable sediment. This groundwater can be extracted from the aquifer by drilling wells. During periods of excessive heat or cold, water is injected into the aquifer, which acts as a large thermal storage reservoir. The stored energy can be recovered when needed by extracting water from the aquifer and using it for heating or cooling.

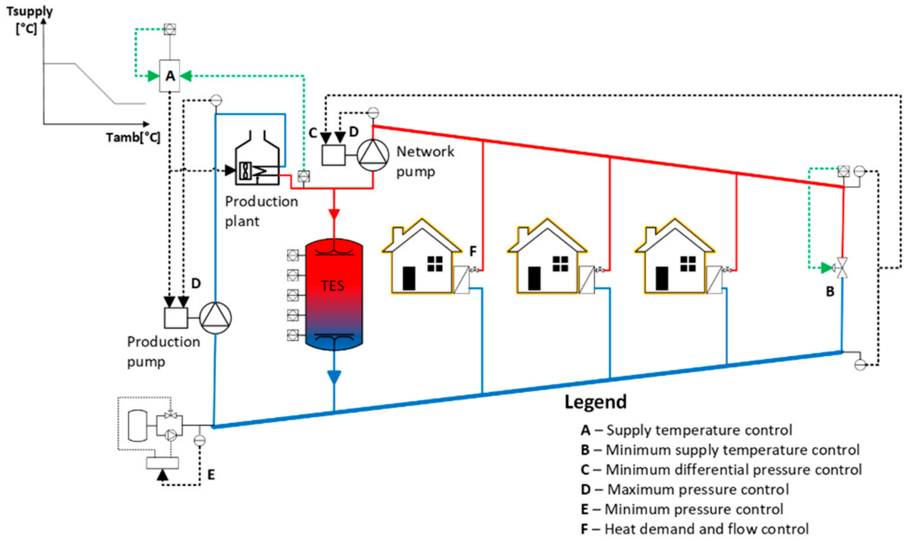

Figure 2.1: Example of a heating network with TES [21]

3. Seasonal Thermal Energy Storage (STES): STES is a long-term energy storage method that involves storing thermal energy across seasons. It typically uses large underground storage tanks or rock caverns to store hot or cold water for several months. The stored energy is then extracted as needed to provide heating or cooling throughout the year.

4. Battery Energy Storage Systems (BESS): Although not as common because they are not well-suited for storing large amounts of thermal energy, which is the primary form of energy used in district heating and cooling systems. Battery storage can play a role in managing peak electricity demands. BESS stores electrical energy in rechargeable batteries and can provide a rapid response to fluctuations in electricity supply and demand.

Another way energy storage can help reduce energy consumption is by increasing the efficiency of energy production and distribution. For example, energy storage can make it possible to store excess renewable energy from sources like wind or solar power and release it during periods when these sources are not available, reducing the need for additional fossil fuel-powered generation. Energy storage can help to manage peak demand by storing excess energy during periods of low demand and releasing it during peak demand to reduce the need for additional energy generation. By using these strategies to manage peak demand, the energy system can operate more efficiently, reducing the amount of energy required while improving system performance and reliability [22][23]. Additionally, energy storage can help balance the energy supply and demand, ensuring that energy is available when it is needed and avoiding energy waste or shortages. Therefore, energy storage plays a key role in ensuring that the energy system in 4GDHC operates effectively and efficiently. Thermal energy storage can take many forms, including water tanks, underground thermal energy storage (UTES) systems, phase change materials (PCMs), and others. Each type of storage has its advantages and disadvantages, and the optimal storage solution will depend on the specific requirements and characteristics of the 4GDHC system.

Advantages	**Disadvantages**
Energy optimization	Capital costs
Flexibility and reliability	Space requirements.
Load levelling	Efficiency losses
Demand response	Environmental impact

Table 2.1: Advantages and disadvantages of using energy storage in 4GDHC

Advantages of storage management in 4GDHC

1. Energy optimization: Storage management allows for the optimization of energy supply and demand by storing excess energy during off-peak periods and releasing it during peak demand, thereby reducing energy waste and improving overall system efficiency.

2. Flexibility and reliability: Storage systems provide flexibility in the operation of 4GDHC networks. They enable the integration of various energy sources, such as renewable energy, waste heat, and surplus electricity, making the system more resilient and reliable.

3. Load levelling: By storing excess heat or cold, storage management helps to balance the load across different periods, mitigating the challenges of intermittent energy sources and ensuring a stable supply of heating and cooling to consumers.

4. Demand response: Storage management enables participation in demand response programs. Adjusting the release of stored energy based on grid conditions and pricing signals facilitates grid stability and can help reduce peak loads during high-demand periods.

Disadvantages of storage management in 4GDHC

1. Capital costs: Implementing storage systems can involve significant upfront capital costs, including the installation and maintenance of storage infrastructure. The cost-effectiveness of storage management depends on factors such as the size of the system, the energy storage technologies used, and the local energy market conditions.

2. Space requirements: Large-scale storage systems, especially those based on physical storage media like water tanks or underground reservoirs, require adequate space for installation. Limited space availability in urban areas can pose challenges for the deployment

of storage systems.

3. Efficiency losses: Energy storage systems are not 100% efficient, meaning there will be some losses during the charging and discharging processes. These losses can impact the overall system efficiency and should be considered when evaluating the cost-effectiveness of storage management.

2.2 Different control strategies in 5GDHC

Various control strategies can be used in 5th-generation district heating and cooling (5GDHC) systems [15], depending on factors such as the specific network design and the goals of the system. Here are some examples of different control strategies used in 5GDHC systems:

1. Temperature control: A temperature control strategy involves regulating the temperature of the heating and cooling water to improve system efficiency and reduce energy consumption. This can involve adjusting the temperature based on the outside temperature, the time of day, or user demand.

2. Flow rate control: Flow rate control involves adjusting the flow rate of the heating and cooling water to balance supply and demand among different buildings. This can involve using sensors to measure flow rates and regulate the system accordingly.

3. Pressure control: Regulating pressure can help to balance the heating and cooling loads among different buildings and ensure that the system operates efficiently. This can involve using pressure sensors and control valves to adjust system pressure as needed.

Overall, these control strategies can be combined and customized to suit the specific needs of a 5GDHC system and new strategies are continually being developed and refined to improve system performance and efficiency.

2.3 Deeper research on 5GDHC

2.3.1 Temprerature control

In fifth-generation district heating and cooling (5GDHC) networks [24], temperature control is crucial to ensure efficient and sustainable operation. The supply and return temperatures in 5GDHC systems are typically lower than those in fourth-generation systems, which helps to reduce heat losses from the grid and increase overall efficiency.

Various temperature control strategies can be used in 5GDHC systems, including:

1. Demand-driven temperature control: This involves adjusting the supply temperature based on the actual demand from connected buildings [25]. This can be achieved using smart control systems that incorporate real-time data on energy demand and weather conditions.

Smart control systems are capable of adjusting the temperature of thermal energy supplied to buildings according to their specific heating or cooling needs. This is achieved by regulating the temperature of water or brine in the network based on real-time demand signals. Such an approach helps to optimize energy usage and minimize waste by providing buildings with only the necessary amount of energy at any given moment.

2. Decentralized temperature control: With this method, every building has its temperature control system that can communicate with the central grid to request a desired temperature. This allows each building or group of buildings to independently manage their temperature within predetermined limits [26].

The utilization of decentralized temperature control has proven to be extremely beneficial for 5GDHC systems that rely on low-grade renewable heat sources. This feature enables the efficient utilization of energy while optimizing the use of waste heat from industries or other sources. This optimization leads to a substantial reduction of carbon emissions and supports sustainability goals.

3. Set-point temperature control: This involves setting a fixed temperature for the supply heat or cold, which can be adjusted based on the needs of the connected buildings.

This type of control allows the temperature to be adjusted at a central location, such as a district heating plant, to maintain a specific setpoint temperature.

However, set-point temperature control may not be the most efficient option for 5GDHC systems as it could lead to energy waste if the temperature delivered to each building does not match its heating or cooling needs. In contrast, decentralized temperature control provides individual buildings with the exact amount of energy they need based on real-time demand signals, which can help optimize energy consumption and reduce waste.

4. Feed-forward temperature control: This approach involves using data on external factors such as weather conditions or occupancy levels to predict energy demand and adjust the supply temperature accordingly [4]. This control system uses real-time data on building

heat demand to adjust the temperature of the thermal energy delivered to each building, optimizing energy use and reducing waste.

In a feed-forward temperature control system, data on outside air temperature, solar radiation, and other factors that affect building heat demand are used to determine the optimal amount of thermal energy to deliver to each building in real time. This helps to ensure that each building receives the exact amount of energy it needs at any given time, minimizing waste and maximizing efficiency.

5. Model predictive temperature control: Using models based on past data, this approach predicts energy demand and adjusts the supply temperature accordingly in real-time.

This control system uses mathematical models of the thermal behaviour of individual buildings and data on real-time demand signals to adjust the temperature of the thermal energy delivered to each building, optimizing energy use and minimizing waste [27].

A temperature control system that utilizes predictive modelling employs optimization algorithms to anticipate a building's future heat demand using current data. This enables the system to regulate the thermal energy delivered to each building more effectively. This helps to ensure that each building receives the optimal amount of energy it needs at any given time, reducing waste and maximizing efficiency.

The most used sensors in this field are:

Thermocouples - These sensors use two wires made of different metals that generate a voltage proportional to the temperature difference between the wires.

Resistance temperature detectors (RTDs) - These sensors measure changes in resistance as a function of temperature and are often made from metals such as platinum, nickel, or copper.

Thermistors - These are temperature-sensitive resistors that change resistance in response to temperature changes.

Infrared sensors - These sensors measure temperature by detecting infrared radiation emitted by an object.

2.3.2 Pressure control

When it comes to fifth-generation district heating and cooling (5GDHC) networks [28], pressure control is a crucial aspect of the overall control strategy. By regulating flow rates and maintaining sufficient pressure levels, heat transfer efficiency throughout the network can be ensured.

As water pressure increases, so does its velocity, leading to heightened fluid turbulence and convection that ultimately result in greater heat loss. The relationship between mass flow and pressure is expressed as $\dot{m} = \rho A v$ and shows that boosting pressure also increases mass flow, further elevating heat losses.

Some common pressure control strategies in 5GDHC systems include:

1. Setting pressure limits: This involves setting upper and lower pressure limits for the network, beyond which the control system will take action to maintain the desired pressure [4].

The pressure limits must be set based on the specific design and operating conditions of the network to prevent pipe damage or leakage that can lead to energy waste and safety hazards. Hydraulic modelling and simulations are usually performed to determine the flow rates and pressure drops at various points within the network for setting pressure limits. This can help identify the optimal pipe sizes, pump locations, and operating conditions needed to maintain a safe pressure range throughout the network.

2. Variable-speed pumps: By adjusting the speed of pumps within the network, pressure can be controlled in real-time to maintain the desired flow rate and heat transfer efficiency. Variable-speed pumps can deliver the exact amount of thermal energy needed to each building, minimizing waste and optimizing energy use. In addition, these pumps can help maintain safe pressure levels within the network by adjusting the flow rate as needed, thereby reducing the risk of pipe damage or leakage [29].

3. Pressure-drop control valves: These valves are used to adjust the pressure within specific sections of the network, allowing for precise control overflow rates and heat transfer efficiency.

These valves are typically installed at various points throughout the network to regulate the pressure drop across each component, including heat exchangers, pumps, and valves [29]. By adjusting the pressure drop across each component, pressure-drop control valves can help ensure that the network operates within safe pressure limits and reduce the risk of pipe damage or leakage. In addition, these valves can optimize the flow rate of thermal energy within the network, reducing energy waste and improving overall efficiency.

4. Smart control systems: Advanced control systems using artificial intelligence and machine learning algorithms can monitor pressure within the network and make adjustments

to maintain optimal flow rates and heat transfer efficiency.

Including pressure drop control valves, variable speed pumps, and model predictive temperature control. These systems work together with real-time demand signals and data monitoring to adjust the pressure and flow of thermal energy delivered to each building, minimizing waste and improving overall system efficiency [30]. In addition, digital control systems can be used to remotely monitor and manage the pressure levels within the network, enabling operators to act if the pressure exceeds safe limits. For example, the use of wireless sensors can allow for real-time monitoring of pressure and flow conditions, enabling operators to quickly and efficiently respond to any issues that arise.

2.3.3 Flow rate control

In fifth-generation district heating and cooling (5GDHC) systems [31][32] , flow rate control is critical to ensuring efficient and sustainable operation. The flow rate of the thermal fluid through the network affects the heat transfer efficiency and energy consumption. Since heat losses can be expressed as the following equation $\dot{Q} = \dot{m}Cp\Delta T$, an increase in flow rate or mass flow will also increase heat losses.

Some common flow rate control strategies in 5GDHC systems include:

1. Flow control valves: These valves are used to adjust the flow rate within specific sections of the network, allowing for precise control of overheat transfer efficiency and energy consumption. These valves can be installed at various points throughout the network, including heat exchangers, pumps, and other components [29].

Flow control valves play a crucial role in managing the flow of thermal energy across different components. Their primary function is to maintain safe pressure levels within a network, thereby minimizing the chances of pipe damage or leakage. Moreover, these valves are instrumental in optimizing the flow rate of thermal energy throughout the system, leading to reduced energy wastage and enhanced overall efficiency.

2. Smart control systems: Sophisticated control systems equipped with AI and machine learning algorithms can oversee the flow rate in a network and regulate it to ensure maximum heat transfer efficiency and minimal energy usage.

Model Predictive Control (MPC) uses mathematical models to predict the behaviour of the network and adjust the flow of thermal energy, accordingly, ensuring that each building receives the exact amount of energy it needs at any given moment. In addition, digital control systems can be used to remotely monitor and manage the flow rate within the network, enabling operators to act if the flow rate exceeds safe limits [33].

Additionally, 5GDHC systems are often designed with modular grids that are interconnected with multiple buildings with different thermal energy needs.

Here are some of the sensors that are used for measuring flow rate [34]:

Ultrasonic flow meters - These flow meters use ultrasound to measure flow rate and can be used for both heating and cooling applications.

Differential pressure flow meters - These meters measure the difference in pressure across a flow restriction and are commonly used for liquids in piping systems.

Magnetic flow meters - These flow meters measure the electromotive force generated by magnetic fields as fluid flows through a pipe.

Vortex flow meters - These meters measure the frequency of vortices generated by fluid flow across a bluff body inside a pipe.

2.3.4 Thermal energy storage

Integration with thermal energy storage is a key aspect of 5th-generation district heating and cooling (5GDHC) systems [24]. Thermal energy storage can improve the efficiency and flexibility of 5GDHC networks by allowing excess thermal energy to be stored and used later when demand is higher.

Several types of thermal energy storage systems can be integrated into 5GDHC networks, including

1. Underground thermal energy storage (UTES): This involves storing excess thermal energy in the ground using boreholes or other methods [35]. The energy can then be retrieved later using heat pumps, for example, to meet heating or cooling demand.

Various types of UTES systems can be used in 5GDHC networks, including [35][36]:

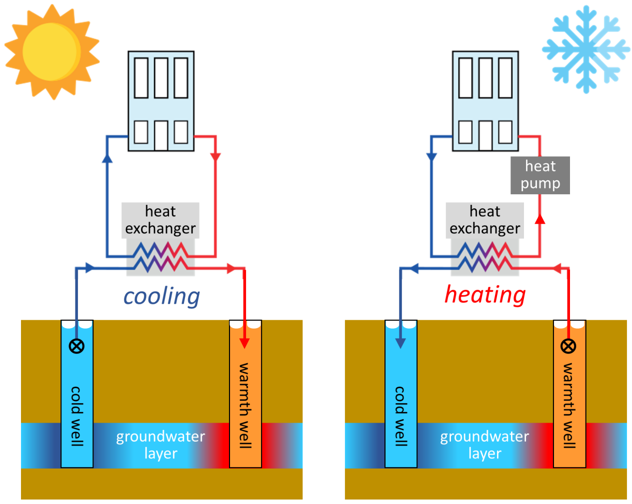

Figure 2.2: Example of UTES

1. Aquifer thermal energy storage (ATES) - In this type of system, water is pumped into and out of a porous underground aquifer layer to store and retrieve thermal energy.

2. Borehole thermal energy storage (BTES) - This system involves the use of vertical boreholes to store and extract thermal energy from the subsurface, typically through the use of a closed-loop circulation system.

3. Seasonal thermal energy storage (STES) - This type of system involves the storage of thermal energy over an extended period, typically on a seasonal basis, to provide heating and cooling as needed throughout the year.

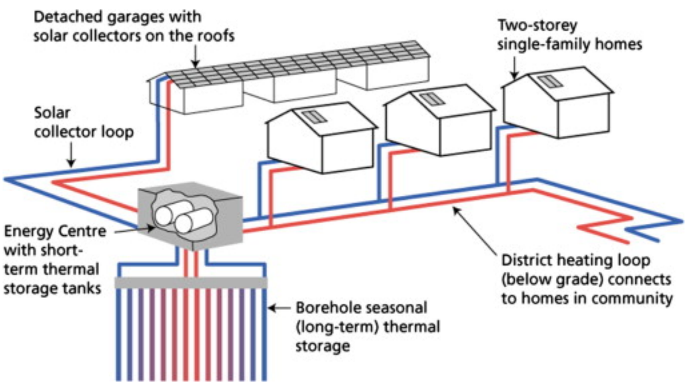

Figure 2.3: Example of seasonal thermal storage

Type of UTES	Advantages	Disadvantages
ATES	Energy Efficiency Renewable Energy Integration Long-Term Storage Capacity Scalability	Site Constraints Initial Cost Regulatory Challenges System Complexity
BTES	Reduced Environmental Impact Space Efficiency Flexibility in System Sizing Efficient Heat Transfer Long-Term Storage Capacity Renewable Energy Integration	Water Availability and Quality Initial Cost Geological Suitability Thermal Imbalance Regulatory Considerations Maintenance and Monitoring
STES	Long-Term Energy Storage Reduced Energy Costs Integration with Renewable Energy Enhanced Grid Resilience Scalability and Adaptability	Initial Cost Space Requirement System Efficiency Technological Complexity Environmental Consideration

Table 2.2: Advantages and disadvantages of different types of UTES

2. Water-based thermal energy storage: In a water-based TES system for 5GDHC, thermal energy is stored in the form of sensible heat in large water tanks. The water is typically heated using surplus heat from various sources, such as industrial processes, waste heat recovery, or renewable energy systems like solar or geothermal [37][24]. During periods of low demand or excess heat generation, the surplus energy is transferred to the water and stored in the TES system.

When there is a demand for heating or cooling in the district, the stored energy can be retrieved from the TES system. In heating mode, the hot water from the storage tanks is circulated through heat exchangers, transferring the heat to the district's heating network. Similarly, in cooling mode, the cool water from the storage tanks is circulated to absorb heat from the district's cooling network. There are also some decentralized energy storage systems such as:

1. Decentralized water tanks in buildings: These storage tanks can be located in individual buildings and can be used to store thermal energy for later use. The decentralized nature of these storage tanks allows for more flexibility in the network and can help to reduce distribution losses.

2. Hybrid substations: Hybrid substations are designed to store thermal energy in water or brine, and they come equipped with Water Source Heat Pumps (WSHP). These pumps can be used for both heating and cooling purposes.

By extracting heat from the water or brine, the WSHPs transfer it to the building's heating and cooling systems and during periods of high demand, the thermal energy stored in the water or brine can supplement the energy supply in the network. These types of substations can also help the network adjust to changes in demand and supply, which is called demand response reducing the need for additional energy generation and stabilising the network.

Advantages	**Disadvantages**
Energy storage capacity	Space requirements
Cost-effectiveness	Heat loss
Environmental friendliness	Freeze protection
Scalability	
Flexibility	

Table 2.3: Advantages and disadvantages of water-based thermal energy storage

3. Phase-change materials (PCMs): These materials can store thermal energy by changing phases (such as from solid to liquid) at a specific temperature. They can be integrated into building elements or other systems to provide thermal energy storage.

Integration with thermal energy storage can be managed through control systems that optimise peak heating and cooling loads using intelligent management of electricity demand and offer the possibility to match thermal energy supply and demand. PCMs are materials that can absorb or release large amounts of latent heat during a phase change, such as from solid to liquid or vice versa [37]. By incorporating PCMs into building envelope materials such as walls, floors, and ceilings, these materials can help reduce fluctuations in indoor temperatures and reduce the need for additional heating or cooling. This can in turn reduce energy consumption and improve the efficiency of the 5GDHC network.

Advantages	**Disadvantages**
High thermal energy storage capacity	Limited cycling capability
High energy efficiency	Selection and compatibility challenges
Precise temperature control	Cost considerations
Smaller storage footprint	PCM containment and leakage risks
Reduced heat loss during storage	

Table 2.4: Advantages and disadvantages of PMCs

2.4 Comparison between both systems 4GDH & 5GDHC

Category	**4GDH**	**5GDHC**
Topology	Traditional single energy center supply heat outwards Unidirectional water flow	Decentralized plant supplying Bidirectional water flow
Temperature	Wider ΔT Heating range: 40º-70º	Lower ΔT Heating range: 10º-25º Cooling range: 5º-20º
Storage	Very large thermal storage (larger than 3GHD due to lower temperatures so, lower energy density) Some short thermal storage	Seasonal thermal storage
Pipework	Highly insulated	Un-insulated
Advantages	More efficiency compared with previous technologies Lower investment cost than 5GDHC	Higher flexibility Ability to accommodate various types of heat sources and users Higher efficiency and lower CO2 emissions Heat recovering between buildings Heat losses are almost irrelevant New buildings can be easily added
Disadvantages	Limited capacity for load balancing Limited potential for thermal storage and flexibility Requires high operating temperatures Higher heat losses Impossibility to exchange heat between buildings	Higher investment costs compared to 4GDHC Requires advanced control strategies Limited experience and knowledge in the industry Larger pipework than 4GDHC Less storage density

Table 2.5: Comparison between 4th and 5th generation of technologies[8] [27]

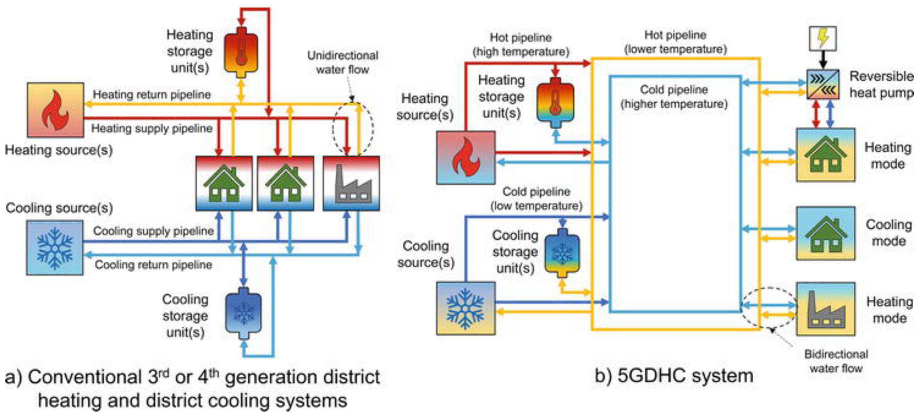

Figure 2.4: Comparison between 4GDH and 5GDHC

There are significant differences between the two generations, especially in terms of energy flow. The 5th generation allows bi-directional energy flow between buildings, whereas the previous generation did not. The working temperature range is also smaller in the new generation, which results in lower heat losses. Therefore, it is not necessary to insulate the pipes.

Based on the analysis of this section, it can be concluded that the 5th generation is significantly superior in terms of flexibility and adaptability to incorporate new alternative energy sources in comparison to fossil fuels. This factor makes the 5th generation the most preferred choice for upcoming constructions, which in turn makes control systems essential.

3 District where the project takes place

The district in which the project is to be carried out is a residential and commercial district in Mönchengladbach. It will have a residential area of approximately 150,000m2 and has a planned construction of approximately 1,500-2,000 dwellings.

The planned district will have an approximate energy consumption of 5.4 GWh/y in terms of heating demand, 2.5 GWh/y of hot water demand and will have an approximately installed power of 7.9 MWh/y of photovoltaic power.

It will also have 3 supply stations of which the supply station one will only need heating while the rest will need both heating and cooling. Supply station two will have a geothermal collector field as well.

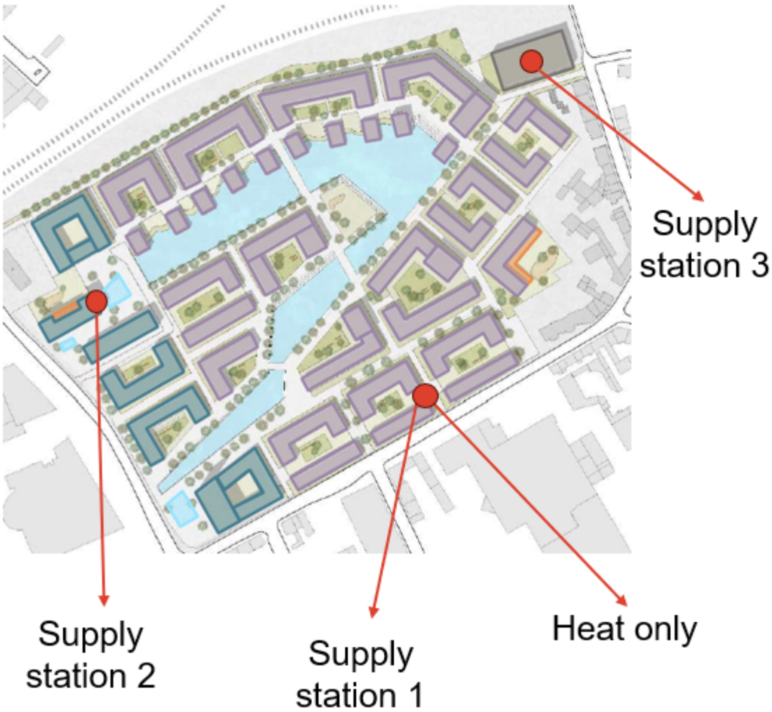

Figure 3.1: Panoramic view of the district distribution

Here in figure 3.1, the whole district with the three different supply stations can be observed.

The supply station two and three will need both heating and cooling, so these stations can be classified as 5GDHC. However the supply station one will only need heating, so in that manner, we can classify the supply station one as a middle way between the 5th and 4th generation, so it is a cold district heating network.

The geothermal energy will be used only in the supply station two. The heat will be collected from the ground via thermal collectors and it will be transferred to the substation through a heat exchanger.

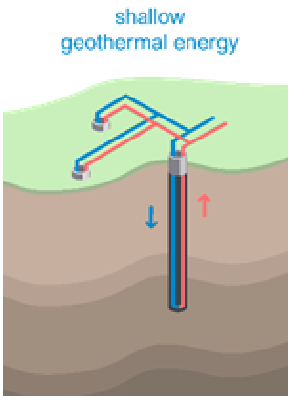

Figure 3.2: Geothermal heat capture scheme

Our work will focus on the supply station one and in the 4 buildings it supplies. Station one has two thermal storage tanks of approximately 1000L each. This supply station will be also using water waste heat recovery to increase the temperature of the network in order to be more energetic and efficient.

4 Optimal control configuration

The objective of this section is to establish two control system configurations by mixing several possible methods of those discussed in section 2.4 of this document.

These configurations will be applied in the first instance to the four buildings already constructed in the district, which make up the first supply station. These configurations will control the components in the building´s side of the system to fulfil the energy needs. Once they have been established they will be simulated to compare them and see what are the most relevant parameters to control.

Figure 4.1: Panoramic view of the 4 buildings that make up the supply station 1

The configurations will be built and simulated using $Modelica(Dymola)$.

4.1 Choosing the best configuration

We have three possible variables to control and adjust to meet the energetic demand in the most efficient way: temperature, pressure and mass flow.

Based on both the hydraulic model of the substation and the urban heating networks we will determine: which variables need to be monitored, why they need to be monitored, and where the sensors will be installed to monitor them. We will also determine how to control the system on the secondary side of the substation to meet the demand.

4.2 Examples of existing 5GDHC networks

In this point, the existing 5GDHC networks are considered, from which ideas will be obtained to establish the possible configurations that best fit our system.

4.2.1 Paris-Saclay

The Paris-Saclay 5GDHC (Fifth Generation District Heating and Cooling) is an innovative and sustainable heating and cooling network located in the Paris-Saclay area in France. The system is designed to provide efficient and environmentally friendly heating and cooling services to the district [38][39].

The 5GDHC concept focuses on several key aspects:

1. Integration of multiple energy sources: The system integrates various sources of energy, including renewable sources like solar and geothermal, as well as waste heat from industrial processes and data centers. This diverse mix of energy sources helps reduce dependency on fossil fuels and promotes a cleaner energy supply.

2. Smart grid technology: The 5GDHC system incorporates smart grid technology to optimize energy distribution and consumption. This includes advanced monitoring and control systems, automation, and real-time data analysis to ensure efficient energy management.

3. Energy storage and management: The system includes inter-seasonal heat storage solutions, allowing excess heat to be stored during the summer months and used during the colder seasons.

4. Flexibility and scalability: The 5GDHC system is designed to be flexible and scalable, allowing for future expansion and integration with other energy systems. This flexibility enables the system to adapt to changing energy demands and technologies over time.

The paris-saclay system is a decentralized system that regulates the temperature using a demand-driven control, which is controlled mainly with an MPC. It adjusts the temperature using the different heat pumps installed along the network.
As for the pressure control system, it is controlled and adjusted by means of a differential pressure control.The operation of a differential pressure control typically involves comparing the pressure difference between two points with a setpoint. If the measured pressure difference deviates from the setpoint, the control mechanism takes action to bring the pressure back to the desired level.

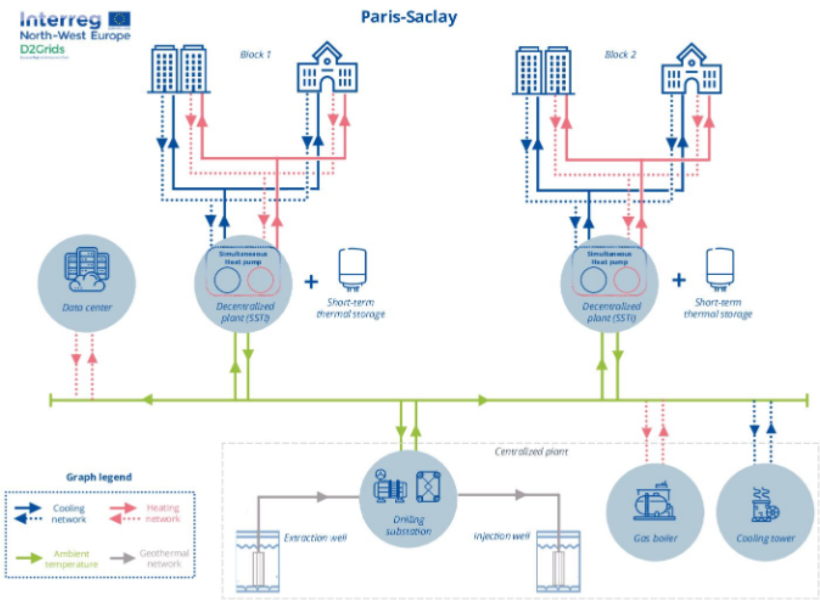

Figure 4.2: Blueprint of the Paris-Saclay 5GDHC [40]

4.2.2 Bochum

The Bochum 5GDHC (Fifth Generation District Heating and Cooling) project is an innovative heating and cooling network implemented in Bochum, Germany.

The Bochum 5GDHC grid utilizes a unique approach by harnessing the heat from abandoned coal mines in the region. The heat is extracted from water in these mines and is then used for heating purposes. This approach demonstrates the potential for utilizing existing infrastructure and resources to create sustainable and efficient heating and cooling systems[41][42].

The project in Bochum involves connecting around 23 customers to the 5GDHC grid, enabling them to benefit from the sustainable and cost-effective heating and cooling services provided. Heat pumps are used to raise the temperature of the extracted mine water to around 45 degrees Celsius before distributing it to the connected customers. This network, as in the Paris-saclay network, is a decentralized network that regulates the temperature using a demand-driven control regulated by an MPC.
This control system is the most widely used in this type of network since it provides high energy efficiency, comfort optimization, flexibility and reduced energy consumption.

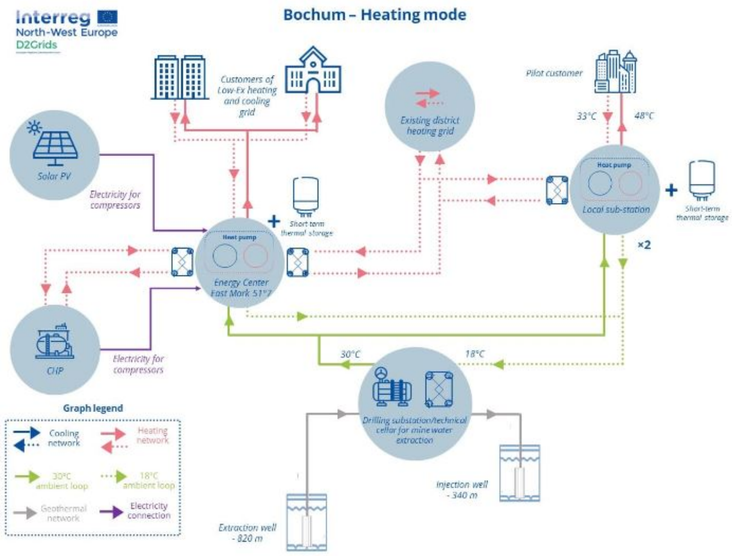

Figure 4.3: Blueprint of the Bochum 5GDHC in heating mode [43]

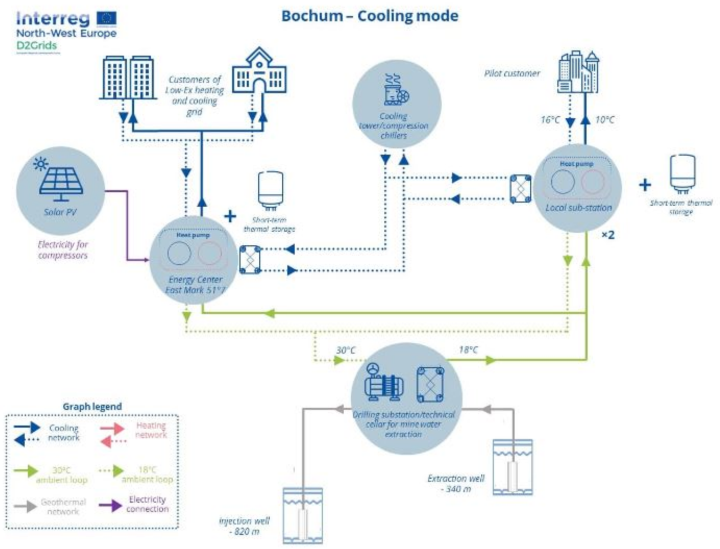

Figure 4.4: Blueprint of the Bochum 5GDHC in cooling mode [43]

4.2.3 Brunssum

The Brunssum 5GDHC project is a heating and cooling network implemented in Brunssum, in the Netherlands.

The Brunssum pilot site is built and operated by Mijnwater Energy , a company specializing in sustainable energy solutions. The project involves connecting houses and buildings to the 5GDHC network, providing them with sustainable heating and cooling services without relying on natural gas.

The project enables connected houses and buildings to benefit from the efficient use of renewable energy sources. The network utilizes the Mijnwater system, which taps into underground mine water to extract heat for heating purposes. This allows for the utilization of a local and renewable heat source, contributing to the reduction of greenhouse gas emissions.

The Brunssum installations showcase the realization of an innovative, sustainable, and cost-effective heating and cooling system. The project started connecting dwellings in 2021, and the expansion of the network is ongoing. By 2024, it is expected that an additional 91 dwellings will be connected to the Brunssum 5GDHC system [44].

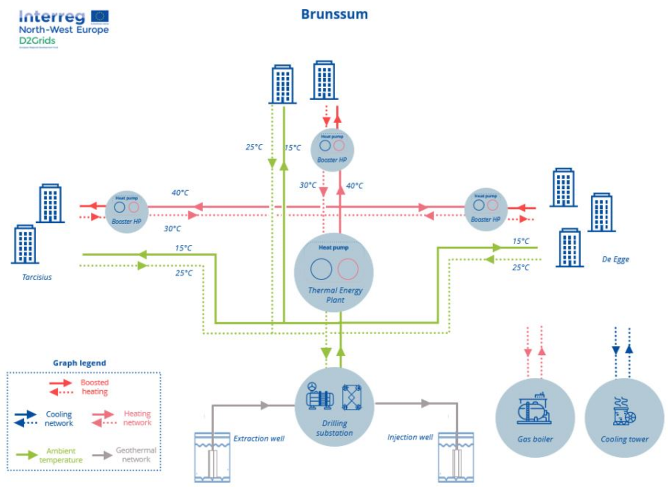

Figure 4.5: Blueprint of the Brunssum 5GDHC [45]

4.2.4 Heerlen

The location of this 5GDHC is the city of Heerlen, a city located in the Netherlands, which is reallr close to Aachen[30].

Some key aspects of this 5GDHC are:

1. Energy Exchange without a Central Energy Plant: The 5GDHC grid in Heerlen has the capability to exchange energy without the need for a central energy plant or source . This means that the energy is distributed and shared among the connected buildings and infrastructure, making the system decentralized.
2. Heat Recovery from Abandoned Coal Mines: The system in Heerlen utilizes the heat energy from abandoned coal mines to provide heating..

3. Cooling Capacity: In addition to heating, the grid in Heerlen also has the capacity to provide cooling. This is achieved by storing cold energy in the system and distributing it to the connected buildings when needed.
4. Environmental Sustainability: The grid contributes to environmental sustainability by utilizing renewable energy sources and reducing carbon emissions.
5. Decentralized Energy Distribution: The network operates on a decentralized energy distribution model, where the energy is shared among multiple buildings and infrastructure.

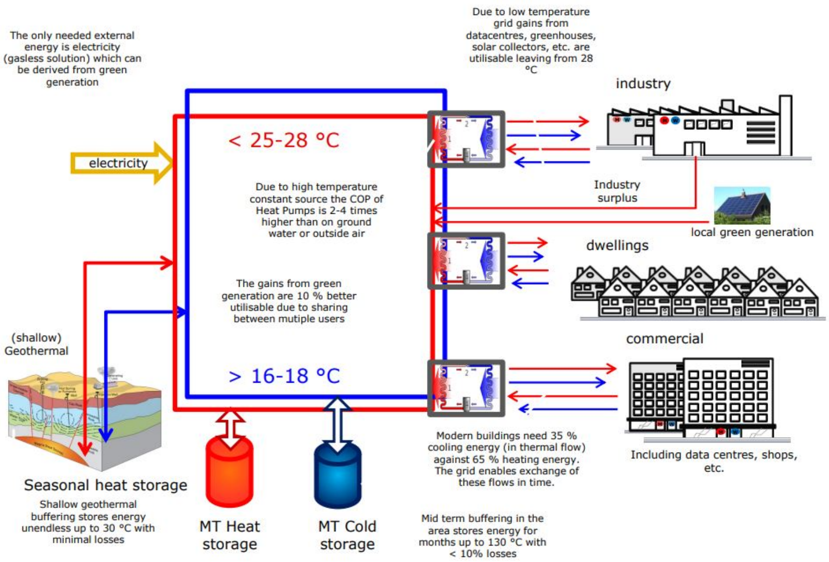

Figure 4.6: Blueprint of the Heerlen 5GDHC [46]

This system, also like the other systems above, uses decentralised heat pumps to control the temperature by means of demand-driven control, which is adjusted by means of an MPC. This mode of control is the most popular as it allows demand to be adjusted in real time by means of demand prediction.

4.2.5 Conclusions based on the technologies described

After reviewing the examples provided, it is evident that direct temperature control is crucial and cannot be overlooked. This is achieved through demand-driven control using heat pumps, which are regulated by a MPC. It is apparent that the direct adjustment of temperature is a common feature in all the examples given.

When adjusting the pressure, the temperature can also be affected. Higher pressure will lead to higher temperature and vice versa. Since we are only controlling the secondary side or the consumption side, it is recommended to maintain a stable and consistent pressure range to avoid any potential malfunctions.

The temperature of the heat exchanger on the primary side cannot be controlled as it depends on the main temperature. However, the amount of energy sent to the secondary side can be regulated by adjusting the mass flow of water that passes through the heat exchanger.

Therefore, we can only change two things on the secondary side: temperature and mass flow. On the other hand, we can only adjust the mass flow that goes through the heat exchanger on the primary side.

5 Hydraulic installation

In this section, the operation of the existing hydraulic system in the installation and its different parts will be explained.

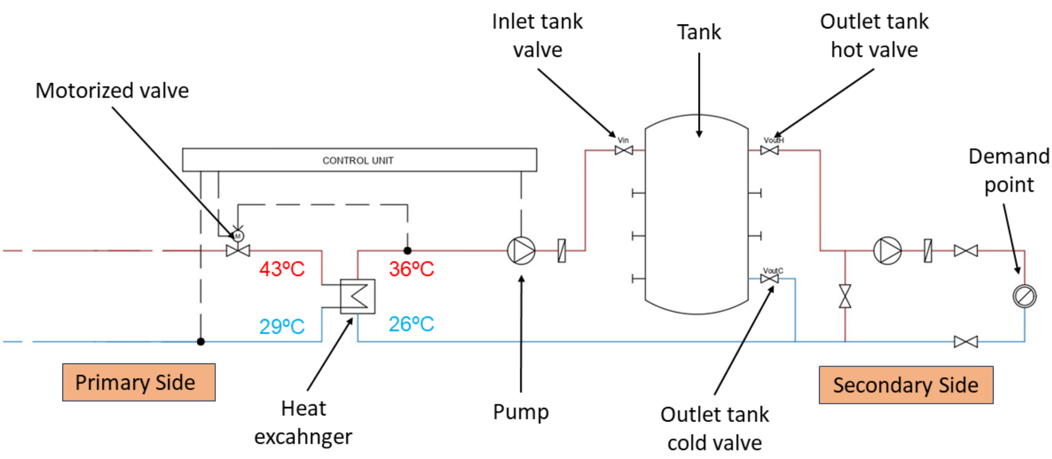

Figure 5.1: Hydraulic schematic before fitting sensors

As can be seen there is a primary side (left), which is the mains side and a secondary side (right) which is the substation side.

Within this hydraulic system we can highlight the following parts:

1. **Motorized Valve:** This is the element that we will use to regulate the amount of energy sent from the primary side to the secondary side. By opening and closing it we regulate V_M
2. **Inlet tank valve:** Is installed just for security, in case we have to stop the flow of water.
3. **Tank:** The function of the tank is to supply the necessary amount of hot water at peak periods.
4. **Outlet tank hot valve:** Its mission is to let the hot water flow from the tank to the point of consumption.

5. **Demand point:** It is the point where energy is demanded.
6. **Outlet tank cold valve:** The function of this valve is to remove the cold water from the bottom of the tank in order to refill it with hot water, this is done to keep the water in the tank always at a certain temperature.
7. **Pump:** The purpose of the pumps is to move water throughout the installation.
8. **Heat exchanger:** The heat exchanger transfers the energy from the primary side to the secondary side. Its efficiency is not optimal so heat losses are estimated to be between 15% to 20% for a cross-flow plate heat exchanger.

The maximum outlet temperature of the heat exchanger is T_{max} =36ºC and the minimum night-time temperature is $T_{backmin}$ =26ºC and the maximum flow rate is $\dot{m}_{secondarymax} = 20m^3/h$

Work mode of the tank

Here we explain the self-cycling of the thermal storage tank (2000L), which has hot water to be used in case of not being able to meet the demand. This tank also provides domestic hot water, but as our system has a maximum temperature of 36ºC, electric heaters will be used to increase the domestic hot water temperature up to 60ºC.

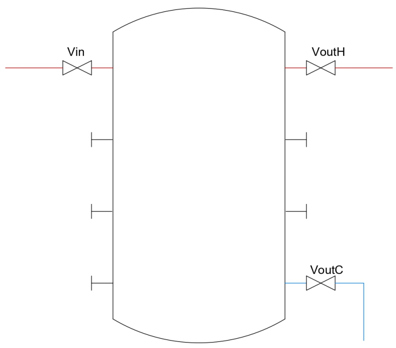

Figure 5.2: Simplified tank scheme

The tank has 3 valves: V_{in}, V_{outH} and V_{outC}.

The first two valves, which are installed in the top layer of the tank, can not be controlled directly to regulate the energy deliver. This will be used in case any failure happens.

The only valve that can be controlled is the V_{outC}, which is installed at the bottom layer of the tank. The purpose of this valve is to drain the cold water stored in the bottom layer if its temperature goes below a certain value.

The tank will be involved in the first configuration by solving the overload peak hours. In the second configuration, it will be the component that regulates the amount of energy delivered to the consumption point.

5.1 Temperature drop on demand point configuration

5.1.1 Workflow of the - Temperature drop on the demand point configuration

The following picture shows the process scheme that the hydraulic system follows during its operation.

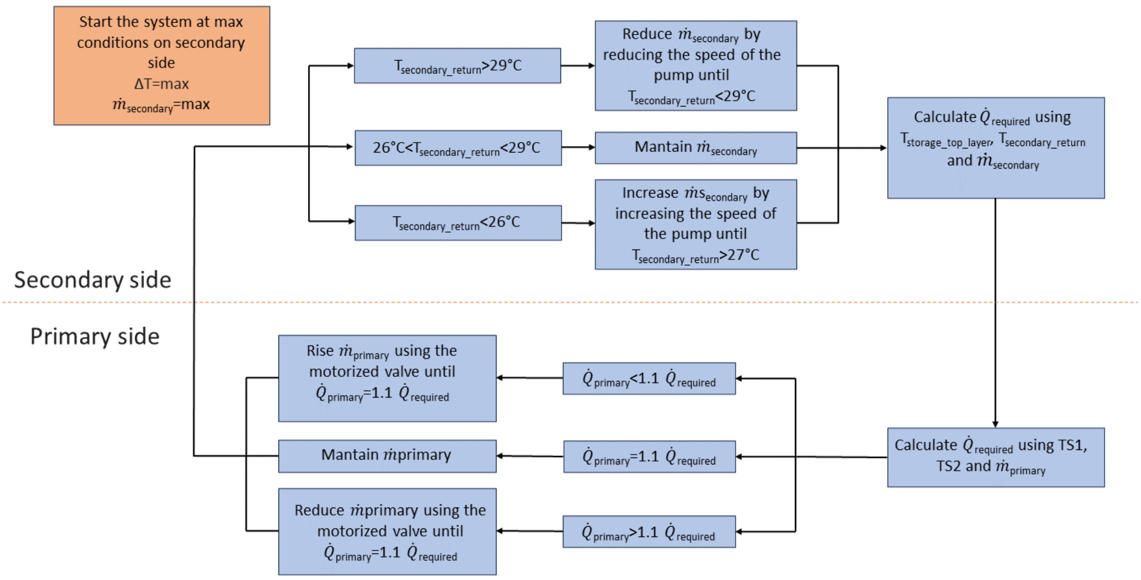

Figure 5.3: Flowchart of the configuration 1

Detailed description of the control system flowchart

This process is measured by directly comparing the amount of energy demanded by the buildings and the amount of energy delivered by the grid using the expression:

$$\dot{Q} = \dot{m} \cdot Cp \cdot \Delta T \tag{5.1}$$

Secondary side

Pump 2 (installed just downstream of the tank) is responsible for supplying the necessary flow to the point of consumption to meet the demand.

When the system is started it will be at full capacity, with ΔT at maximum at the return point and with the flow rate of pump 2 ($\dot{m}_{secondary}$) at maximum. The flow rate will be automatically regulated by the return temperature of the system.

There are three possible scenarios:

1. If $T_{secondary\_return}$<26ºC it means that the energy consumption is higher than expected. To solve this, the pump speed will be increased to increase the delivered flow rate ($\dot{m}_{secondary}$) until the $T_{secondary\_return}$ is greater than 27ºC.
2. If $T_{secondary\_return}$ is between 26ºC and 29ºC, the demand flow rate is close to the flow rate being delivered by pump 2, so $\dot{m}_{secondary}$ will be maintained.
3. If $T_{secondary\_return}$>29ºC it means that the demand flow is lower than what pump 2 is delivering. The pump will reduce its speed, thus reducing the flow rate delivered until the return temperature is at least 29ºC. At this point the pump will stop reducing the flow rate and the flow rate will remain constant until the return temperature again exceeds the upper or lower limit.

Knowing the delivered mass flow ($\dot{m}_{secondary}$), the return temperature ($T_{secondary\_return}$) and the inlet temperature at the point of consumption, $\dot{Q}_{required}$ is calculated by the expression:

$$\dot{Q}_{required} = \dot{m}_{secondary} \cdot Cp \cdot (T_{secondary\_inlet} - T_{secondary\_return}) \tag{5.2}$$

Primary side

$\dot{Q}_{primary}$ will be calculated in the same way as for $\dot{Q}_{required}$.

$$\dot{Q}_{primary} = \dot{m}_{primary} \cdot Cp \cdot (T_{primary\_inlet} - T_{primary\_outlet}) \tag{5.3}$$

Where $\dot{m}_{primary}$ is the flow rate through the heat exchanger, $T_{primary\_inlet}$ is the inlet temperature of the heat exchanger and $T_{primary\_outlet}$ is the outlet temperature of the heat exchanger.

Once $\dot{Q}_{primary}$ is calculated, it shall be compared with $\dot{Q}_{secondary}$ to achieve equality $\dot{Q}_{primary} = 1.1\dot{Q}_{secondary}$ in order to balance the energy delivered to the secondary side. As there are losses the $\dot{Q}_{demand}$ will be overestimated by 10 %.

We have three possible scenarios:

1. If $\dot{Q}_{primary} > 1.1\dot{Q}_{required}$ means that the primary side is delivering more energy to the secondary side than it is consuming. To avoid this, the primary side valve V_M will be gradually closed until $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ is satisfied.
2. If $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ the energy delivered is balanced with the energy consumed, so the $\dot{m}_primary$ remains equal.
3. $\dot{Q}_{primary} < 1.1\dot{Q}_{required}$ means that the primary side is delivering less energy to the secondary side than it is consuming. To avoid this, the primary side valve V_M will be closing until $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ is satisfied.

5.1.2 Place of installation of the sensors for the first configuration

In this section, the relevant sensors will be placed in the hydraulic scheme for the system to work as mentioned in the previous point.

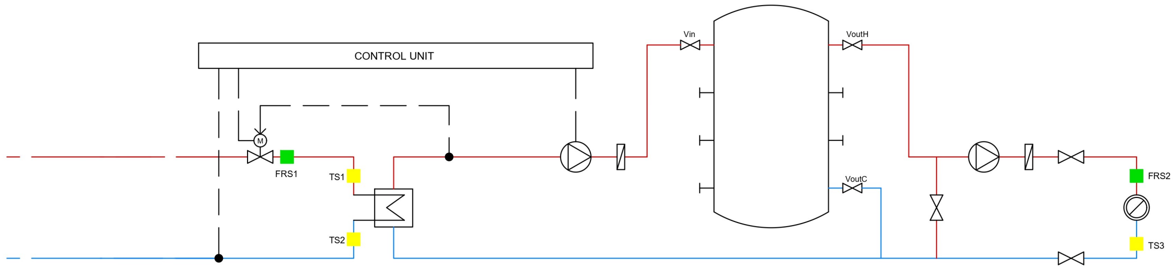

Figure 5.4: Locations of the sensors for the first configuration

What each sensor measures and why it is positioned is explained below.

Temperature sensors

TS1/TS2: They are placed one right before and the other one right after the exchanger. Their goal is to measure the ΔT in the primary side. With the expresion: $\dot{Q}_{primary} = \dot{m}_{primary} \cdot Cp \cdot (T_{primary\_inlet} - T_{primary\_outlet}$ the amount of heat the primary side is producing can be calculated ($\dot{Q}_{primary}$).

TS3: It is placed one right after the demand point. Its mission is to give us the temperature reading at the outlet of the demand point so that we can calculate the $\dot{Q}_{required}$. The temperature reading also allows the regulation of the flow rate delivered by pump 2.

Flow-rate sensors

FRS1: Placed right after the motorized valve V_M. It gives us the reading of the flow rate in order to calculate the $\dot{Q}_{primary}$.

FRS2: Placed right before the demand point. It gives us the reading of the flow rate ($\dot{m}_{secondary}$) in order to calculate the $\dot{Q}_{required}$.

5.2 Tank based configuration

5.2.1 Workflow of the - Tank based configuration

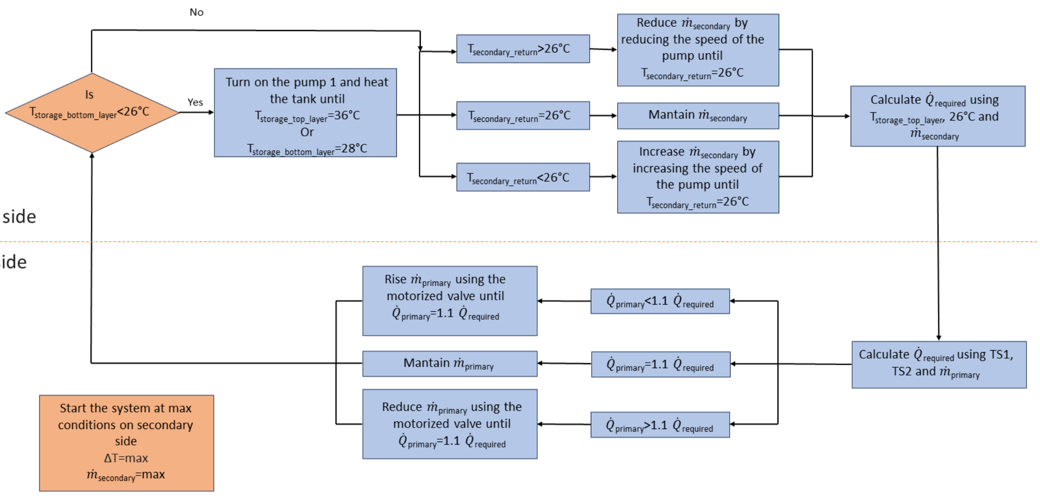

Figure 5.5: Flow chart of the configuration 2

Detailed description of the control system of the tank based configuration

Assumptions

1. The return temperature of the demand point will be fixed in: $T_{secondary\_return}$ =26ºC
2. The inlet temperature of the demand point will be the same temperature as$T_{storage_top_layer}$. This temperature may not always be 36ºC
3. $T_{primary\_inlet}$ = 43ºC
4. $T_{primary\_outlet}$ = 29ºC

Secondary side

26ºC is the minimum return temperature on the secondary side, This value is setted as the lower operating limit of the tank heating system.

If the temperature at the bottom of the tank falls below 26ºC, the system will automatically turn on the pump 1 and replace the cold water with hot water at a temperature of 36ºC. This process will continue until one of the following two conditions is met: either the temperature of the tank reaches 36°C or the temperature at the bottom of the tank reaches 28°C.

It's important to note that if the temperature at the bottom of the tank falls below 26ºC, the temperature at the top of the tank will also be lower than 36ºC.

The flow rate delivered by pump 2 ($\dot{m}_{secondary}$) will vary to always maintain 26°C in the return circuit. As in the first configuration there will be three possible scenarios:

1. If $T_{secondary\_return}$>26ºC the speed of the pump 2 will be reduced until the outlet demand temperature is 26ºC. This will adjust $\dot{m}_{secondary}$ with the demand.

2. If $T_{secondary\_return}$=26ºC means that $\dot{m}_{secondary}$ is balanced with the demand.

3. If $T_{secondary\_return}$<26ºC the speed of the pump 2 will be rised until the outlet demand temperature is 26ºC. This will adjust $\dot{m}_{secondary}$ with the demand.

In this configuration the water extracted from the heat exchanger is used to heat the tank. Thus $\dot{Q}_{secondary}$ will be calculated using this expression:

$$\dot{Q}_{secondary} = \dot{m}_{in} \cdot C_p \cdot (36 - 26) \tag{5.4}$$

Where $\dot{Q}_{secondary}$ is the energy needed to heat the water from 26ºC to 36ºC and $\dot{m}_{in}$ is the flow rate of hot water entering the tank to heat it in case $T_{storage\_bottom\_layer}$<26ºC.

Primary side side

To determine the energy delivered from the network the next equiation will be used:

$$\dot{Q}_{primary} = \dot{m}_{primary} \cdot C_p \cdot (T_{primary\_inlet} - T_{primary\_outlet}) \tag{5.5}$$

In this case $\dot{Q}_{primary}$ will be compared with $\dot{Q}_{required}$ to achieve the following balance $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$.

We have three possible scenarios:

1. If $\dot{Q}_{primary} > 1.1\dot{Q}_{required}$ means that the primary side is delivering more energy to the secondary side than it is consuming. To avoid this, the primary side valve V_M will be gradually closed until $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ is satisfied.

2. If $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ the energy delivered is balanced with the energy consumed, so the $\dot{m}_primary$ remains equal.

3. $\dot{Q}_{primary} < 1.1\dot{Q}_{required}$ means that the primary side is delivering less energy to the secondary side than it is consuming. To avoid this, the primary side valve V_M will be closing until $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$ is satisfied.

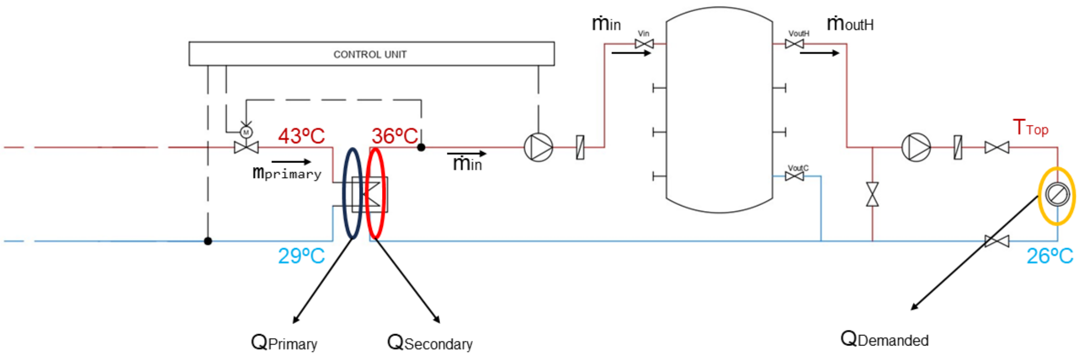

Figure 5.6: Explanation of variables

5.2.2 Place of installation of the sensors

The following diagram shows the position of the chosen sensors.

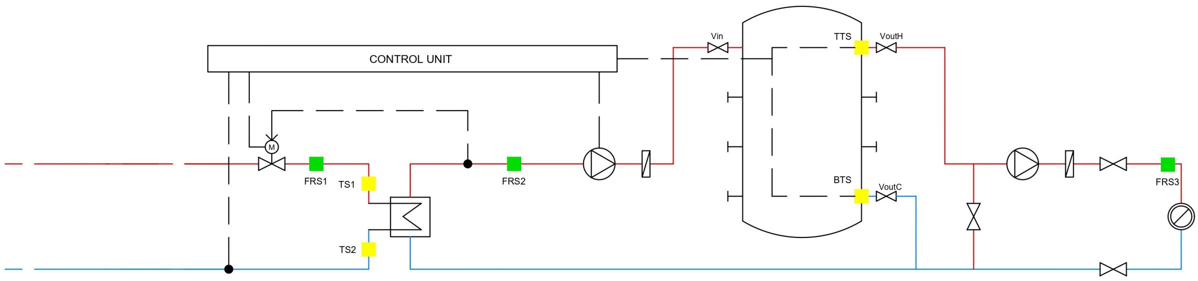

Figure 5.7: Location of the sensors for the second configuration

Temperature sensors

To ensure proper monitoring and operation of the system, the following sensors are neede:

TS1/2: These are the sensors placed both at the inlet and outlet of the heat exchanger. They monitor the temperature rise in the heat exchanger in order to calculate the $\dot{Q}_{primary}$.

TTS: This is the temperature sensor at the top of the tank $T_{storage\_top\_layer}$. This is the inlet temperature at the point of consumption.

BTS: This is the temperature sensor at the bottom of the tank T_{Bot}. This temperature should be at least 26°C.

Flow rate sensors

FRS1: This one measures the flow rate in the primary side ($\dot{m}_{primary}$) in order to calculate $\dot{Q}_{primary}$. This sensor is located right after the motorized valve.

FRS2: Placed just right after the heat exchanger. It indicates the value of the quantity of water introduced into the tank ($\dot{m}_{Secondary}$). As we know that the temperature jump on the secondary side in the heat exchanger is 10ºC and knowing the value of the mass flow, we can calculate $Q_{Secundary}$.

FRS3: Placed before the consumption point. It gives us the value for $\dot{m}_{outH}$ (that is the same as $\dot{m}_{secondary}$) to calculate the energy demand.

5.3 Choice of sensors

In this section the sensors necessary for the operation of the control logic described above will be presented and compared.

5.3.1 Temperature sensors

There are several types of temperature sensors, but for district heating we can highlight 2 of them:

1. Thermocouples
2. Resistance Temperature Detectors (RTDs)

	Advantages	**disadvantages**
Thermocouples	Cheaper Faster response time (0,5s) Wide temperature range Higher durability	They do not work well if the control unit and the sensor are too far away Less accuracy than RTDs
RTDs	Higher accuracy than Thermocouples Higher stability	More expensive Slower response time (1s-7s) Lower durability Lower temperature range

Table 5.1: Comparison between RTDs and Thermocouples[47][48]

(a) Thermocouple

(b) RTD

Figure 5.8: Examples of thermal sensors

Our district heating sensors prioritize reliability and precision, which is why we consider RTDs as the optimal choice. While thermocouples are known for their quicker response time and robustness, the low-temperature network means that the sensors won't be exposed to as much stress. Moreover, RTDs have a rapid response time (averaging around 2 seconds), which makes them effective for use.

5.3.2 Pressure sensors

We have 4 types of pressure sensors used in district heating, such as:

1. Pressure transducers
2. Differential pressure sensors
3. Pressure gauges
4. Absolute pressure sensors

	Advantadges	**Disadvantages**
Pressure transducers	High accuracy Wide range of pressure levels High resistance to the enviroment Easy to connect to data acquisition	Require external power to work Expensive May require calibration over the time Can be affected by noise
Differential pressure sensors	Can be used to measure flow-rate as well Fast response time Compact size High accuracy Mesure the pressure in two points and makes a comparison	Can be clogged Expensive May be affected by temperature fluctuations Complex to install
Pressure gauges	Direct visual indication of pressure readings Simple Wide range of pressure Cheaper than pressure transmiters and transducers	Not suitable for remote monitoring Lower accuracy Mechanical components can wear out over time
Absolute pressure sensors	Highly precise Eliminate the need of atmospheric pressure compensation Suitable for highly precise applications	Most expensive sensors Require periodical calibration Limitations in maximum pressure capability Can be affected by temperature vibrations

Table 5.2: Comparison between different pressure sensors

(a) Pressure transducer

(b) Differential pressure sensor

Figure 5.9: Examples of pressure sensors

To remotely monitor our system, we require accurate sensor readings, thus discarding pressure gauges.

Sensors wanted to be installed before and after the motorized valve (V_M), the best option is the differential pressure sensor, as only one will be needed to install instead of two.

5.3.3 Flow rate sensors

Some of the most commonly used flow sensors are:

1. Differential Pressure Flow Sensors
2. Velocity Flow Sensors
3. Mass Flow Sensors
4. Ultrasonic Flow Sensors

	Advantadges	**Disadvantages**
Differential flow rate sensors	Simple design Relatively low cost Good accuracy	Pressure drop Limited flow range Sensitive to flow properties Potential clogging
Velocity flow sensors	Wide range Low pressure drop High accuracy Suitable for high flow rates	Limited fluids Expensive Difficult installation
Mass flow sensors	High accuracy Wide range Real-time measurement High durability	Expensive Limited fuids Difficult installation Limited pressure or temperature range
Ultrasonic flow sensors	Non intrusive design Wide range of fluids No pressure drop Wide pipe diameter range	Expensive Difficult installation Need or power source Lower accuracy

Table 5.3: Comparison between different flow rate sensors[49][50]

To ensure the system can respond quickly and accurately, we have decided to choose the mass flow sensor. This sensor has a wide range of flow rates, making it perfect for our needs. However, it is expensive and can only measure a limited number of fluids. Fortunately, since our working liquid is water, this won't be an issue. Additionally, it only works within certain temperature and pressure ranges, but our system operates at a low temperature (between 25ºC and 39ºC), so this is not a concern. After considering all the factors, we have concluded that the mass flow sensor is the best option for our requirements.

Figure 5.10: Mass flow sensor

5.4 Pump used

The pump used will be the "Magna 3" from the company GRUNDFOS which is an intelligent, high-efficiency circulator pump[51][52].
Some of its key features are:

1. Energy Efficiency: The MAGNA3 is an intelligent circulator designed to reduce energy consumption by up to 75%.
2. Intelligent Control: The MAGNA3 has built-in heat energy monitoring, wireless connectivity, and extra inputs and outputs for increased system intelligence. It also allows for handheld pump control via Grundfos GO.
3. Multi-Pump Functionality: The MAGNA3 offers multi-pump functionality. Two pumps can be connected in parallel and operate in alternating, backup or cascade mode.
4. The installation and operation process is simple and straightforward.

This pump model is suitable for use in a variety of systems, including heating, domestic hot water, air conditioning, refrigeration, geothermal heat pump, and solar heating systems. It has a nominal working pressure of 12 bar and can operate within a temperature range of -10ºC to 110ºC. With these features, it is well-suited for the application of this project.

Figure 5.11: Grundfos Magna 3

6 Modelica models

The chapter will discuss the construction and design in *Modelica* of the models developed on the basis of the two configurations described in the previous chapter. It will explain the reasons for the components chosen as well as the values established for their operation will be explained.

These models have been developed using a mixture of components from the standard Modelica and standard *Modelica* and *AixLib* libraries.

AixLib is an open-source *Modelica* model library for building performance simulations, developed at RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate (EBC) in Aachen, Germany. The library contains models of HVAC systems as well as high and reduced-order building envelope models [53]. AixLib supports different modeling depths ranging from component to district level and covers all relevant domains in building energy systems. Includes specialised components for the construction and simulation of district heating networks.

The objective of this point is to develop the rule based control blocks that allow the correct operation of the system in the two configurations described. The operation of these blocks will be explained, as well as the choice of the different components that make them up. These blocks will be made up of elements from the standard *Modelica* libraries[54] such as *Math*[55], *Continuous*[56] and *Logical*[57].

6.1 Simulation of the return temperature based configuration

The model of the configuration based on the return temperature is shown in the following picture:

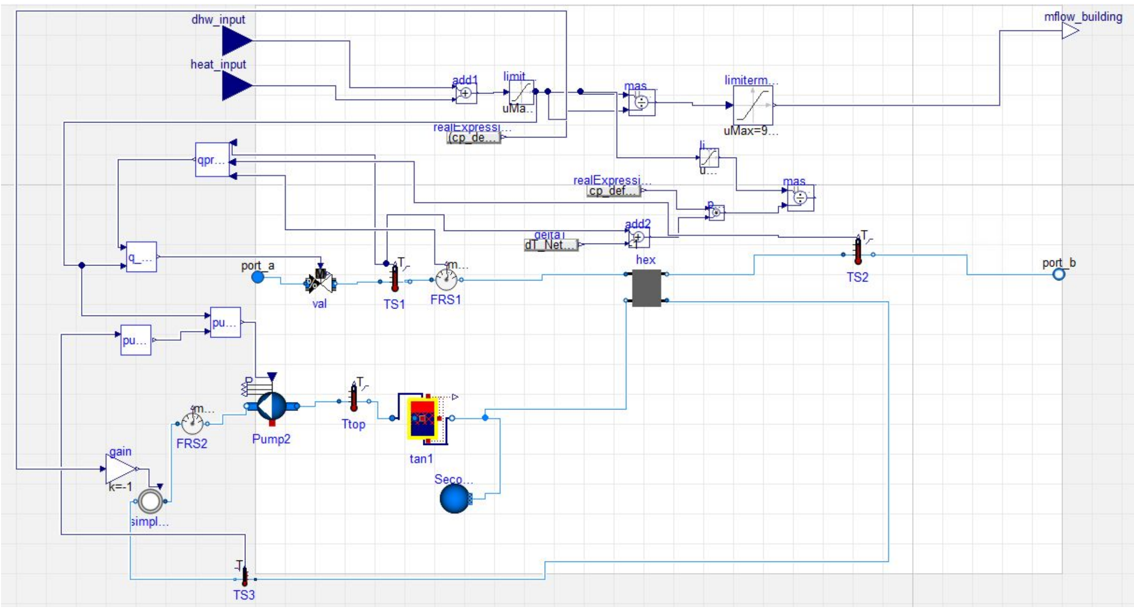

Figure 6.1: Return base configuration model

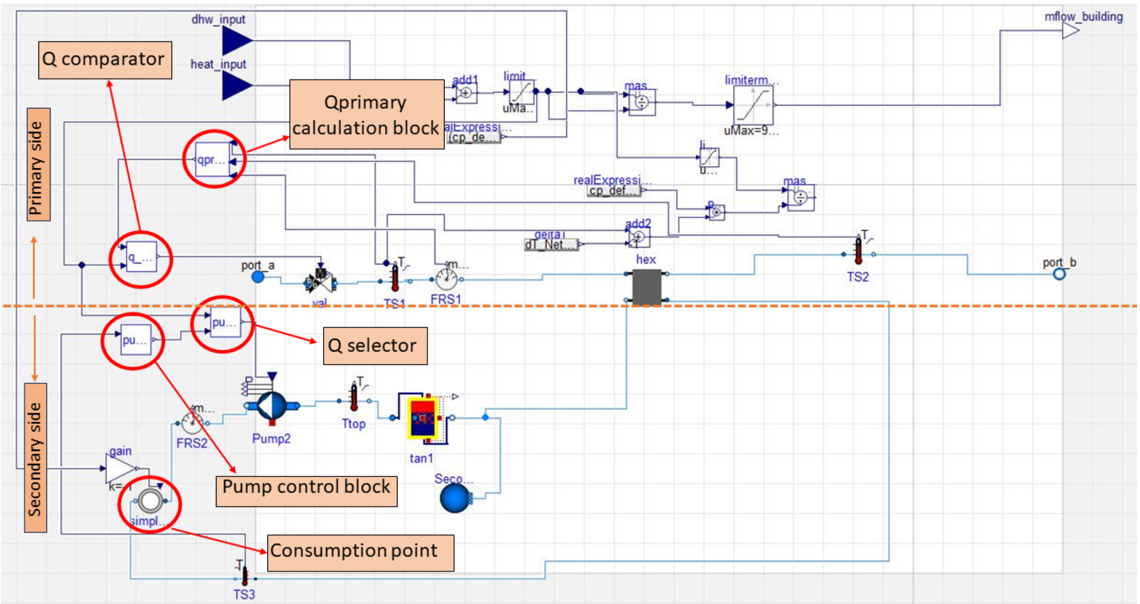

Figure 6.2: Explanation of the return base configuration model

The model is divided into primary side at the top and secondary side at the bottom. The direction of water flow on the primary side is from left to right, i.e. from *port_a* to *port_b*.

On the secondary side it is the other way round (from right to left) so that the flow in the heat exchanger is counter-current and therefore more efficient.

6.1.1 Elements of the model

The model mixes elements from both the Modelica base libraries and elements from the *AixLib* library, such as the pump, the motorised valve and the stratified tank. All the flows in the different elements have been esblished as "$m\_flow\_nominal$" as the flow rate is something that the system has to vary for the correct functioning of the whole system.

Water pumps 1 and 2

The selected pumps are "$AixLib.Fluid.Movers.FlowControlled\_m\_flow$" because they have the possibility to vary their speed by means of an input signal.
The working conditions of both pumps have been taken from the catalogue of the pump that will actually be installed, Magna 3 from grundfos. The nominal working pressure is 12 bar and the maximum pressure drop between pump outlet and pump inlet is 2 bar.

Motorized valve

The valve "$AixLib.Fluid.Actuators.Valves.TwoWayEqualPercentage$" has been chosen because it can be partially open or partially closed, unlike the others, which can only be fully open or fully closed.

Stratified tank

The choice of the stratified tank among all available tank models lies in the fact that in the actual system the water in the tank is also separated into 3 different layers. The upper layer with a higher temperature, the lower layer with a lower temperature and the middle layer with an intermediate temperature. "$AixLib.Fluid.Storage.Stratified$" is the model of the tank.
The number of segments used is $nSeg = 6$ in order to make the simulation more accurate. The higher the number of sectors, the higher the accuracy, but also the longer the simulation time.

Sensors

Both temperature and flow rate sensors used are the sensors from the Modelica standard library.
The temperature sensor used are the $AixLib.Fluid.Sensors.TemperatureTwoPort$ which

are located in different point in the installation and provide temperature inputs for the different control blocks.
The flow rate sensor also provides information as an input for the $\dot{Q}_{required}$ and $\dot{Q}_{primary}$ blocks. The sensor used in particular is $AixLib.Fluid.Sensors.MassFlowRate$

6.1.2 Control blocks

In order to control the elements necessary for the system to function as described in the previous point, 5 control blocks have been developed. These blocks are:

1. Pump control block
2. $\dot{Q}_{primary}$ calculation block
3. $\dot{Q}$ comparator
4. $\dot{Q}$ selector

For the construction of these blocks logic blocks as switches or major or minor limits, mathematical blocks such as products or sums, PI controllers and real inputs and outputs have been used.

Pump control block

The pump 2 will be variable speed depending on the return temperature of the system (measured with TS3).

The PI controller has been chosen for its simplicity and economy. This controller has the setpoint on the side and the input of the measured variable at the bottom. The controller provides an output between 0 and 1 based on the comparison of the setpoint with the measured variable.

The setpoint of the PI controller varies depending on the return temperature. If it is lower than 26ºC, "Switch 2" activates the signal at the bottom, making the setpoint 26ºC (which is the minimum return temperature set). If the temperature is higher than 26ºC, the upper signal is activated, activating "Switch 1". If the temperature is higher than 29ºC, "Switch 1" makes the setpoint 29ºC and if it is lower the setpoint will be 28ºC. All of this means that the return temperature is always between 26ºC and 29ºC.

The PI block provides an output of a value between 0 and 1 but the input to control the water pump must be a flow rate. For this reason, before the output of the control block, the value of the PI output is multiplied by a constant with a value of 5.55.

This number is determined by the maximum flow rate that our pump can deliver, which is $20m^3/h$, which in conversion is $5.55kg/s$. In this way the output of the control block will be a value between 0 and $5.55kg/s$.

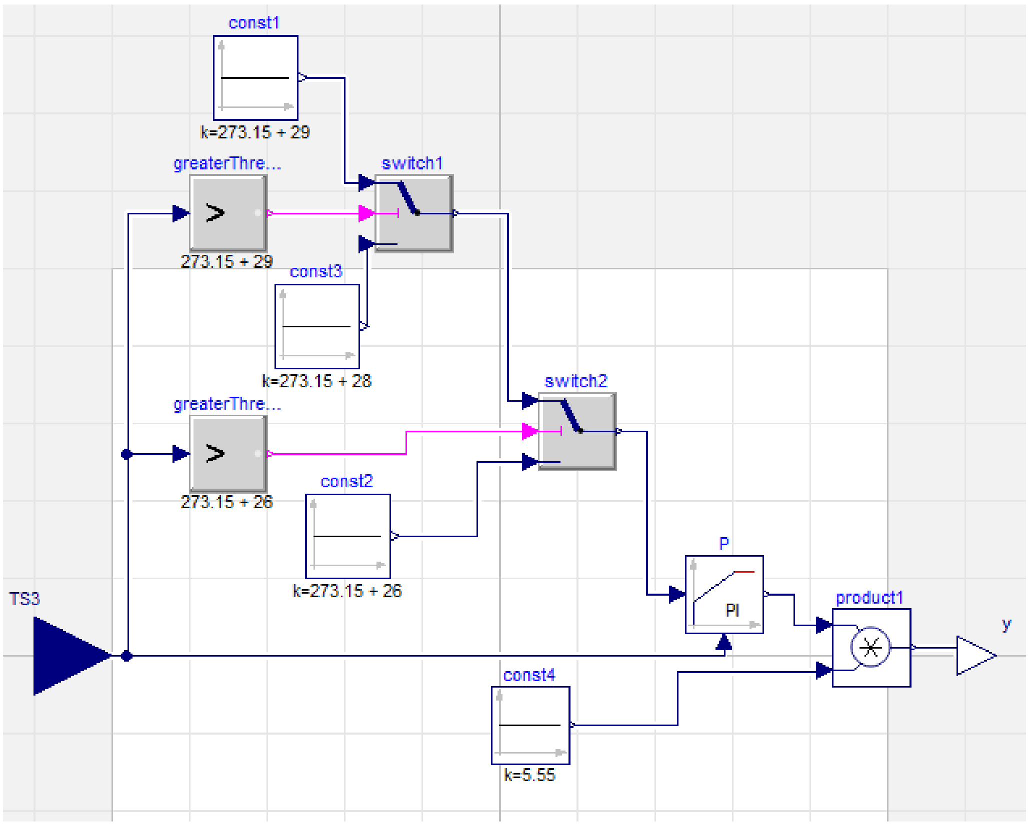

Figure 6.3: Pump control block of the configuration 1

$\dot{Q}$ selector

The function of this block is to stop the pump when the consumption is zero.

If the consumption is 0 or less, the switch will activate the upper signal, making the output of the block the constant $K = 0.01$. Otherwise the lower signal will be activated, causing the "Switch" to provide the control of pump 2 (described above) as output.
The K is not exactly 0 so that during the simulation the model does not give negative temperatures at times when the $\dot{Q}$ is 0. This occurs in cases where the pump has stopped and has to be started again because the $\dot{Q}$ is greater than 0 because the response of the controller is not immediate, but has a minimum delay.The logic behind the limiter in the lower section is the same as described above.

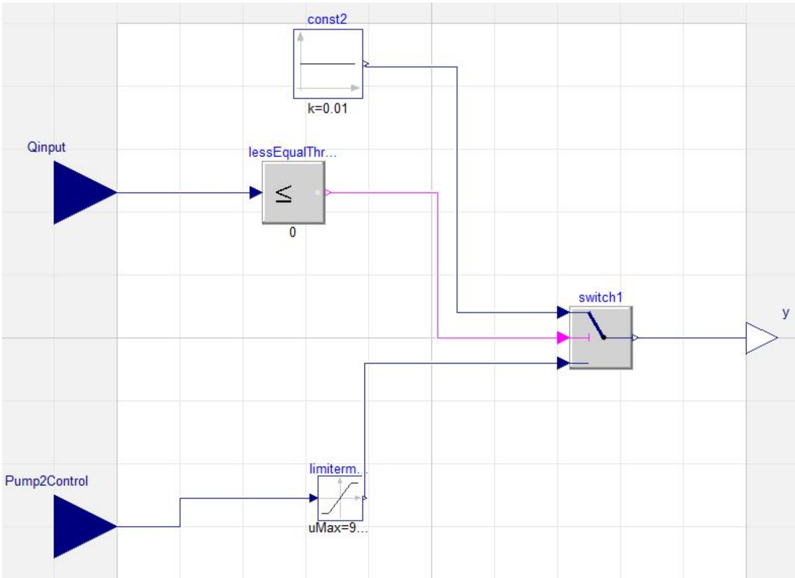

Figure 6.4: Pump control block of the configuration 1

$\dot{Q}_{primary}$ calculation block

This block is in charge of calculating the $\dot{Q}_{primary}$ of the consumption point using the expression $\dot{Q}_{primary} = \dot{m}_{primary} \cdot C_p \cdot (TS1 - TS2)$. The inputs of this control block are the inlet ($TS1$) and outlet ($TS2$) temperature of the heat exchanger on the primary side and the flow rate ($FRS1$) of the primary side as well. A constant with a value of $k = 4.18kJ/kg \cdot K$ is used as for the C_p.

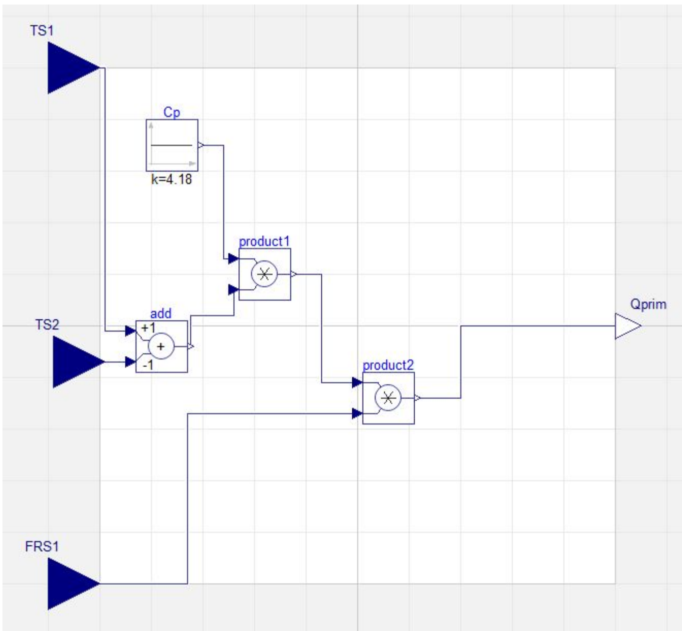

Figure 6.5: $\dot{Q}_{primary}$ calculation

$\dot{Q}$ comparator block

This block compares the $\dot{Q}_{required}$ with the $\dot{Q}_{primary}$. The PI controller setpoint is $1.1\dot{Q}_{equired}$ and the measured variable is the $\dot{Q}_{primary}$.

The block tries to achieve equality $\dot{Q}_{primary} = 1.1\dot{Q}_{required}$, providing an output between 0 and 1. This output is used to control the valve V_M, so that 1 is the valve fully open and 0 fully closed.

The limit means that the system cannot provide an exact 0 as an output but at least provides an output of 0.01. This is done to prevent zero mass flow related errors.

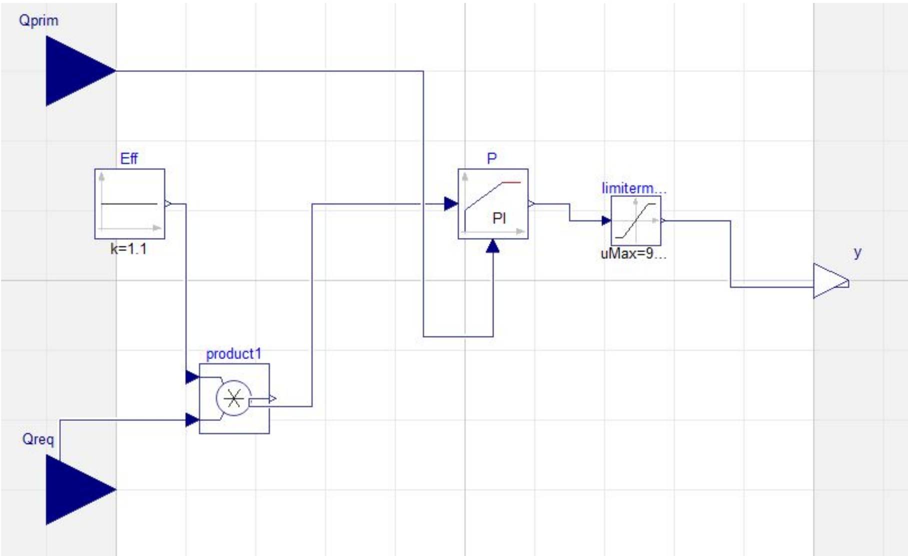

Figure 6.6: $\dot{Q}$ comparator block

6.2 Simulation of the tank based configuration

Unlike the previous configuration, this one has two pumps instead of one. Pump 1 controls the tank temperature while pump 2 is responsible for providing sufficient mass flow to meet the demand.

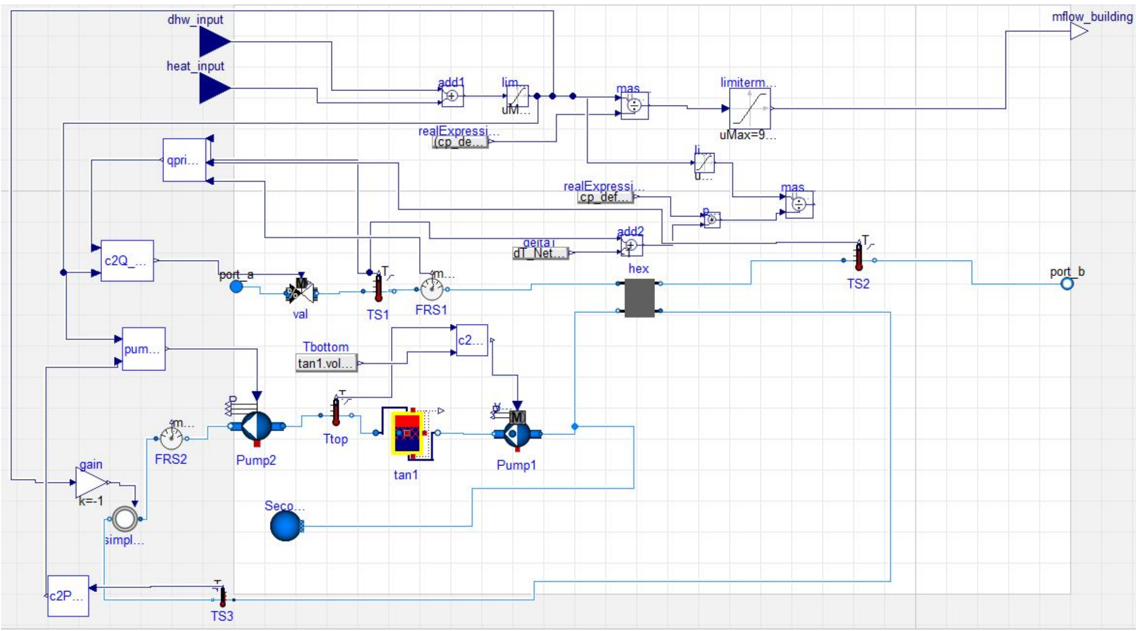

Figure 6.7: Tank based configuration model

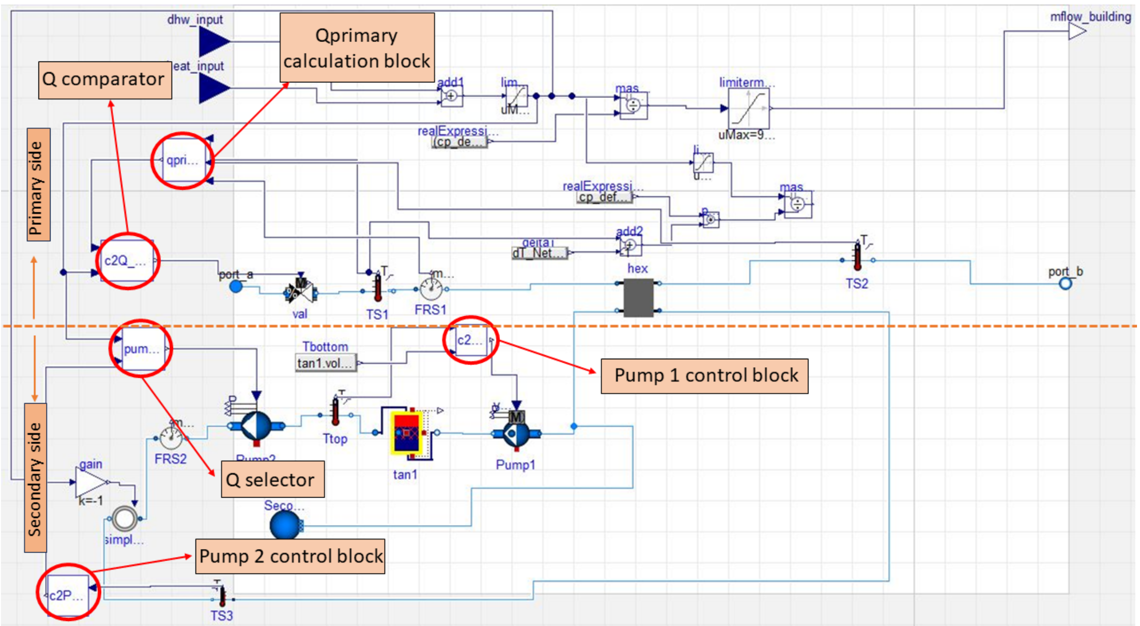

Figure 6.8: Explanation of the tank based configuration model

6.2.1 Control blocks of the second configuration

The only blocks that change in this configuration with respect to the first one are the control blocks of pump 1 and pump 2. The rest of the control blocks are identical.

Pump 1 control block

Pump 1 is still an off/on system. In this case the temperature limit is not only at the top, but also at the bottom, so the structure of the controller changes from that of configuration one. This control block has 2 inputs, the temperature at the top of the tank and the temperature at the bottom of the tank.

If the bottom temperature is below 26°C the "$Switch3$" automatically switches the pump on by means of a constant $K = 1$.

If the temperature of is higher than 26ºC the signal at the bottom of "$Switch3$" will be activated. If the bottom temperature is not between 26ºC and 28ºC it will mean that it is higher than 28ºC so the pump will be switched off using a constant signal of $K = 0$.

If, on the other hand, the temperature is within this range, "$Switch2$" will activate the upper input and switch "$Switch1$" into operation. In the latter case, if the temperature of the upper part is greater than or equal to 36ºC or the temperature of the lower part is greater than or equal to 28ºC, the pump will stop using a constant $K = 0$. If neither of these 2 conditions is met, "$Switch1$" will activate the lower input, causing the pump to operate with $K = 1$.

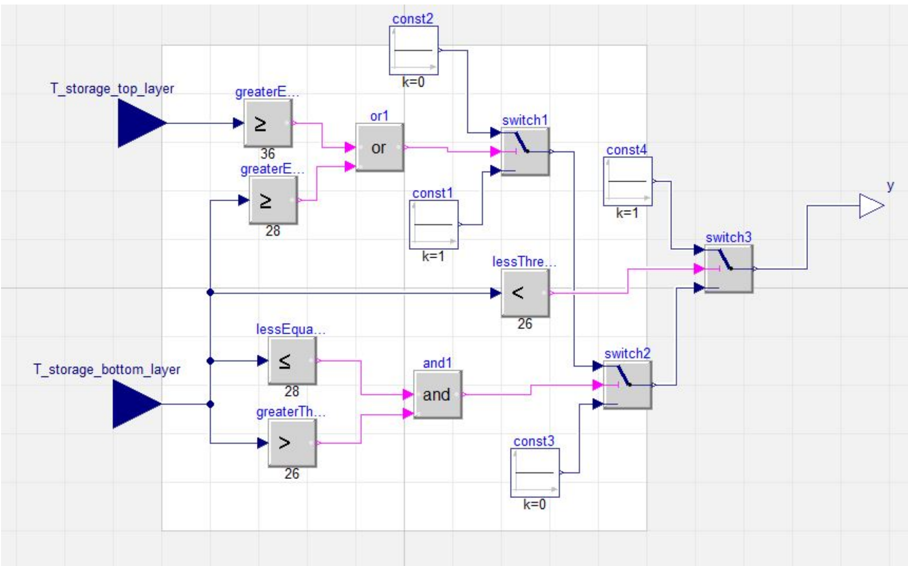

Figure 6.9: Control block for the pump 1 of the second configuration

Pump 2 control block

The function of this controller is to keep the return temperature of the system fixed at 26ºC. The input to the system is the return temperature TS3, which is the variable to be measured in the PI controller. On the other hand, the setpoint is 26ºC, as this is the desired return temperature.

As mentioned with the pump in the first configuration, the pump needs a mass flow input and our PI controller gives an output between 0 and 1. To convert this signal, we multiply the PI output by the maximum flow rate that the pump can give, which is $5.55 kg/s$.

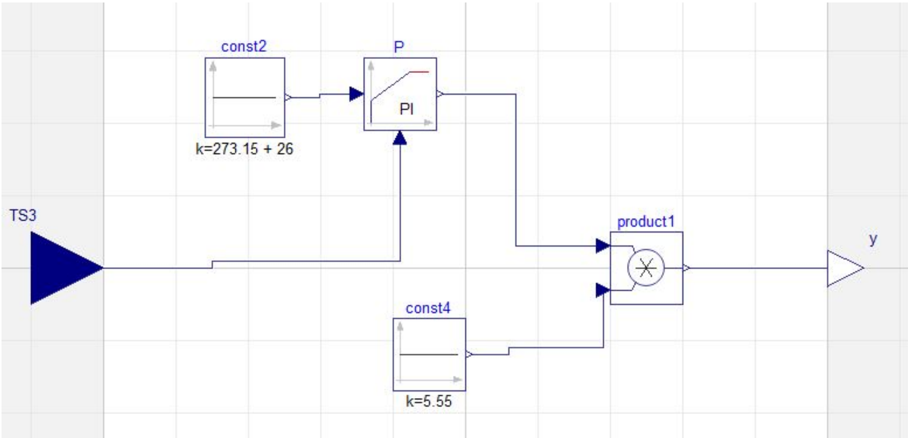

Figure 6.10: Control block for the pump 2 of the second configuration

6.3 Simulation algorithm

The simulation algorithm will be ”*CVODE*” which stands for "Constant Variable Ordinary Differential Equation " solver. CVODE is an efficient solver used for initial value problems in ordinary differential equation (ODE) systems. It is a part of the Suite of Nonlinear and Differential/Algebraic equation Solvers (SUNDIALS). It uses Backward Differentiation Formulas (varying order from 1 to 5) as a linear multi-step method and a modified Newton iteration with fixed Jacobian as a non-linear solver by default. For non-stiff problems, an Adams-Moulton formula (varying order from 1 to 12) as a linear multi-step method, along with a fixed-point iteration as a non-linear solver, can be selected. Both non-linear solver methods are internal functions of CVODE and use its direct dense linear solver CVDense [58].

Advantages [59]:

1. Is a solver that can be used to allow value problems of ordinary differential equation systems with variable-order, variable-a-step multistep methods, making it incredibly versatile.
2. Is part of a larger software suite called SUNDIALS, which includes nonlinear and differential/algebraic equation solvers.
3. It has sensitivity analysis capabilities, allowing for the computation of first-order derivative information, through either forward sensitivity analysis or adjoint sensitivity analysis.
4. Is designed in a data-independent manner, with a highly modular structure that allows the incorporation of different preconditioning and/or linear solver methods. Can solve very large-scale problems on massively parallel computers.

Disadvantages [59]:

1. Is a solver that is specifically designed for ODEs with constant coefficients, limiting its applicability to other types of differential equations.
2. CVODES uses a combination of Backward Differentiation Formulas as a linear multistep method and a modified Newton iteration with a fixed Jacobian as a non-linear solver by default, which may not be the most efficient method for all problems.
3. May require the user to supply their own linear solver module, which may require additional programming skills.
4. May have a steep learning curve for users unfamiliar with the SUNDIALS software suite.

7 Analysis of results

The configurations described in chapter 6 have been introduced in the general model of the 4 buildings that make up suppply station 1, which is shown in the following image:

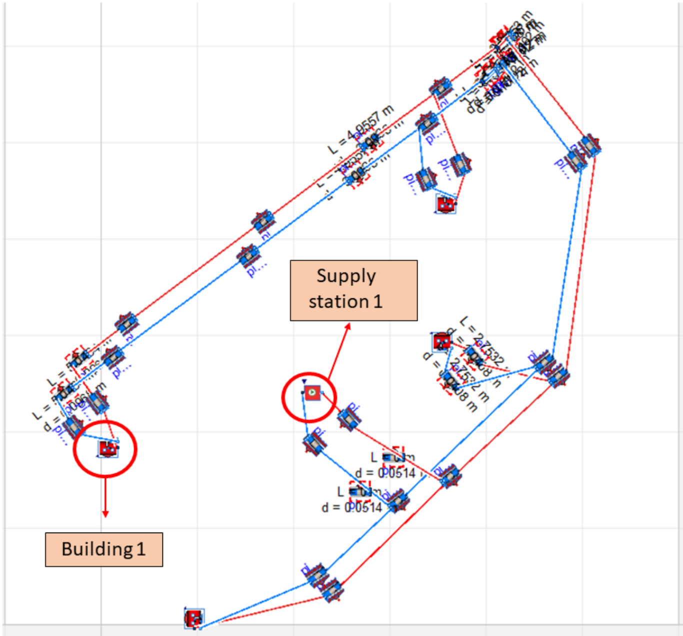

Figure 7.1: Tank based configuration model

Of the four buildings, the analysis of results will focus mainly on the one furthest away, which is number 1, called "*demand*11_1". The reason behind this is that as it is the furthest building from the supply station it is the one with the worst conditions.

7.1 Results of the return temperature based configuration

The main elements of this configuration are the return temperature sensor TS3, the flow rate delivered by the pump and the opening of the motorised valve that controls the flow rate on the primary side V_M.

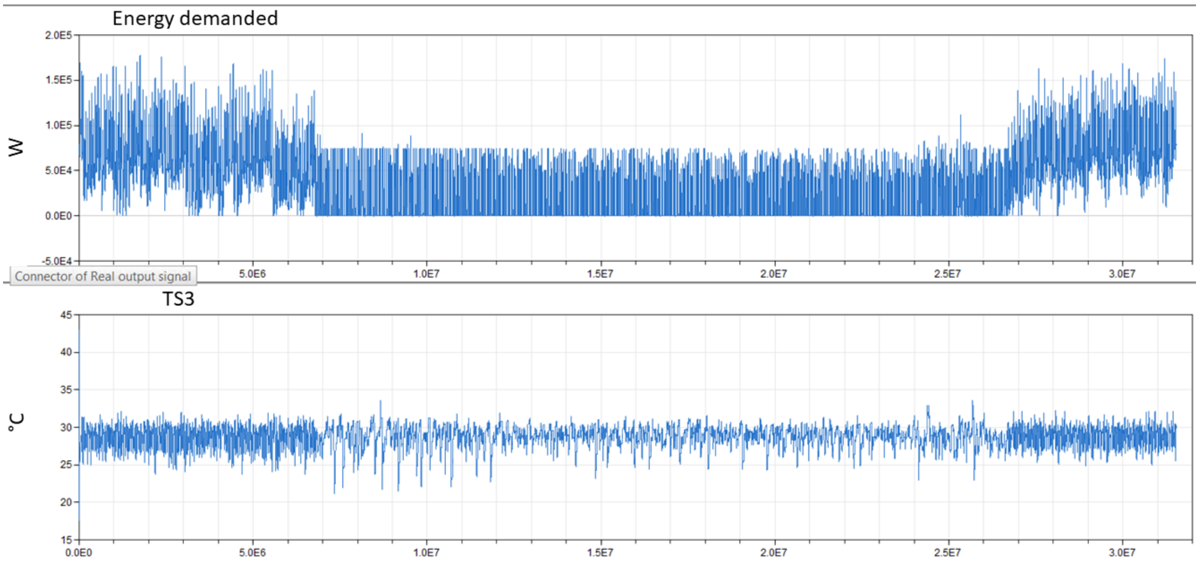

Figure 7.2: Comparison between the energy demanded and the return termperature

The image compares the energy consumption and compares it with the return temperature measured with the TS3 sensor. During the time when the demand is higher the return temperature is more constant. This is due to the delay that the control blocks have, because when the power consumption is no longer zero, the control block takes some time to adjust the flow rate, thus lowering the return temperature.

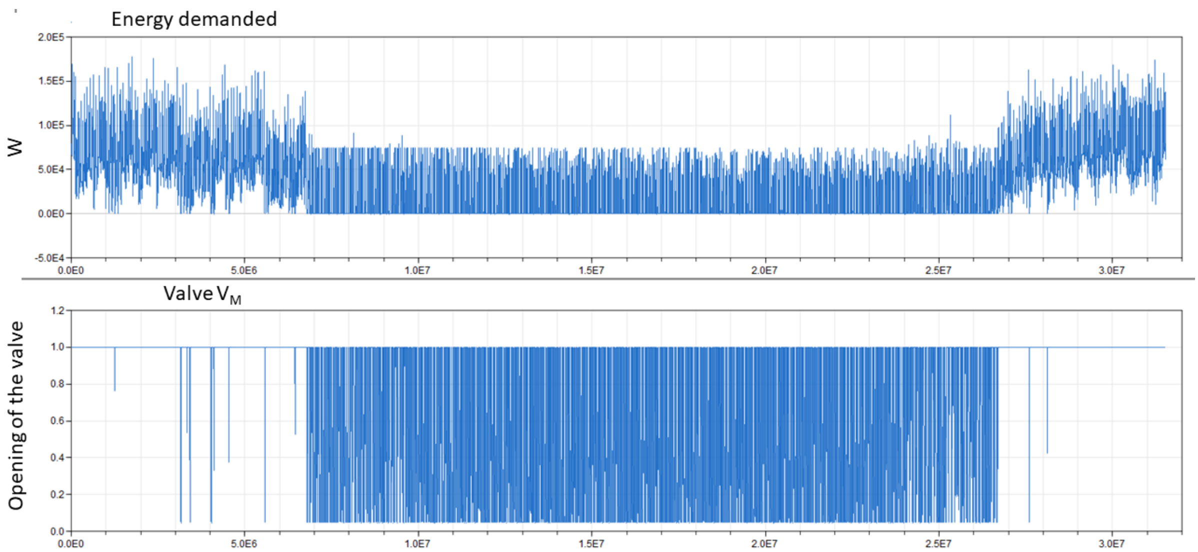

Figure 7.3: Comparison between the energy demanded and the grade of openess of the valve

As for the comparison between the energy demand and the degree of opening of the motorised valve, it can be observed that during the periods of maximum consumption the valve is fully open. During the period when the consumption is constant, it can be observed that the degree of opening of the valve is not constant. This is due to the delay of the controllers as described above.

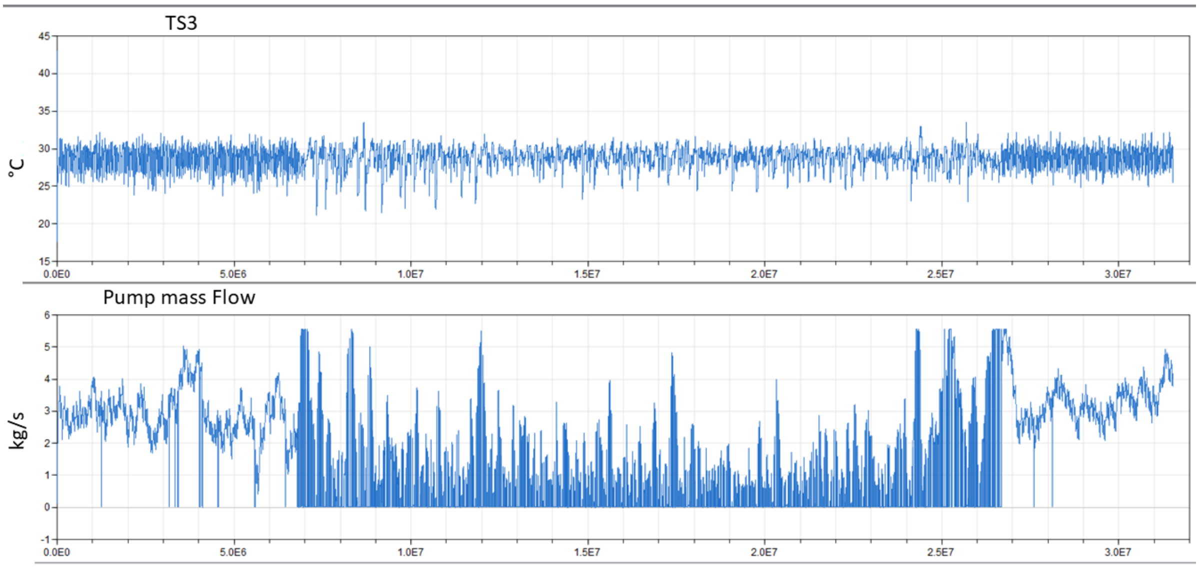

Figure 7.4: Comparison between the return termperature and the flow rate of the pump

In this last picture you can see the relationship between the continuity of the return temperature and the mass flow. In the period of time in which the return temperature fluctuates the most, so does the flow rate delivered by the pump.

7.2 Results of the tank based configuration

The main elements of this configuration are the return temperature sensor TS3, the flow rate delivered by pump 1 and 2, the opening of the motorised valve that controls the flow rate on the primary side V_M, and the temperature of the top and bottom of the thermal storage tank.

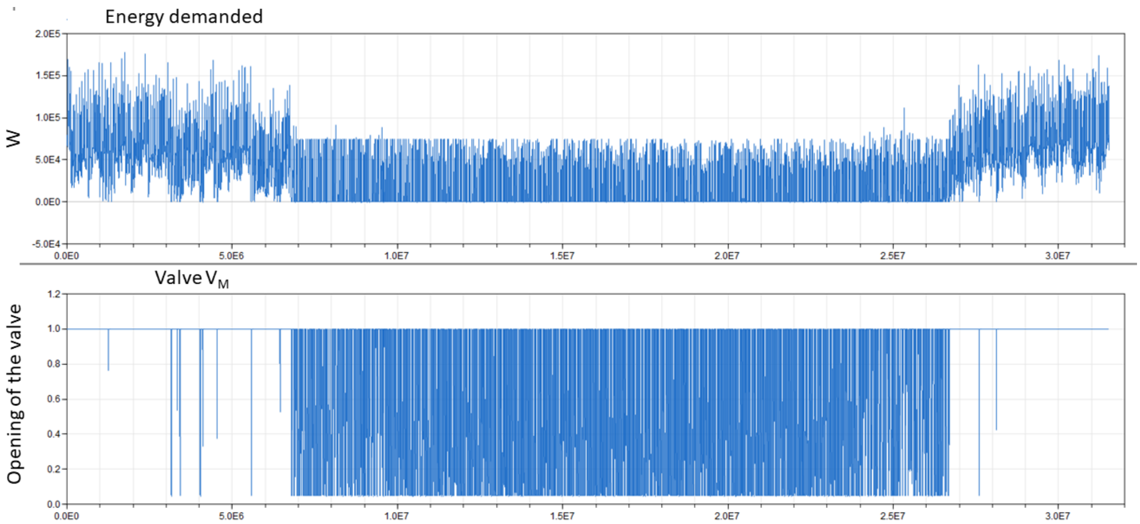

Figure 7.5: Comparison between the energy demanded and the grade of openess of the valve

As in the previous configuration, the same relationship between the degree of opening of the valve and the energy demand is observed. The higher the consumption the higher grade of openess of the valve.

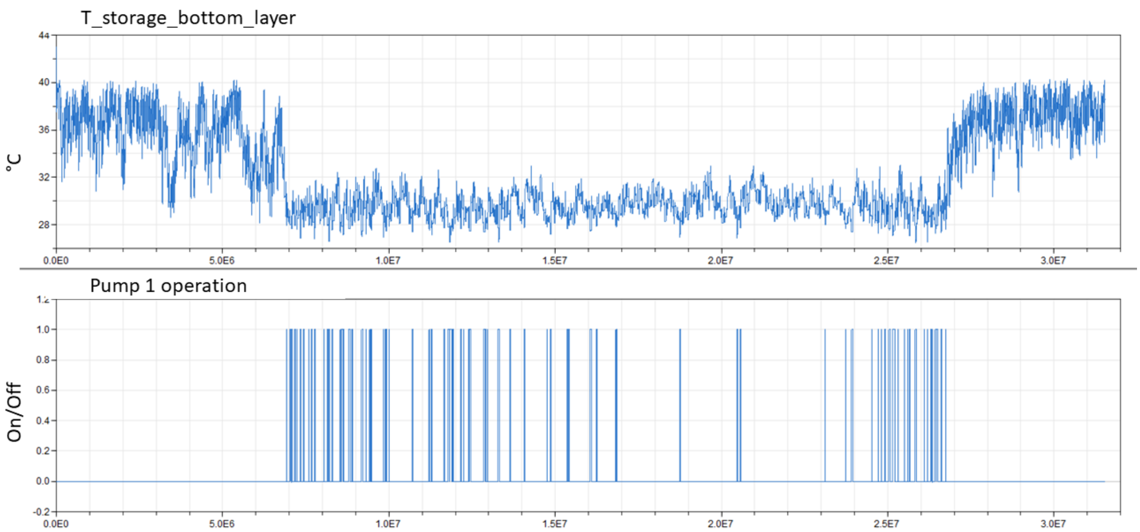

Figure 7.6: Comparison between the temperature of the bottom layer of the tank and operation of pump 1

The temperature of the lower part of the tank is higher during periods of higher energy consumption because more energy is consumed and there is no time for the water to cool down. When the demand stabilises, the water does cool down, and it is only when the temperature drops below the limit that it starts to operate.

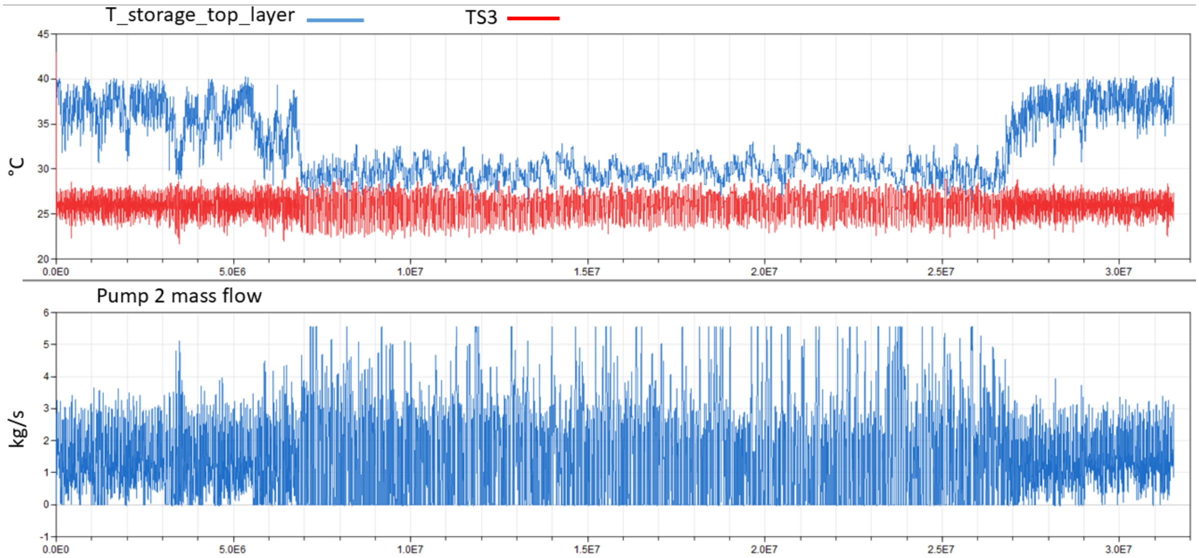

Figure 7.7: Comparison between the temperature of the bottom layer of the tank, the return temperature and the flow rate of the pump 2

When the temperature at the top of the tank drops the flow rate delivered by the pump increases to try to keep the return temperature within the set limit. This is also the reason why the return temperature starts to fluctuate more.

It should be noted that the temperature at the top of the tank drops so low because the tank is not large enough to have a temperature difference as noticeable as the limits imposed.This makes the system prefer to keep the temperature of the lower layer within a certain limit.

8 Conclusions

Looking at the results and looking more specifically at the control signal of both pumps supplying the control point, it can be seen that the response of the first configuration is smoother than that of the second. This is due to the fact that the pump control in the return temperature based configuration has a range of temperatures whereas in the tank based configuration it is a fixed value. Thus, the larger the temperature range to be controlled, the smoother the response of the controller.

Another factor that influences the greater fluctuation of temperatures in the second configuration is the fact that there are more variables to control. The reason behind this is, as mentioned above, the delay in the control blocks. Pump 2 is already delayed by the controller itself, but if we add the delay of the controller of pump 1, the overall delay increases. This causes the temperature to be more frequently above or below the desired values, causing the flow rate to be regulated more abruptly.

The first configuration provides better control because the control is simpler. However, this does not mean that the simpler the control the better. The tank-based configuration, while giving more erratic results, can still be valid for system control. As mentioned above, the biggest problem with configurations that control more variables is the overall delay time of the system. But if the controllers of both configurations were optimised, the second configuration would be able to provide better results than the first given the greater number of variables to control, which increases the potential for optimisation.

In conclusion, the simpler the controller and the fewer variables it involves, the more robust it will be for a low optimisation value compared to a more complex controller. However, for a high degree of optimisation, the controller that involves more variables is better, as it allows a finer optimisation of the operation. The more complex the control system, the higher the optimisation, the greater the complexity of balancing and the greater the number of possible errors. The most important thing for a control system is robustness, which can be achieved by simplicity or by optimisation.

Finally, the aim of this thesis is to establish control configurations and compare them in order to draw conclusions regarding control systems. However, this work can be used as a basis for future projects to optimise the controls shown throughout the thesis. As this work has focused only on the first four buildings supplied by supply station 1, such optimisation is essential before a control structure can be implemented for the rest of the district.

Bibliography

[1] United Nations. *United Nations Conference on the Human Environment, 5-16 June 1972, Stockholm*. United Nations. URL: https://www.un.org/en/conferences/environment/stockholm1972#:~:text=The%20first%20world%20conference%20on,the%20environment%20a%20major%20issue..

[2] Wikipedia. *Sustainable Development Goals*. Wikipedia. URL: https://en.wikipedia.org/wiki/Sustainable_Development_Goals.

[3] Wikipedia. *Paris Agreement*. Wikipedia. URL: https://en.wikipedia.org/wiki/Paris_Agreement.

[4] Wikipedia. *District heating*. Wikipedia. 2023. URL: https://en.wikipedia.org/wiki/District_heating.

[5] Plastic Pipe Institute (PPI). *DISTRICT ENERGY HEATING & COOLING*. Plastic Pipe Institute (PPI). 2023. URL: https://www.plasticpipe.org/BuildingConstruction/BuildingConstruction/-Applications-/DistrictEnergy-Heating-Cooling.aspx.

[6] International District Energy Association. *District Cooling*. International District Energy Association. 2023. URL: https://www.districtenergy.org/topics/district-cooling.

[7] Meg Waltner. *Consideration of Staff Recommendation Regarding Financing District Heating and Cooling Projects*. CALIFORNIA ALTERNATIVE ENERGY and ADVANCED TRANSPORTATION FINANCING AUTHORITY. September 24, 2008. URL: https://www.treasurer.ca.gov/caeatfa/heating_cooling/heating_cooling.pdf.

[8] Miha Kavcic. *District Cooling*. Esmagazine. July 14, 2020. URL: https://www.esmagazine.com/articles/100588-todays-business-case-for-hot-water-district-energy-systems.

[9] International District Energy Association. *District Cooling*. International District Energy Association. 2023. URL: https://www.districtenergy.org/topics/district-cooling.

[10] D2Grids. *5GDHC in short*. D2Grids. 2023. URL: https://5gdhc.eu/5gdhc-in-short/.

[11] Annelies Vandermeulen, Bram van der Heijde, and Lieve Helsen. "Controlling district heating and cooling networks to unlock flexibility: A review". In: *Energy* 151 (2018), pp. 103–115. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2018.03.034. URL: https://www.sciencedirect.com/science/article/pii/S0360544218304328.

[12] Morris A. Pierce. *District Heating And Cooling*. Macmillan Encyclopedia of Energy. September 19, 2023. URL: https://www.encyclopedia.com/environment/encyclopedias-almanacs-transcripts-and-maps/district-heating-and-cooling.

[13] Committee on District Heating and Cooling, National Research Council. *District Heating and Cooling in the United States, Prospects and Issues*. National Academy Press. 1985. URL: https://www.districtenergy.org/topics/district-cooling.

[14] Karnitz, M A. *Description of district heating: US history and current status*. Oak Ridge National Lab., TN (USA). January 01, 1981. URL: https://www.osti.gov/biblio/6801150.

[15] Marwan Abugabbara. "Modelling and Simulation of the Fifth-Generation District Heating and Cooling". PhD thesis. May 2021. DOI: 10.13140/RG.2.2.18483.96809.

[16] Michel Gross et al. "Implementing prosumers into heating networks". In: *Energy* 230 (2021), p. 120844.

[17] O. Angelidis et al. "District heating and cooling networks with decentralised energy substations: Opportunities and barriers for holistic energy system decarbonisation". In: *Energy* 269 (2023), p. 126740. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2023.126740. URL: https://www.sciencedirect.com/science/article/pii/S0360544223001342.

[18] Jonathan Amirmadhi, Muditha Abeysekera, and Jianzhong Wu. "Modelling of Electrical–Thermal-Hydraulic System Interdependencies in 5th Generation District Heating and Cooling Networks". In: (2021).

[19] Nicolas Cuvelier. *ANALYSIS OF THE WORKING OF MIJNWATER B.V. AND POSSIBILITIES TO DEVELOP SUCH A MODEL IN WALLONIA*. Tech. rep. BUREAU D'EXPERTS PH. DEPLASSE & ASSOCIES S.P.R.L., 2019.

[20] HeatNet NWE. *Developing District Heating in North-West Europe*. Tech. rep. North-West Europe. URL: https://vb.nweurope.eu/media/6462/heatnet-nwe_business-case-to-energy-sector-brochure_web.pdf.

[21] Simone Buffa et al. "Advanced Control and Fault Detection Strategies for District Heating and Cooling Systems—A Review". In: *Applied Sciences* 11.1 (2021). ISSN: 2076-3417. DOI: 10.3390/app11010455. URL: https://www.mdpi.com/2076-3417/11/1/455.

[22] National Energy Technology Laboratory. *Thermal Energy Storage*. Tech. rep. U.S. Department of Energy. URL: https://netl.doe.gov/sites/default/files/2021-02/Thermal_Energy_Storage_1Pager.pdf.

[23] HeatNet NWE. *Guide to Integrating 4DHC with Energy Efficiency Retrofitting*. Tech. rep. North-West Europe. URL: https://guidetodistrictheating.eu/wp-content/uploads/2020/05/HeatNet-NWE_4DHC-Energy-Efficiency-Retrofitting_District-Heating.pdf.

[24] Michael Taylor et al. "Model Predictive Control of Smart Districts With Fifth Generation Heating and Cooling Networks". In: *IEEE Transactions on Energy Conversion* 36.4 (2021), pp. 2659–2669. DOI: 10.1109/TEC.2021.3082405.

[25] Marco Wirtz et al. "Temperature control in 5th generation district heating and cooling networks: An MILP-based operation optimization". In: *Applied Energy* 288 (2021), p. 116608. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2021.116608. URL: https://www.sciencedirect.com/science/article/pii/S0306261921001422.

[26] Stef Boesten et al. "5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply". In: *Advances in Geosciences* 49 (Sept. 2019), pp. 129–136. DOI: 10.5194/adgeo-49-129-2019.

[27] Manuel Lammle et al. "Valuation of Novel Waste Heat Sources and a Path Towards Adoption: Preprint". In: (Aug. 2022). URL: https://www.osti.gov/biblio/1885581.

[28] Marwan Abugabbara. "Modelling and Simulation of the Fifth-Generation District Heating and Cooling". English. PhD thesis. Division of Building Services, May 2021. ISBN: 978-91-85415-14-4.

[29] Justus von Rhein et al. "Development of a topology analysis tool for fifth-generation district heating and cooling networks". In: *Energy Conversion and Management* 196 (Sept. 2019). ISSN: 0196-8904. DOI: 10.1016/j.enconman.2019.05.066. URL: https://www.osti.gov/biblio/1544531.

[30] *The Mijnwater 5GDHC Grid in Heerlen*. Tech. rep. URL: https://www.districtenergyaward.org/wp-content/uploads/2019/09/b9508b8e8e7d4e76a0621b8d0c49c629tmp1.pdf.

[31] Justus von Rhein et al. "Development of a topology analysis tool for fifth-generation district heating and cooling networks". In: *Energy Conversion and Management* 196 (2019), pp. 705–716. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2019.05.066. URL: https://www.sciencedirect.com/science/article/pii/S0196890419306211.

[32] Manuel Lammle et al. *Valuation of Novel Waste Heat Sources and a Path Towards Adoption.* Tech. rep. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[33] Ismael Lozano Simone Buffa Mohammad Hossein Fouladfar and Manuel Andrés. *Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks.* Tech. rep. REWARDHeat, Dec. 2020.

[34] Marwan Abugabbara et al. "How to develop fifth-generation district heating and cooling in Sweden? Application review and best practices proposed by middle agents". In: *Energy Reports* 9 (2023), pp. 4971–4983. ISSN: 2352-4847. DOI: https://doi.org/10.1016/j.egyr.2023.04.048. URL: https://www.sciencedirect.com/science/article/pii/S2352484723004092.

[35] Saleh S. Meibodi and Fleur Loveridge. "The future role of energy geostructures in fifth generation district heating and cooling networks". In: *Energy* 240 (2022), p. 122481. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2021.122481. URL: https://www.sciencedirect.com/science/article/pii/S0360544221027304.

[36] Jordi García-Céspedes et al. "Fifth-Generation District Heating and Cooling Networks Based on Shallow Geothermal Energy: A review and Possible Solutions for Mediterranean Europe". In: *Energies* 16.1 (2023). ISSN: 1996-1073. DOI: 10.3390/en16010147. URL: https://www.mdpi.com/1996-1073/16/1/147.

[37] A. Lyden et al. "Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches". In: *Renewable and Sustainable Energy Reviews* 167 (2022), p. 112760. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.112760. URL: https://www.sciencedirect.com/science/article/pii/S1364032122006451.

[38] . *The 5th generation heating and cooling grid of Paris-Saclay.* Construction21. June 2022. URL: https://www.construction21.org/infrastructure/fr/the-5th-generation-heating-and-cooling-network-of-paris-saclay-en.html.

[39] . *Flexibility, key to the Paris-Saclay heating and cooling grid!* Construction21. May 2023. URL: https://www.construction21.org/articles/h/flexibility-key-to-the-paris-saclay-heating-and-cooling-grid.html.

[40] Tangui Lieugard. *Paris-Saclay.* D2Grids. Sept. 2022. URL: https://5gdhc.eu/project-cases/paris-saclay/.

[41] . *5GDHC in practice: recovering heat from abandoned mines.* Construction21. May 2023. URL: https://www.construction21.org/articles/h/5gdhc-in-practice-recovering-heat-from-abandonned-mines.html.

[42] . *Bochum pilot site: 5th generation heating and cooling grid in practice!* Construction21. May 2023. URL: https://www.construction21.org/articles/h/bochum-pilot-site-5th-generation-heating-and-cooling-grid-in-practice.html.

[43] Tangui Lieugard. *Bochum*. D2Grids. Sept. 2022. URL: https://5gdhc.eu/project-cases/bochum/.

[44] . *Brunssum's 5GDHC network digs deep for sustainable heating and cooling!* Construction21. July 2023. URL: https://www.construction21.org/articles/h/brunssum-s-5gdhc-grid-digs-deep-for-sustainable-heating-and-cooling.html.

[45] Tangui Lieugard. *Brunssum*. D2Grids. Sept. 2022. URL: https://5gdhc.eu/project-cases/brunssum/.

[46] Herman Eijdems. *MIJNWATER HISTORY*. Mijnwater Energy B.V. Mar. 2021. URL: https://surd.nl/wp-content/uploads/2020/11/2021-Crossing-Boundaries-5GDHC-netwerken-V3.pdf.

[47] Jon Irvine. "Heat Trace: Importance of Temperature Sensor Placement". In: *Automation Magazine* (Aug. 2013).

[48] . *Thermocouple vs RTDs*. Omega. URL: https://www.omega.com/en-us/resources/rtd-vs-thermocouple.

[49] . *Mass Flow Meter Advantages And Disadvantages*. ZERO Instrument. URL: https://zeroinstrument.com/mass-flow-meter-advantages-and-disadvantages/.

[50] Editorial Staff. *Advantages & Disadvantages of Different Flow Meters*. Inst Tools. URL: https://instrumentationtools.com/advantages-disadvantages-of-flow-meters/.

[51] Grundfos. *Magna 3*. Grundfos. URL: https://product-selection.grundfos.com/us/products/magna-north-america/magna3-north-america?tab=models.

[52] Grundfos. *Introducing the MAGNA3 Circulator Pump*. Grundfos. URL: https://www.grundfos.com/solutions/learn/ecademy/all-courses/the-magna3-circulator-pump-course1/introducing-the-magna3-circulator-pump.

[53] Laura Maier et al. "AixLib: an open-source Modelica library for compound building energy systems from component to district level with automated quality management". In: *Journal of Building Performance Simulation* 0.0 (2023), pp. 1–24. DOI: 10.1080/19401493.2023.2250521. eprint: https://doi.org/10.1080/19401493.2023.2250521. URL: https://doi.org/10.1080/19401493.2023.2250521.

[54] Modelica. *Modelica.Blocks*. Modelica. URL: https://doc.modelica.org/Modelica%204.0.0/Resources/helpDymola/Modelica_Blocks.html.

[55] Modelica. *Package Modelica.Blocks.Math*. Modelica. URL: https://doc.modelica.org/Modelica%203.2.3/Resources/helpMapleSim/Blocks/Math/index.html.

[56] Modelica. *Modelica.Blocks.Continuous*. Modelica. URL: https://doc.modelica.org/Modelica%204.0.0/Resources/helpDymola/Modelica_Blocks_Continuous.html#Modelica.Blocks.Continuous.

[57] Modelica. *Package Modelica.Blocks.Logical*. Modelica. URL: https://doc.modelica.org/Modelica%203.2.3/Resources/helpMapleSim/Blocks/Logical/index.html.

[58] OpenModelica. *Solving Modelica Models: Integration Methods*. OpenModelica. URL: https://openmodelica.org/doc/OpenModelicaUsersGuide/latest/solving.html.

[59] Radu Serban and Alan Hindmarsh. "Cvodes, the sensitivity-enabled ode solver in sundials". In: vol. 6. Jan. 2005. DOI: 10.1115/DETC2005-85597.

Declaration of Originality

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources. This thesis has not been submitted as exam work in neither the same nor a similar form. I agree that this thesis may be stored in the institute's library and database. This work may also be copied for internal use.

Aachen, Friday 10th November, 2023

Alberto Ros