Development and thermal analysis of a 5th generation DHN utilizing data-center waste heat

In collaboration with
Gemeente Amsterdam
AMS institute

MSc. Thesis report

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by

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Abstract

The utilization of waste heat from data centers in low-temperature district heating networks has emerged as a promising trend in the pursuit of enhanced energy efficiency, sustainability, and environmental stewardship. Data centers, known for their significant energy consumption and associated greenhouse gas emissions, have the opportunity to transform into energy providers rather than mere consumers by utilizing their waste heat. This innovative strategy has already gained traction in the Nordic regions, where the waste heat from data centers is harnessed to heat buildings and communities, thereby decreasing reliance on fossil fuels and cutting carbon emissions. Through leveraging waste heat, data centers can markedly reduce their environmental impact, thus aiding in the promotion of a more sustainable future. This transition towards waste heat utilization is essential for the data center sector to reach its net-zero energy targets, alleviate its environmental footprint, and support the global transition to a low-carbon economy. By optimizing energy efficiency, data centers can become a crucial component of sustainable urban development, fostering a healthier environment for future generations.

This report investigates the potential of utilizing residual heat that is continuously produced by the data centers by incorporating low-temperature district heating systems in the Amsterdam neighbourhood. The research highlights the possibility of data centers as a dependable source of waste heat and its integration into low-temperature district heating networks. This will thereby contribute to a more sustainable and energy-efficient future. The study scrutinizes the feasibility of waste heat utilization in a detailed manner, down to the component level. The results from the study presented here are discussed at a component as well as, a system-wide scale. Moreover, the paper elaborates on the potential of low-temperature district heating networks in Amsterdam neighborhoods undergoing upcoming refurbishments involving improving the housing insulation and a shift towards addressing energy poverty. The conclusions drawn from this research have the potential to encourage similar research endeavors aimed at large data centers across diverse regions.

Acknowledgement

I wish to convey my deepest appreciation to all individuals who rendered assistance during the process of completing my Master thesis report. Primarily, I am profoundly thankful to my academic mentor at the institution, Professor Kamel Hooman, for his invaluable direction, perceptive feedback, and unwavering motivation. The expertise and commitment he has shown were pivotal in shaping the outcome of this study. Furthermore, I wish to express my sincere gratitude to Richard Ruijtenbeek from the Municipality of Amsterdam, whose pragmatic perspectives and assistance played a vital role in the successful implementation of this endeavor. His support and collaboration facilitated the completion of this work and significantly enhanced my educational journey.

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Nomenclature

Abbreviations

Abbreviation	Definition
AMC	Hospital neat AM5 data center
AM5	Data center name
ATES	Aquifer Thermal Energy Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
DHN	District Heating Network
EPC	energy performance coefficient
GIS	geographic information system
HE	Heat exchanger
HP	Heat Pump
LTDH	Low temperature District heating
OD	Outside diameter
PE	Poly Ethylene
PV	photovoltaic
QGIS	Quantum geographic information system
SINK	Heat demand customer
SOURCE	Heat recovery station
5GDHC	5th generation District Heating and Cooling

Symbols

Symbol	Definition	Unit
$\dot{V}$	volume flow rate	$[m^3/s]$
ν or V	average fluid velocity through pipe	[m/s]
A_cross	Cross-sectional area	$[m^2]$
d or D	pipe diameter	[m]
δp	pressure difference between two points	[Pa]
ρ	Density	[kg/m^3]
ζ	Pressure loss coefficient	dimensionless
$\dot{Q}$	heat transfer rate	Watts or [J/s]
C_p	specific heat capacity	[J/(kg*K)]
δT	Temperature Difference	[K]
Q	Heat output	[kW]
W	Electrical input	[kW]
hf	head loss due to friction	[m]
f	Darcy friction factor	dimensionless
L	pipe length	[m]
g	gravitational acceleration	$[m^2/s]$
ε	roughness height of pipe	[m]
Re	Reynolds number	dimensionless
μ	dynamic viscosity of the fluid	[Pa-s]

1
Introduction

1.1. Background

District energy, encompassing district heating and cooling, is a permanent fixture in the energy landscape, particularly as the world shifts towards sustainability. Its historical presence underscores its current significance in the realm of decarbonizing heating and cooling systems.

District heating, identified as heat networks, is a mechanism utilized to distribute heat produced in a centralized facility/decentralised (latest generations) via a network of pipelines for both residential and commercial heating needs, encompassing space heating and water heating. The heat is commonly derived from a cogeneration plant fueled by fossil fuels or biomass, though heat-only boiler stations, geothermal heating, heat pumps, central solar heating, and heat waste from industrial facilities and nuclear power generation are also employed.

The attractiveness of district heating as a viable option has grown over time due to various factors. Initially, district heating facilities have the capacity to deliver superior efficiencies and enhanced pollution management compared to decentralized boilers. Moreover, the utilization of district heating in conjunction with combined heat and power (CHP) is regarded as the most cost-effective approach to reducing carbon emissions, exhibiting one of the most minimal carbon footprints among all fossil fuel power plants. With the persistent global challenge of climate change, district heating is poised to assume an increasingly crucial role in diminishing our dependence on fossil fuels and alleviating the repercussions of global warming.

District heating facilities may achieve superior efficiencies compared to decentralized boilers as a result of various factors. A primary contributing factor is the capacity of district heating facilities to employ cogeneration, also referred to as combined heat and power (CHP), for the simultaneous production of heat and electricity. This approach, commonly known as waste heat recovery, enables district heating facilities to capture and utilize heat that would otherwise be dissipated in traditional power generation processes. Through the concurrent generation of heat and electricity, these facilities can attain overall energy efficiencies reaching up to 90%, in contrast to the 40-50% range typical of conventional decentralized boilers. [31]

Another element enhancing the efficiency of district heating facilities is their capability to function on a larger scale. By leveraging economies of scale, district heating facilities can invest in more efficient and sophisticated technologies, including high-efficiency boilers, heat pumps, and thermal storage systems. These technologies contribute to minimizing energy wastage, optimizing energy utilization, and enhancing the overall efficiency of the system. [20]

The integration of renewable energy sources also proves pivotal in augmenting the efficiency of district heating facilities. Through the incorporation of renewable sources like biomass, geothermal, solar, and waste heat, these facilities can diminish their dependence on fossil fuels and decrease carbon emissions. Renewable energy sources offer a reliable and consistent supply of heat, thereby enhancing the efficiency and performance of the district heating system.

To sum up, the higher efficiencies achievable by district heating facilities in comparison to decentralized boilers stem from their capacity to leverage co-generation, operate at a larger scale, and integrate renewable energy sources. By capitalizing on these aspects, district heating facilities can furnish a more efficient, sustainable, and economically viable heat source for residential and commercial structures.

Over time, district energy has evolved to meet evolving requirements, often in response to the need for cost-effective solutions and efficient use of space. This evolution has also addressed concerns regarding energy efficiency and the pursuit of sustainable objectives. The progression of district energy can be delineated into five distinct generations, each marking significant technological advancements. The various generations/development in district heating networks are discussed herewith in the following sections.

1.2. The 5 generations of District heating and cooling

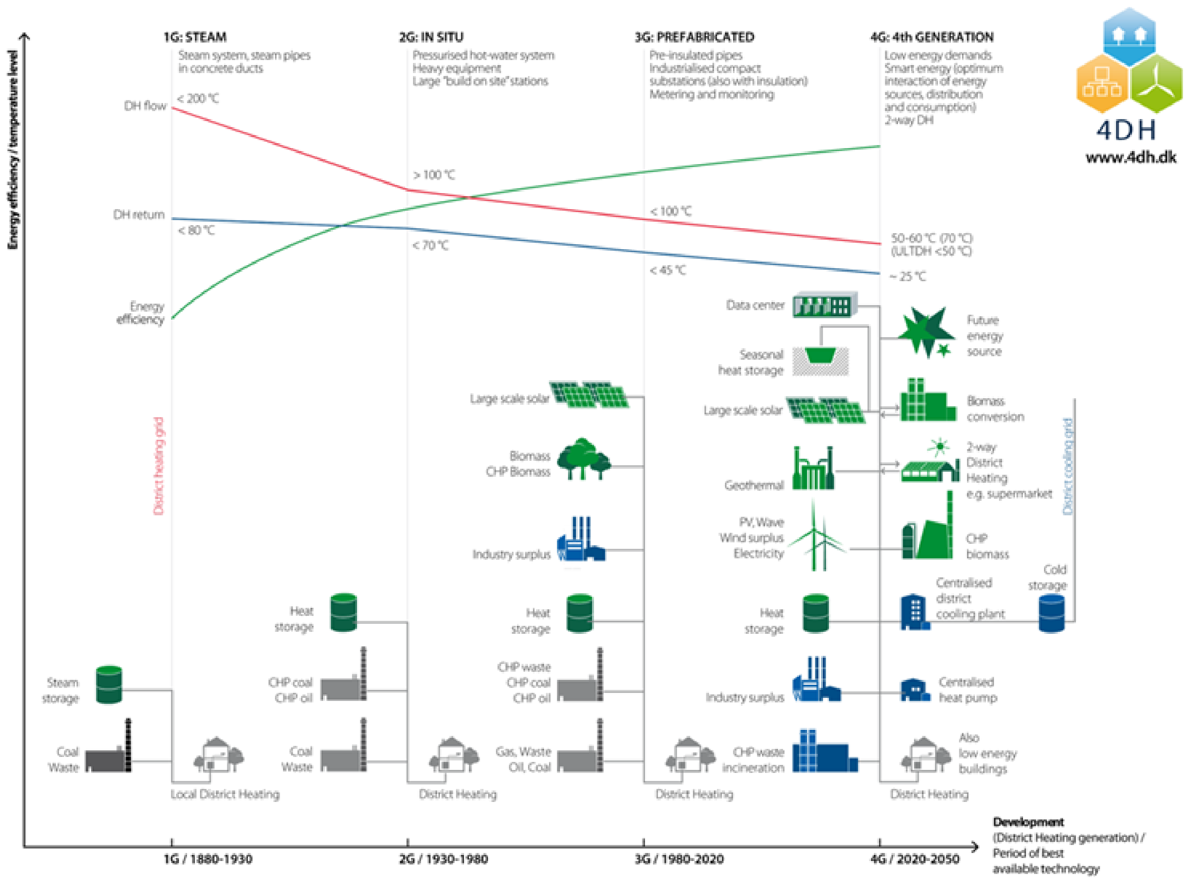

Figure 1.1: Comparison of various DHN generations and development over the years[9]

Figure 1.1 shows the various different generations off DHN over time development. In this section we will discuss the various generations in detail.

1st generation DHN: The primary feature of the 1st generation district heating system involved the conveyance of thermal energy through steam at temperatures of up to 180°C - 200°C. Consumer sectors included small urban industries utilizing steam for operations, as well as significant heat users like hospitals and large residential compounds. The substantial heat density leading to reduced mass flow rates acted as a key factor in the perpetuation and adoption of this method.

2nd generation DHN: The primary feature of the second-generation District Heating system is the transmission of heat through pressurized superheated water at temperatures exceeding 100°C. This disparity is notably observed in contrast to the first-generation DH systems, which rely on steam for heat transportation.

This era facilitated the effective utilization of waste heat from power plants, facilitating their transformation into combined heat and power (CHP) plants. Through harnessing waste heat from power plants, the consumption of fossil fuels witnessed a 50% reduction compared to the distinct production of heat and power conducted in the initial generation.

3rd generation DHN: The material and labor lean components applied in conjunction with generally lower temperatures (below 100°C) were introduced by the 3rd generation DH system. An enhanced energy efficiency is the primary advantage of the third generation DH system over the 2nd generation DH system, attributable to reduced operating temperatures. Moreover, there are decreased investment and operation costs due to increased prefabrication, pre-assembly, and pre-insulation at the factory. Additionally, modifications to the fuel mix include the incorporation of greener and renewable sources, leading to reduced emissions.

4th generation DHN: In the wake of the 3rd generation, a novel trajectory emerges marked by the transition of the energy system towards a sustainable and interconnected paradigm. This paradigm hinges on a significant proportion of variable renewable sources for heating and cooling, intelligent amalgamation of the energy domains, and concurrently decreased building energy consumption alongside supply and return temperature levels.

The above mentioned generations depend on centralized heat plants for the conversion of the energy source into heat at levels of temperature that are readily usable by the end-user. The fifth generation is adopting a distinct strategy: supplying the energy source directly to the consumer, who employs their heating system to transform the energy source into heat at a readily exploitable temperature threshold.

5th generation DHN: For the 4th gen DHN, limitations are not imposed on the form or type of primary energy source utilized and central heat plants. In the context of the 5th generation, the primary energy source consists of low-quality heat, which is insufficient for direct utilization due to its low levels, primarily stemming from ambient heat sources. The heating plant in this generation is characterized by the use of a building-level or end-user heat pump.

From a technical perspective, the relocation of the heating plant from a centralized position to the end-user offers various advantages. One such benefit is that the distribution heat losses may diminish significantly, rendering them inconsequential, given that no energy has been expended in elevating the input energy, ambient heat, to viable temperature thresholds. Eliminating distribution losses renders pipe insulation inconsequential, theoretically resulting in a more cost-effective distribution network. Additionally, the heat plants (end-user heat pumps) can be customized to meet the temperature needs of individual end-users, potentially enhancing heat generation efficiency in theory. Furthermore, there is the potential to incorporate cooling capabilities into the same system by allowing the end-user heat pumps to function in a cooling capacity and channel the excess heat into the distribution grid. [14]

In Europe, the heating of buildings stands out as a significant contributor to CO2 emissions. Following the reduction of heating requirements in buildings, heat pumps emerge as a prospective technological solution in the journey towards carbon-neutral urban areas and enhanced air purity.

Heat pumps utilize a quantity of free renewable energy, specifically thermal energy that is accessible in the external atmosphere, the earth, or bodies of water. A minimal amount of energy is essential for heat pumps to convert the available thermal energy into energy at practical temperature thresholds. The Coefficient of Performance (COP) is the term used to denote the ratio of useful energy supplied to the electrical energy required. This factor primarily relies on the temperature differential between the external free source and the necessary heating temperature: a greater discrepancy necessitates a higher usage of electrical energy. Heat pumps have the capability to provide both heating and cooling services.

In this project, there may be value in utilizing the low grade waste heat as thermal energy to feed a large central heat pump or multiple smaller heat pumps, all contributing to or propelling a comprehensive district-wide heating network. By doing so, the modest heat source can be effectively harnessed and expenses can be distributed among numerous beneficiaries. [1]

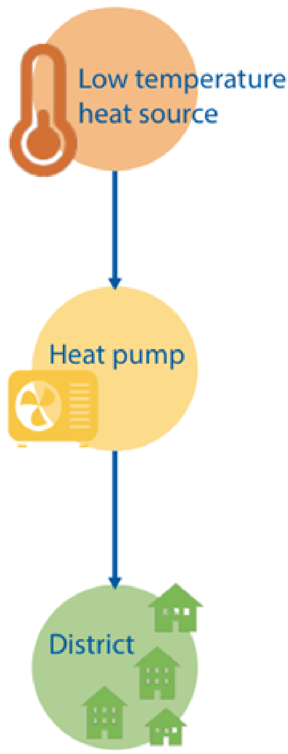

Figure 1.2: Basic DHN flow

Additionally district heating powered by heat pumps offers a direct interface with the electrical grid. The operational flexibility of these heat pumps, which can be enhanced by connecting them to thermal storage systems, holds significant potential for facilitating the integration of increasingly variable renewable energy sources into the electricity production framework. In addition to its environmental advantages, this approach has the capacity to improve the financial viability of heat pump operations. Figure 1.2 shows a basic work flow of the same.

Also the 4th and 5th generation networks exist at a reduced scale. Urban areas typically lack access to centrally located low-temperature heat sources with adequate power capacity. Consequently, these sources are dispersed across various locations, necessitating a decentralized and small-scale approach to heat distribution. Heat pumps plays a major role to employ this idea to district heating.

1.3. Working of a Heat pump

In the initial stage, low-temperature heat is extracted from a source with low temperature. The extraction of heat at low temperatures is utilized to enhance the energy content of the heat pump medium through evaporation, transitioning the liquid phase to a gaseous phase. The effectiveness and efficiency of this process rely on the selection of a heat pump medium capable of evaporating suitably at the low temperature of the heat source, underscoring the absence of a universal heat pump choice for various district heating systems driven by heat pumps.

In the subsequent stage, the current gaseous phase undergoes a rise in temperature through the elevation of pressure. This process is executed utilizing a compressor. The compressor needs electrical power to propel the substance to the requisite temperature threshold for dispensing heat on the side with high temperatures.

The third phase requires the high-temperature gas to transmit heat to the building's heating system through a heat exchanger. This energy outburst lowers the particle's energy content. The primary release occurs when the gaseous phase transitions to the liquid phase, even though the pressure does not change significantly.

The liquid's pressure is released in the last step, which causes the temperature to drop. The same medium will now begin to evaporate at a lower temperature as a result of this temperature drop. Thus, the cycle might begin over. This process is depicted below by the Figure 1.3.

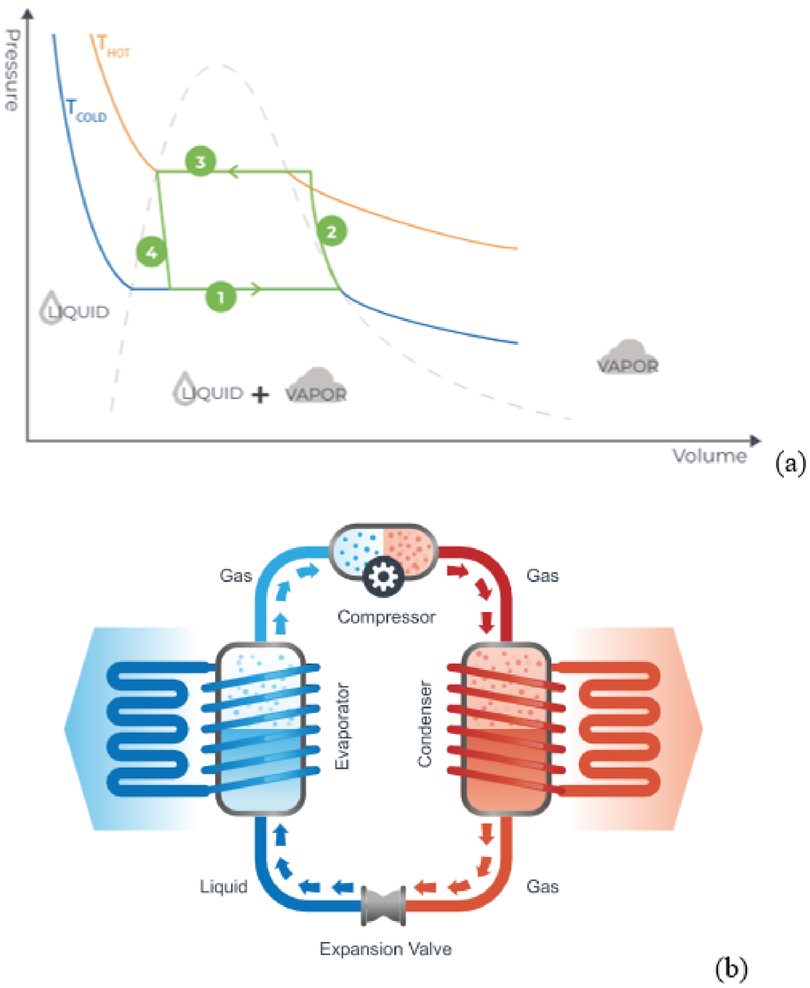

Figure 1.3: Working of a heat pump depicted by a (a) graph showing compression and expansion cycle. (b) schematic of the heat pump [10]

Another important aspect of district heating network to focus in urban areas is the temperature at which the heat to be distributed is circulated through the network. District heating systems have historically operated at elevated temperatures, with some even utilizing steam. This approach facilitated the connection of a diverse range of buildings with varying heat emission systems. The evolution towards more energy-efficient and environmentally conscious buildings has led to the development of alternative heating solutions. Presently, the deployment of fourth and fifth generation district heating systems is underway. Ongoing research is investigating the feasibility of a sixth generation, focusing on upgrading district heating systems up to the fourth generation. The research is based on the assumption of consistent temperature levels from the heat source. Any fluctuations in temperature throughout the year would have dual consequences on the system.

1. It would impact the COP of heat pumps across all scenarios.
2. It would significantly influence the capacity of the distribution grid.

The assessment of temperatures must also consider the geographical distribution or intensity of the heating and cooling requirements, along with the necessity for thermal equilibrium of the low-temperature heat source in the context of geothermal energy.

As we move forward to utilise low grade heat with increasing generations we have the following major benefits [12]:

1. Exergy efficiency and COP are higher due to renewable energy integration.
2. Lower thermal losses and transition to renewable energy sources.
3. Utilizes advanced technologies like bidirectional pumping and thermal energy storage.
4. Decentralised system and a close energy loop.

1.4. The five principles of 5GDHC

The Figure 1.4 presented below shows the five major principles of a 5th generation district heating network. Each of the principles are detailed in this section hereafter.

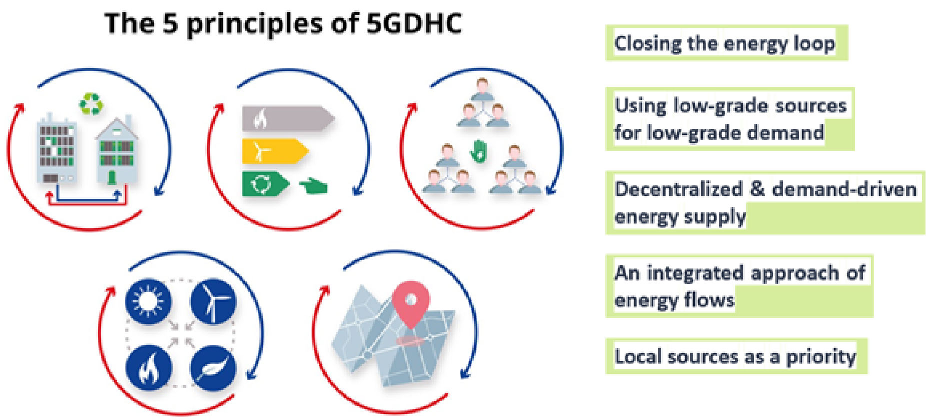

Figure 1.4: The 5 principles of 5GDHC

1.4.1. Closing the energy loop

The primary focus of 5th generation District Heating and Cooling is centered on minimizing energy wastage within the system. 5GDHC networks stand out from other District Heating and Cooling networks due to their ability to transfer energy to interconnected consumers, forming a closed-loop thermal network. This network operates in a circular manner, aiming to maximize energy reuse: buildings that are heated dispense cold to the DHC system, while cooled buildings transfer excess heat to the network. The key emphasis in the 5GDHC strategy lies in efficiently reusing return flows across various spatial and temporal scales. Energy storage plays crucial role in managing temporal discrepancies between energy supply and demand within the system, on both a daily and seasonal basis.

An example of this principle in action is the application of heat pumps in sustainable building designs to produce the required supply temperatures. These heat pumps derive their energy input from external sources like air, water, or soil. While this necessitates investments in source infrastructure that occupy space and may cause disruptions, the energy output is dissipated into the environment. In contrast, within the 5GDHC framework, the waste heat from these heat pumps is integrated back into the system through grid connection, preserving the return flow of energy.

1.4.2. Using low grade source for lower demands

Energy sources can be categorized based on their preferred applications. Fundamental to the concept of 5GDHC is the analysis of the required heating and cooling needs of the network, with energy input being supplied at the necessary quality level. A 5GDHC system primarily relies on low-grade energy sources to fulfill a significant portion of its heating and cooling requirements, as opposed to high-grade (high exergy) sources. This implies that low-grade energy sources such as shallow geothermal, industrial waste streams, waste from conversion processes, cooling-related waste, sewage, etc., are prioritized for meeting any additional heating or cooling demands not satisfied through internal exchanges within the system.

In order to increase the effectiveness of 5GDHC, a proper ranking of energy sources is suggested for utilization in the heating and cooling network of 5GDHC. Higher priority is accorded to thermal energy exchanged among users, followed by ambient thermal sources and renewable thermal sources exceeding the grid's typical 'warm' temperature. The final position in the energy hierarchy is occupied by grey electricity, which is generated from fossil fuels.

1.4.3. Demand driven and decentralized energy

Older energy systems are centralized and circulate a lot of energy which is in fact never used and thus wasted. On the other hand, 5GDHC systems are characterized as "demand-driven", initiating energy generation and circulation solely in response to demand. Thus energy wastage is minimized, as it is generated precisely when and where it is required. Consequently, temperature adjustments are executed only at the necessary time and place. The 5GDHC system has the capability to provide heating and cooling services concurrently at varying temperatures tailored to individual customer needs.

Operationally, 5GDHC represents a transition from large centralized (often monopolized) facilities to a network of interconnected small end-user devices that collaborate within an intelligent network.

1.4.4. Integrated approach

Many energy systems exhibit split incentives, whereby they fail to optimize the integral needs across various systems and sectors. For example, a building owner relying on electricity, causing high peaks in the regional power grid, who may wish to warm the building in the morning following a setback at night. The utilization of thermal mass and buffers may require additional investments for the building but can result in significant savings on the power grid. The aim of 5GDHC is to enhance the maximum efficiency of energy delivery and utilization by adopting an integrated approach to all energy flows within a specific area, including the power grid, transportation, industry, agriculture, and more.

Integrating a 5GDHC network with the electricity grid not only facilitates energy savings but also aids in balancing the electricity grid and enhancing its flexibility. Consequently, this contributes to the development of smaller and more efficient energy infrastructures, with reduced embedded energy in both materials and operations. By operating with smaller peak capacities, the system will also require lower overall investments in infrastructures such as pipelines, pumps, heat pumps, and others, thus decreasing the necessary capacity of the electrical power connection.

1.4.5. Local source utilization

Local sources constrain transportation losses and curb energy wastage. However, the advantage also pertains to expenses. In fact, grand schemes are frequently devised on a significant magnitude with remote energy origins, disregarding societal expenses, which ultimately translate into costs for the consumers. Local sources signify energy that is geographically confined and necessitate financial outlays to enhance grid.

1.5. City heat from Data-centre

Data center facility where business-critical ICT equipment is stored and where both the equipment (such as servers) and data maintain uninterrupted connectivity to the Internet. The level of connectivity varies significantly across different types of data centers. In order to ensure continuous availability, data centers are furnished with multiple redundant facilities. This explains why data centers encompass a substantial facility area (referred to as grey space) in addition to the data floor area (known as white space). Data centers are being contemplated as a potential heat source for city heat demand in district heating networks for various reasons discussed herewith. The recovery of waste heat is a key factor as data centers produce a substantial amount of heat during their operations. Although this heat is typically wasted, it has the potential to be reclaimed and harnessed for heating nearby structures or even entire urban areas. The reliability and consistency of data centers are important factors to note, given their continuous operation. Thus ensuring a steady supply of heat to meet demand.

Also on a city level, the scalability of data centers is advantageous due to their ability to handle large heat loads, rendering them appropriate for supplying heat to entire cities or commercial zones. The proximity of data centers to areas with heat demand is another significant aspect. As they are usually in close vicinity to urban regions, the requirement for extensive heat distribution infrastructure reduces largely, thereby presenting a more efficient and cost-effective alternative. Energy efficiency increases by the utilization of waste heat from data centers. This reduces the dependence on fossil fuels and reduce greenhouse gas emissions. Cost savings are very much achievable as data centers can supply heat at a reduced cost overtime compared to conventional heat sources like boilers or heat pumps.

In the present project the data center in Amstel 3, Equinix AM5 is used as the principle source of residual heat which can be disconnected up to a maximum of 10MW. The low-grade residual heat from the data center is to be used for peak space heating in the neighborhood (Reigersbos and Holendrecht Amsterdam, Netherlands). This would require integrating heat pumps with the network, centralized or de-centralized system. With the introduction of new houses/buildings, it leaves a scope to extend and optimize the network as the energy demand is modified.

1.6. Problem statement and challenges

1. Development - As there is no pre-existing network, the network needs to be developed from scratch. Thus requiring to propose an initial backbone to work upon.
2. Collaboration and social aspect - Increase of buildings that are energy efficient proves that there's consumer interest for more green energy initiative. Thus aspects effecting the development of the network also includes: Consumer willingness to join the network and data collection (Privacy hand in hand with precise data collection is questionable)
3. Financial aspects – a qualitative differentiation between Capital expenditures and Operational expenditures for all the considered scenarios.
4. Recommendations - To identify future scope of the project.

2

Literature review

2.1. Agenda Gemeente Amsterdam

The Netherlands has set a goal to phase out natural gas as the primary source of heat supply for more than 7 million households by 2050 in the National Climate Agreement (2019) (also known as the ”Klimaatakkoord”). A new, environmentally friendly heating system is required for these homes to cut down on greenhouse gas emissions.

The Dutch government has set a first-step aim of connecting 1.5 million homes to a new heating system by 2030. Municipalities are taking the lead in developing a heat plan (or ”Warmteplan”) as part of the National Climate Agreement, which will specify the design of every neighbourhood’s future sustainable heating system. The city of Amsterdam recently released its ”Transitievisie Warmte” (heating transition vision). Their goal is to link 250,000 domestic equivalent units—the number of homes that would require the same amount of thermal energy to provide space heating and hot water—to the current 70°C district heating network. Currently, this district heating system provides the equivalent of 102,000 homes. Amsterdam also plans to connect 85,000 similar households to a district heating network with a 40°C - 20°C temperature Warmteplan [4]. As Amsterdam is the location of the significant (AM 4 AND 5) internet exchange point, data centres may be significant in this. These data centres’ heat will need to be recycled. The scope of low temperature district heating network using data-centers as primary heat source is as shown by Figure 2.1 here by Amsterdam heat guide [3]: (Yellow zones).

The data center market is experiencing robust growth and this upward trend is projected to persist. In the Netherlands, the Amsterdam region has traditionally served as a prominent hub for data centers, attributed in part to the presence of the AMS-IX internet exchange; 72% of colocation data centers are situated in the MRA. Amsterdam also holds a prominent position within the European landscape. The consistent provision of energy, extensive connectivity, and the advantageous, steady political environment in the Netherlands have contributed to this status.

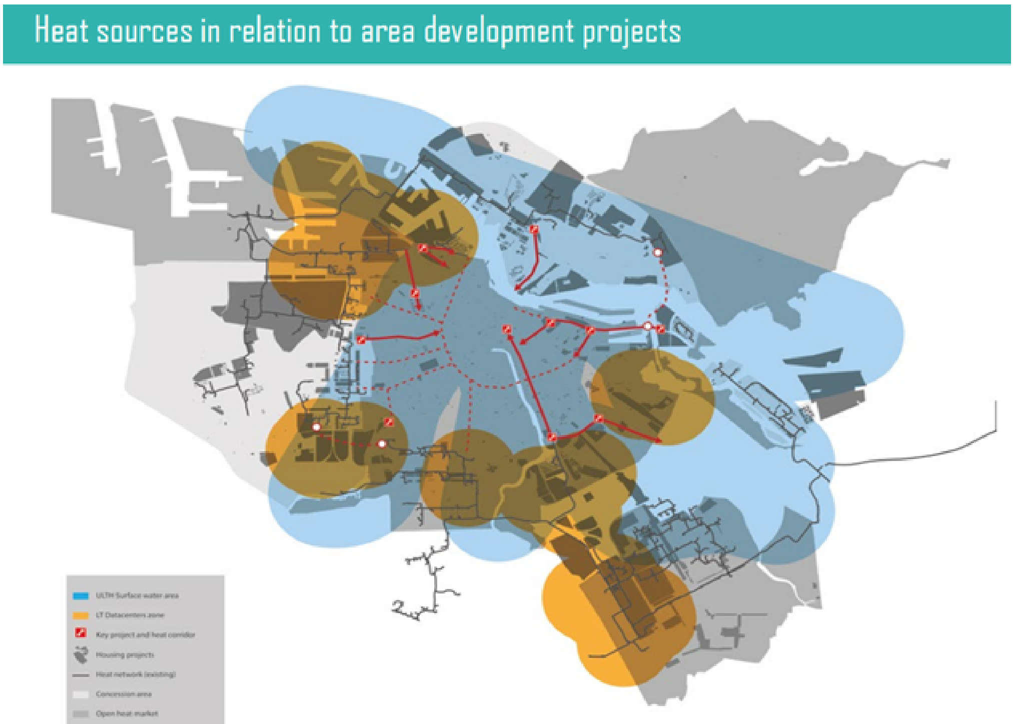

Figure 2.1: Heat sources in Amsterdam in relation to development area [3]

2.2. Research and case studies

Stanislav Chicherin [7] presented a technique in this study for predicting heat recovery from data centers. The study presents a 5th generation district heating and cooling infrastructure for the same. The significance of water-based cooling systems is highlighted in relation to optimizing energy usage and reducing carbon emissions.

Jordi García-Céspedes [12] in his paper has highlighted the following aspects: Exergy-Efficient Decarbonization: The study underscores the significance of shallow geothermal energy (SGE) and 5th-generation district heating and cooling (5GDHC) networks as the most exergy-efficient combination for decarbonizing residential and tertiary buildings. This particular pairing effectively aligns low-grade demands with low-grade energy sources, thereby providing a flexible approach to different configurations.

Synergistic Effect of SGE and 5GDHC: The interdependent connection between SGE and 5GDHC networks is highlighted as a pivotal factor for effective implementation in urban settings. This merging, particularly when integrated with solar photovoltaics and energy storage, offers a hopeful resolution for reducing carbon emissions in the heating and cooling sector.

Barriers to Deployment: The research paper pinpoints two primary non-technical obstacles impeding the widespread integration of SGE throughout Europe. These obstacles encompass the substantial capital investment required for ground-source heat pumps (GSHPs) and the insufficient awareness among governmental organizations, academic institutions, investors, and the general populace. Economic incentives and the notion of Integrated Local Energy Communities (ILEC) are suggested as potential strategies to surmount these challenges.

In this scholarly article, the authors Gianni and Daniele [23] have delineated a comprehensive blueprint of a prototype substation belonging to the 5th generation. This undertaking aims to authenticate the functionality and oversee the efficacy of this particular substation model through empirical investigation.

The research paper is centered on the development of a prototype for a 5th generation district heating substation in Brescia, Italy, tailored for ultra-low temperature networks. During the design phase, there was a careful selection of components like a bidirectional pumping system, a reversible water-to-water heat pump, a heat exchanger, and an inertial thermal energy storage to enhance the substation's efficiency. A thorough examination was carried out to identify the most appropriate refrigerant for the heat pump, leading to the selection of R134a due to its optimal performance within the temperature range specific to the case study. The performance of the heat pump connected to the grid was assessed, revealing a notable enhancement compared to an independent air-to-water heat pump solution. This played a critical role in ensuring the effective operation and performance monitoring of the 5th generation substation prototype in a practical environment.

The examination of the literature that was carried out by Uwe [29] in the present study was centered on the methodologies utilized for organizing data related to district heating, a process that entails the generation of heat at a central facility and its distribution to end-users through a network of pipelines. Diverse approaches were considered, encompassing those that rely on consumption data as well as those that are based on heat load/demand data.

The PRISMA flow chart was employed to sift through more than 60 articles and carry out the review of literature, leading to the identification of 12 papers that specifically tackle the organization of district heating data. The majority of these papers made use of either the K-means methodology directly or a methodology that is founded on K-means. An important discovery was the research gap detected in terms of data sources and method explanations originating from eastern Europe, indicating a necessity for further exploration in this geographical area to improve the organization of district heating data.

The scholarly article by Ieva and Armands [26] a hybrid methodological strategy is employed to analyze the waste heat capacity of data centers in district heating systems in Latvia. This methodology consisted of four primary stages:

- Development of a statistical computation method for estimating the waste heat capacity. Execution of a stakeholder questionnaire to assess energy usage trends.
- Visualization of quantitative findings to evaluate technical capacity and distribution trends. Application of system dynamics modeling to assess potential adoption scenarios for the technological solutions.

The research provided suggestions for incorporating data center waste heat into district heating systems based on system dynamics simulations, offering insights into potential tactics and possibilities for optimizing the utilization of this energy source.

The research paper presented by Marco and Thomas [38] conducted a survey among utility companies and engineering offices in order to acquire data regarding 53 5th Generation District Heating and Cooling (5GDHC) systems in Germany. This particular survey encompassed technical, economic, and political metrics, along with design choices. The outcomes of the survey reveal that 5th Generation District Heating and Cooling (5GDHC) infrastructures in Germany are predominantly designed for small newly constructed districts comprising fewer than 100 buildings. The primary heat sources identified in the examined networks include horizontal geothermal collectors, present in 23 networks, and geothermal probes, utilized in 17 networks. Moreover, about 74% of the networks surveyed not only supply heat but also deliver cold to the buildings connected to them. The network temperatures observed in the surveyed 5GDHC networks typically fall within the range of -5 to 20 °C.

The investigation done by David and Viktoria [17] revolves around the advancement of fifth-generation district heating and cooling (5th DHC) systems The objective mainly focus on reducing carbon emissions from space heating, cooling, and domestic hot water use. The analysis employed the thermal energy grid simulation tool TEGSim in order to develop an ultra-low-temperature district heating network which is later customized to the unique features of the region, integrating borehole thermal energy storage used for long-term storage.

Numerous models regarding thermo-hydraulic pipe networks have been explained and used in existing literature. Academic research models have been formulated and predominantly executed through MATLAB or Python programming. Conversely, commercial software packages like TRNSYS and IDA-ICE incorporate specific network calculation capabilities. Moreover, various component libraries have been developed utilizing the Modelica language. The operation of these models necessitates a run-time setting, where advanced commercial Modelica platforms such as DYMOLA and SIMULATIONX are frequently obligatory.

Oppelt et al.[25] introduced a framework for modeling district cooling networks, utilizing the Lagrangian technique for the representation of thermal dynamics in the pipeline system and executing the computational solution in MATLAB. In contrast to the prevalent Euler method that employs a fixed spatial coordinate system, the Lagrangian method involves the observer moving along with the fluid, thereby circumventing spatial discretization. Another methodology was outlined by Menapace et al.[24], which also adopts a Lagrangian approach. This method segregates the resolution of hydraulic and thermal equations, utilizing the GCA solver (based on Newton-Raphson) for the former and an explicit numerical method for the latter. The specific details of the software implementation are not delineated.

A thorough examination of literature on modelling tools for district energy systems can be located in the studies conducted by Allegrini et al.[2] and Schweiger et al.[32]. Within TRNSYS, there are existing models for the simulation of thermal network pipes, which have been utilized in various case studies, as evidenced by the research of Bestenlehner et al.[5]. Perschk [27] introduced an adapted version of TRNSYS that enables the resolution of hydraulic equations, a feature not included in the original iteration. However, this revised version is currently inaccessible to both the research community and industry.

Furthermore, the current numerical solution techniques commonly encounter performance issues as the system scales up in size. Real-world scenarios with larger networks often necessitate simplification of physical complexity for computability [15]. Moreover, techniques such as aggregation are employed to streamline the network's structure [22][11]. Notably, in the realm of Modelica-based solutions, there is a distinctive presence of prolonged symbolic analysis and model preparation durations alongside extended simulation periods, especially with an increasing number of differential equations. This issue has been extensively discussed by Casella [6], who highlighted various numerical challenges that arise when dealing with extensive systems of equations in Modelica.

The model used in this report has been used to dismiss these challenges. The phenomenas such as the temperature-dependency of kinematic viscosity and a Darcy friction factor contingent on the flow regime are explicitly taken into account in the model. The sophisticated numerical solution methodology exhibits good scalability even with extensive district network models. Furthermore, the model is integrated into SIM-VICUS [33], a publicly available software with a graphical user interface, enabling access for other scholars for scrutiny and thorough examination, as well as for industrial applications. Moreover, the incorporation adheres to the FMI standard, ensuring compatibility with numerous other simulation tools, and facilitating the interaction of the network model with specialized geothermal heat exchanger models.

3 Methodology

Modelling a 5th generation district heating network requires complex tools/computational methods. This is done to ensure accurate results before a heating network is planted in real to work. Over a long period of time tools like Modelica, TRYNSYS, Energy Plus have been used to design and analyse district heating networks.

A significant number of models and simulation tools are available in existing literature, but there are still some concerns that have not received sufficient attention. Specifically, in 5GDHC low temperature networks - the temperature ranges from 5 to 20 degrees Celsius, which necessitates the use of fluids with antifreeze additives, such as propylene glycol or ethylene glycol. Although the densityand most of the other properties of the fluid do not fluctuate much within this temperature range, kinematic viscosity can change by approximately 200% [16]. Unfortunately, this critical factor is often overlooked by most of the models discussed above and in literature.

In addition, 5GDHC network pipes usually lack proper insulation, leading to considerable heat exchange with the surrounding soil and between the supply and return lines. Regrettably, numerous models were initially developed for well insulated pipe networks, and heat loss calculations often employ simplified methods. In many cases, models fail to account for thermal resistances resulting from fluid convection and heat conduction through the pipe wall.In addition to this generally, the soil temperature is approximated using a one-dimensional radial symmetrical model, with an undisturbed ground temperature serving as the surrounding environment boundary condition.

Furthermore, existing solution methods often struggle with larger systems due to performance limitations. Real-world challenges frequently involve extensive networks, which necessitate simplifications to enable computation. A common approach is to apply simplification techniques to the network topology, particularly in Modelica-based solutions. These solutions are infamous for their extended symbolic analysis, model preparation times, and longer simulation times as the number of differential equations grows. Casella [6] has thoroughly documented these numerical challenges when solving large systems of equations in Modelica, emphasizing the difficulties inherent in such models. Taking into account the above mentioned problems. A suitable numerical modelling tool was selected that helped to subside many of the above mentioned problems.

3.1. Realization of the Data-centre heat capacity

3.1.1. Residual heat Supply

There exists a data center located in Amstel 3 named Equinix AM5, where it is feasible to detach residual heat of up to a maximum of 10MW in prospective scenarios. This residual heat, otherwise wasted can be brought to use in neighbourhood and be utilised thus promising greener future.

At present, an excess of 2MW of residual heat is being allocated to refurbished structures. It remains viable to disconnect a range of 7-8MW for potential utilization as a heat reservoir for proximate regions. The fundamental premise lies in the utilization of residual heat in alignment with the current system configuration on Paasheuvelweg.

3.1.2. Disposal of residual heat

This research assesses the neighborhoods within Gaasperdam by utilizing key figures and public data. The estimated amount of residual heat sales for existing residences totals around 16.8 MW. For the redevelopment zones of Holendrecht Centrum, Reigersbos Centrum, and Senso 1 and 2, the expected residual heat sales amount to approximately 2.3 MW. A simultaneity rate of 50% has been computed, and this assumption needs validation in a subsequent phase.

3.2. Energy Label and Data Collection

In the Netherlands, the classification of buildings is determined based on an energy label scale ranging from A to G, where A signifies the highest level of energy efficiency and G denotes the lowest level. The energy label assigned to a building is established on the basis of its energy performance coefficient (EPC), which considers various elements such as insulation, heating, ventilation, and lighting. The EPC value is denoted in kWh/m2 per year and is computed utilizing a standardized approach. Structures with an EPC below 0.6 receive an A rating, while those with an EPC of 1.5 or above are designated with a G rating. Buildings falling within the EPC range of 0.6 to 1.5 are allocated a label between A and G, contingent upon their specific EPC value. This is shown by Figure 3.1 and 3,2 below.

It is of significance to highlight that the Netherlands has recently implemented a novel energy label grading system, ranging from A++ to G, with A++ representing the utmost energy efficiency and G indicating the lowest level of energy efficiency. This updated scale aims to mirror the escalating energy efficiency standards of modern constructions and to stimulate the refurbishment of pre-existing structures to enhance their energy efficiency. Furthermore, the Netherlands has also enforced a fresh directive mandating all buildings to possess an energy label by the year 2020, and for all leased properties to exhibit a minimum energy label of C or higher by 2023.

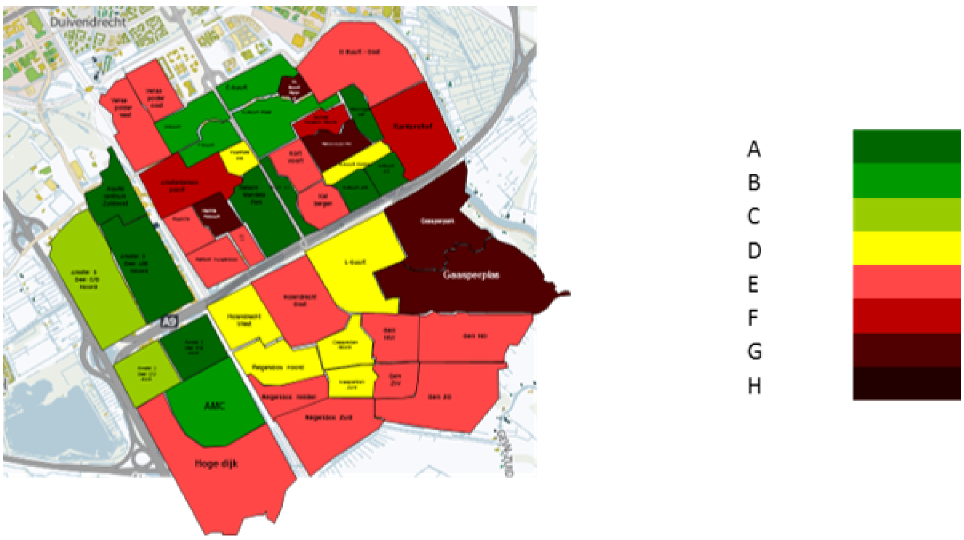

Figure 3.1: Energy labels for establishments Reigersbos and Holendrecht area Amsterdam

The heat demand data per hour for a whole year was extracted from the **TNO WARMTEPROFIEL GENERATOR** tool. In the setup, the data is referenced to the year 2019. As the data provided is for old establishments, the new set out vision and plan by Gemeente Amsterdam was considered for the manipulation of the data as also mentioned above under [Disposal of residual heat].

Energiela bel NV	Gebruiksoppervlakte volgens NTA 8800 <25 m² Eensgezin	Meergezir	>=25 m² en < 40 m² Eensgezin	Meergezir	>=40 m² Eensgezin	Meergezins	Energiela belklasse	EP-2 vanaf 1 januari 2021 KWh/m²
	52	48	48	44	44	40	A++++	<= 0,00
	52	48	48	44	44	40	A+++	0 – 50,00 (nieuwbouw)
A	52	48	48	44	44	40	A++	50,01 – 75,00
A	48	44	44	40	40	36	A+	75,01 – 105,00
A	44	40	40	36	36	32	A	105,01 – 160,00
B	40	36	36	32	32	28	B	160,01 – 190,00
C	36	32	32	28	22	15	C	190,01 – 250,00
D	32	28	22	15	14	11	D	250,01 – 290,00
E	22	15	14	11	8	5	E	290,01 – 335,00
F	4	1	4	1	4	1	F	335,01 – 380,00
G	0	0	0	0	0	0	G	>380

Figure 3.2: Energy labels for establishments explained as per energy demand in kWh/m^2

3.3. Recognizing the potential neighbourhoods to connect to the network

Knowing the waste heat energy capacity that can be recovered from the data centre to be 10MW. The areas of the neighbourhood that can be connected to the heat network were realised as per the yearly peak space heating demand. **In the following research only the heating energy requirement for space heating was taken into account**. These areas were mapped and are as shown in Figure 3.3:

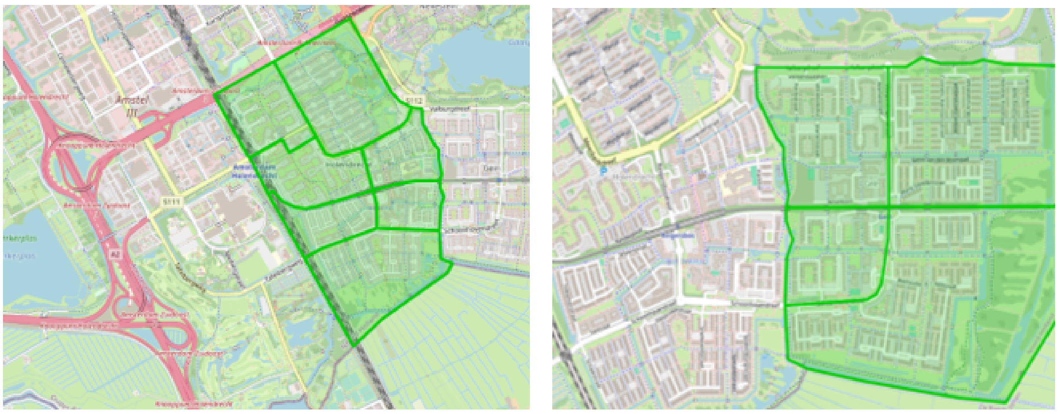

Figure 3.3: Reigersbos and Holendrecht area Amsterdam (the area of interest for this project)

3.4. Network Layout in QGIS software

QGIS [28], recognized as a geographic information system (GIS) application, facilitates the visualization, modification, reproduction, and interpretation of geospatial data across various data structures. Formerly identified as Quantum GIS, QGIS operates as GIS software, enabling users to scrutinize and modify spatial data, as well as create and export graphical representations. The software accommodates raster, vector, mesh, and point cloud strata, with vector information being classified as point, line, or polygon components. Various configurations of raster graphics are compatible, and QGIS possesses the capability to perform georeferencing on images.

As per the data sets available from the **TNO WARMTEPROFIELGENERATOR** [35] the SINK points were set up for the decided neighbourhood. The SINK points represents a cluster of houses/buildings. Smaller groups of the same were preferred to provide more flexibility and convenient distribution topology to the network. The building/house clusters were addressed and divided into groups ranging from a peak space heating demand of 400 kW to 1200 kW. By operating with smaller peak capacities, the system will also require much lower overall investments in infrastructures such as pipelines, pumps, heat pumps, thus decreasing the necessary capacity of the electrical power connection. Having smaller cluster as a base of distributed energy network can also help with future integration of local heat sources into the base network backbone of the DHN.

Thus the SINK points and the SOURCE (Space heating clusters described above are referred to as SINK and the AM5 in combination with the recovered heat from AMC is referred to as the SOURCE) are as depicted here by the Figure 3.4

Figure 3.4: The DHN network backbone mapped on the QGIS software

In Fig. above, the red points shows a yearly peak space heating demand of >=700 kW whereas the blue points show a yearly peak of <700kW. The complete network setup was done to introduce a base backbone connecting the neighbourhood from the SOURCE to the SINKs. The setup details are as follows:

- Length of the network: 5334 m
- No of SINK points: 13
- SOURCE point: 1
- Working fluid: Ethylene glycol 30% (30% ethylene glycol + 70% water)

The use of the 30% concentration in district heating networks is prevalent due to its ability to strike a favorable equilibrium between freeze protection and heat transfer efficiency. By lowering the freezing point of water, the ethylene glycol mixture renders it suitable for application in outdoor pipelines and heat exchangers, even amidst low temperatures.

There are multiple more reasons for the same. Firstly, it ensures freeze protection by impeding water from solidifying within outdoor pipelines and heat exchangers, even in severely cold conditions. Additionally, its heightened specific heat capacity compared to water enables the absorption and release of more thermal energy per unit of mass, thereby enhancing the overall efficiency of the district heating network. Lastly, the corrosion-inhibiting properties of ethylene glycol safeguard the pipelines and equipment against corrosion and ensuing damage.

3.5. Network import to SIM-VICUS

SIM-VICUS software [33] facilitates the examination of thermal losses and pressure reductions through dynamic thermo-hydraulic simulation. It involves the integration of existing GIS data for this purpose. The software also employs efficient algorithms to establish the network topology. It assists in sizing complex heat networks based on either pre-existing or tailored pipe databases.

Furthermore, the software aids in the configuration of supply and sub stations, incorporating unique models for circulation pumps, controlled valves, heat pumps, and heat exchangers using parameters from data sheets. The monitoring of all parameters is done continuously through false color visualization and visually adjusted pipe diameters. Additionally, the software allows for the export of the finalized network topology in geoJSON format.

The model works with closed-loop pipe District heating networks. The following assumptions are established[16]:

- The fluid within the network is incompressible.
- As there are minimal changes in the relevant temperature range, the density and heat capacity are considered constant
- Thermal conductivity and kinematic viscosity can be temperature-dependent, as they may exhibit significant variations (up to 200%) within the considered temperature range.
- Mass conservation within the network.
- The temperature of the fluid stays consistent within individual fluid volumes. Extensive pipes have the ability to be segmented into numerous fluid volumes in the direction of flow. Every other component retains a sole fluid volume with an unchanging temperature.
- The heat capacity of pipe walls is regarded as supplementary thermal storage capacity within thermal balances.

3.5.1. Network connection and initial load definitions

To setup the working model of the District heating network backbone in SIM-VICUS the network was conceptualised with needed calculations and discretization as per the following consideration. This subsection explains the solution methods and the working of the DHN model setup in the software:

- The network is conceptualized as a system comprised of nodes and components. These components exhibit specific characteristics.

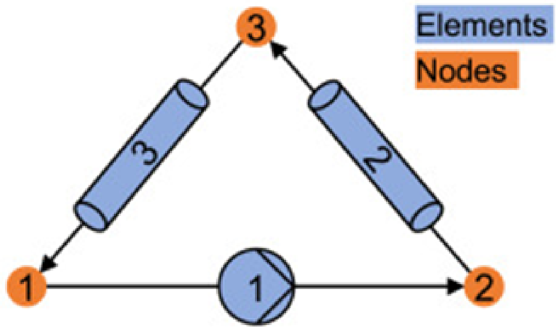

Figure 3.5: Network conceptualized as a system comprised of nodes and components[16]

- Components encompass a variety of hydraulic entities distinguished by pressure differentials, such as pumps, pipes, and valves.
- Every component is equipped with a singular inlet and outlet for fluid flow, with the network configuration determining the connection of nodes as either inlet or outlet points.
- The conservation of mass flux within a component ensures uniformity on both sides, rendering them unsuitable for modeling expandable storage containers. Given the incompressibility and constant density of the fluid medium, such components are typically unnecessary in network representations. Moreover, components uphold energy conservation principles through enthalpy exchange, contingent on the direction of mass flux, and potential heat transfer interactions with external surroundings or other elements in the model.

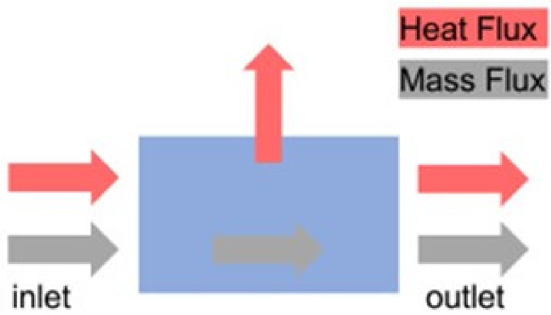

Figure 3.6: Conservation of mass flux within a component [16]

- Each component possesses an energy state that remains constant, housing a finite volume of fluid with an associated heat capacity. The temperature of the component or its distribution is derived directly from the preserved energy content within the component.

3.5.2. Pipe definition and sizing

Dimensioning of hydraulic network pipes involves the objective of determining the necessary pipe diameters during nominal (steady state) operation. This necessitates the consideration of various parameters such as the nominal heating demand (Qnom), temperature difference (Delta-Tnom) at each substation, physical characteristics of the network fluid, maximum permissible pressure drop per unit pipe length, and a range of feasible inner pipe diameters.

The algorithm then follows the following steps:

1. Find the most efficient route from the origin to every distribution point by employing Dijkstra's algorithm [37]. The pathway generated is recorded as a collection of interconnected segments. If

there are several starting points, the route to the nearest point is chosen. Despite the potential adequacy of a more straightforward approach, the advantage of Dijkstra's algorithm lies in its ability to be utilized across various network configurations, encompassing interconnected networks.

2. For every substation, the mass flux at nominal conditions is determined by the heating demand at nominal conditions (Qnom) and the temperature difference (Delta-Tnom). This calculated mass flux is allocated to all edges located on the established flow path of the substation, as identified in step (1). Consequently, network edges in proximity to the source exhibit a higher assigned mass flux, whereas those at a distance have a lower assigned mass flux.
3. For every edge, the pressure reduction is computed based on the assumption of the minimum pipe diameter that is available. If the calculated pressure decrease exceeds the specified maximum limit, the subsequent larger pipe diameter is selected for recalculation. If the pressure drop is lower or there are no larger pipe diameters available, the existing pipe diameter is retained. Consequently, each edge is allocated a specific pipe diameter, concluding the network sizing algorithm.

Limitations allotted due to underground crowding: PE 400 (OD) – PE 110 (OD). This data was provided by the municipality of Amsterdam, as they account for the underground pipe crowding information. All the pipes allotted to undergo the pipe sizing algorithm are as shown by the figure 3.7 below.

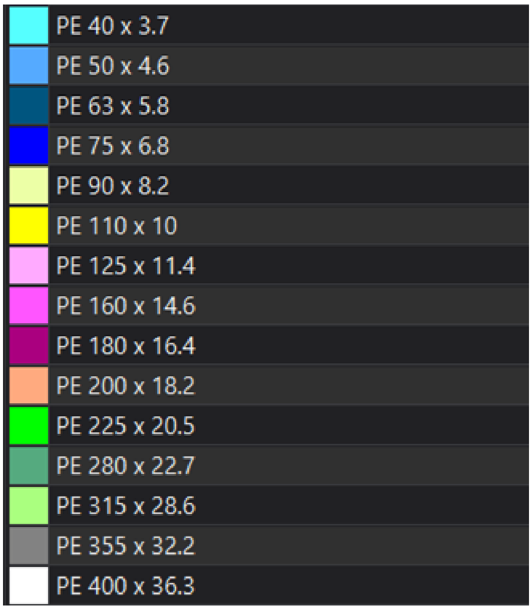

Figure 3.7: List of pipe inputs setup for pipe sizing analysis

The pipe setup was done manually in the software by defining each pipe characteristics separately. While selecting the pipes the commercial availability was kept in mind and a reference sheet was used (available in APPENDIX 1). An example of the same is depicted by the figure 3.8 shown below.

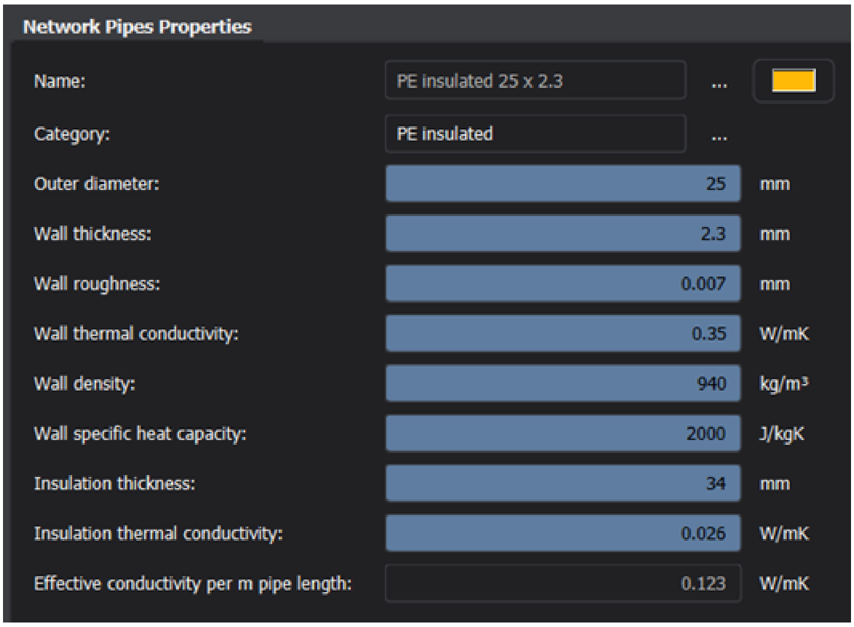

Figure 3.8: Example of pipe definition as an input for the analysis

As per the literature the starting working fluid circulation velocity for the simulations were taken to be around 1.5 m/s [18]. The initial values can further be adjusted as the results are gathered from iterations during simulation of the network. The various formulations used to size the pipes and attached components like circulation pump and heat pump connections are as follows:

$$\nu = \frac{\dot{V}}{A_{\text{cross}}} = \frac{\dot{V}}{\frac{\pi}{4}d^2} \tag{3.1}$$

ν: This represents the average velocity of the fluid flow through the pipe.

$\dot{V}$: This represents the volume flow rate, which is the volume of fluid passing a point in the pipe per unit time.

Across: This represents the cross-sectional area of the pipe.

$\frac{\pi}{4}d^2$: This is the formula for the area of a circle, where 'd' is the diameter of the pipe.

$$\Delta p = \frac{\zeta v^2}{2\rho} \tag{3.2}$$

Δp: This represents the pressure difference between two points in the pipe due to the flow.

ζ: This is a dimensionless factor known as the "loss coefficient" which accounts for energy losses due to friction between the fluid and the pipe walls. It depends on factors like the pipe roughness and the flow rate.

v^2: This represents the square of the average velocity.

ρ: This represents the density of the fluid.

The loss coefficient (ζ) in the pressure difference formula is a dimensionless factor that accounts for energy losses due to friction between the fluid and the pipe walls. Various factors can influence the loss coefficient, including:

Pipe Roughness: The roughness of the pipe's inner surface can significantly affect the loss coefficient. Rougher surfaces cause more friction, leading to higher energy losses and a larger loss coefficient.

Flow Regime: The flow regime, or the nature of the fluid flow, can also impact the loss coefficient. Laminar flow, characterized by smooth and parallel fluid layers, generally results in lower loss coefficients compared to turbulent flow, which is characterized by chaotic and irregular fluid motion.

Pipe Geometry: The geometry of the pipe, such as its length, diameter, and shape, can influence the loss coefficient. For example, sudden changes in pipe diameter, elbows, and valves can cause significant energy losses and increase the loss coefficient.

Fluid Properties: The properties of the fluid, such as its density and viscosity, can also affect the loss coefficient. For instance, fluids with higher viscosity experience more friction and thus have higher loss coefficients.

Flow Velocity: The velocity of the fluid flow can impact the loss coefficient, as higher velocities generally result in higher energy losses and larger loss coefficients.

It's important to note that the loss coefficient is often determined empirically through experimental data or published correlations, as it can be challenging to predict analytically due to the complex interactions between the fluid and the pipe. Finally, to account for the amount of heat transferred to and back from the pipes (with a mass flow rate) we use the formulation given below.

$$\dot{Q} = \dot{V}\rho c_p \Delta T \tag{3.3}$$

Q: This represents the heat transfer rate through the pipe.

$\dot{V}$: This represents the volume flow rate.

ρ: This represents the density of the fluid.

c_p: This represents the specific heat capacity of the fluid, which is the amount of heat required to raise the temperature of a unit mass of the fluid by one degree.

ΔT: This represents the temperature difference between the fluid entering and exiting the pipe.

Thus to get the proper diameter for the pipe and the needed hydraulic diameter for the central circulation pump, heat pump and heat exchanger fed into the software database, we end up with the following formulation given below.

$$d = \sqrt{\frac{\dot{Q}}{\rho c_p \Delta T v \frac{\pi}{4}}} \tag{3.4}$$

Here in the above equation, d is the pipe diameter. This is the same procedure flow that is followed to get to the hydraulic diameter compatible to the pumps, heat exchangers and heat pumps used in the simulation. The d was calculated as above and provided as an input to the software. This is referring to the components modelled and used in the setup for various substations, discussed later in the report.

After running the sizing algorithm in SIM-VICUS for both the scenarios, the allotted PE pipe-lines are as shown below. The colours of the pipelines shows different diameters chosen from the list (FIGURE–). The pipelines were self-defined in the software based on the commercial available PE pipelines.

3.6. Why a water source HP

A Water Source Heat Pump is frequently deemed to be more efficient than an Air Source Heat Pump for various reasons:

The aspect of Temperature Stability is a key factor to consider. Water, being a more stable medium for heat exchange compared to air, exhibits higher density and specific heat capacity. Consequently, it can absorb and release heat in a more effective manner. Water source systems generally extract heat from or discharge heat to a water reservoir like a pond, lake, or well, which typically maintains more constant temperatures throughout the year in contrast to air temperatures. This stability enables water source heat pumps to function with greater efficiency than air source heat pumps.

Moreover, the Higher Coefficient of Performance (COP) attained by water source heat pumps is noteworthy. The enhanced temperature stability of water sources enables these heat pumps to achieve superior Coefficients of Performance (COPs) in comparison to air source heat pumps. COP, serving as a metric for heating or cooling efficiency, represents the ratio of heat output to energy input. Water source heat pumps can achieve elevated COPs due to their access to a more consistent heat source, thereby reducing the energy input required for heating or cooling a space.

Additionally, Lower Energy Consumption is a significant advantage associated with water source heat pumps. Owing to their heightened efficiency, these pumps typically require less energy to deliver the same level of heating or cooling output when compared to air source heat pumps. This can lead to reduced operating expenses and decreased energy consumption over the long run.

Furthermore, the aspect of Longer Lifespan is notable for water source heat pumps. This is primarily attributed to the fact that water sources are less susceptible to temperature variations and severe weather conditions, which can strain the components of air source heat pumps. The more stable operational conditions of water source heat pumps can contribute to an extended system lifespan and reduced maintenance needs.

Lastly, the Flexibility aspect is worth mentioning. Water source heat pumps offer greater versatility in terms of installation possibilities. They can be deployed in various water sources such as rivers, lakes, ponds, or wells, providing more flexibility in system design compared to air source heat pumps, which are constrained by outdoor space availability and air temperature fluctuations.

While Water Source Heat Pumps are generally acknowledged to be more efficient than Air Source Heat Pumps, the suitability of each type of heat pump hinges on factors such as the presence of a suitable water source, installation expenses, and local climatic conditions. It is imperative to take these factors into account when determining the most suitable heat pump system for a specific application.

The compatibility of Ethylene glycol 30% with water source heat pumps is a critical factor to take into account within district heating networks. Ethylene glycol 30% represents a common blend which is used in heating and cooling systems, such as water source heat pumps. This glycol mixture offers protection against freezing, resistance to corrosion, and better heat transfer.

But the point to requiring attention is that the existence of glycol within the system impacts the calculations of friction loss and thermal conductivity. The viscosity of the this solution increases with glycol concentration, thus resulting in higher friction losses and much lower thermal conductivity. In order to guarantee proper sizing of the system and achieve optimal performance, it is imperative to consider these effects when designing a system of water source heat pumps with Ethylene glycol 30%. This process may require to adjust the size of the heat pump and recirculation pumps to counterbalance the lower thermal conductivity and higher friction losses. Opting for pipes with larger diameters to decrease pressure drops and ensure ideal flow rates.

3.7. Pressure loss at pumps

Pressure drop in a pump for the working fluid, occurs as a result of a number of factors. The major one is frictional losses that comes from the interaction of the fluid and the internal surfaces of the pump. This leads to the conversion of some of the kinetic energy of fluid in heat, thereby causing a reduction in pressure. The viscosity of the fluid also contributes to this phenomenon, with thicker fluids necessitating more energy for flow, hence escalating the pressure drop. The occurrence of turbulent flow within the pump can further exacerbate pressure drop by inducing eddies and swirls that augment the velocity fluctuations of the fluid. Moreover, flow separation, where the fluid becomes detached from the walls or surfaces, generates regions of low pressure, thereby adding to the pressure drop. The pump's internal configuration, encompassing bends and turns, can similarly prompt pressure drop owing to alterations in flow direction and the ensuing turbulence. Additionally, the inclusion of valves, fittings, and other elements along the pump's flow path can introduce extra pressure drop by constraining the flow. Factors such as pump inefficiency, cavitation, air entrapment, and also it could be the formation of scale. To mitigate pressure drop, designers and engineers employ various strategies, such as optimizing the pump's internal structure and flow path, utilizing materials with low coefficients of friction, and minimizing turbulence. By comprehending the origins of pressure drop, pump designers and operators can take measures to alleviate its effects and enhance pump efficiency.

The head loss estimation for the central circulation pump and the heat pump was done with the help of the available data sheet provided by a commercial supplier GRUNDFOS [13] and RUIDONG [30] respectively. The expected head loss value was taken from the sheet for a water source heat pump and a corresponding the size of heat pump in terms of the Nominal heating capacity in kW. The nominal heating capacity of a heat pump in kW represents the upper limit of heat energy output achievable by the heat pump within defined operational parameters, often corresponding to specific temperature and moisture conditions. It serves as an indicator of the heat pump's efficiency for heat displacement. This is usually denoted by the producer as a benchmark for the device's operational efficiency. The details collected were as follows:

- Heat pump: 70-90kPa for each side – condenser and evaporator
- Central circulation pump: 0.5bar

This data was used as a first estimation for the simulations.

3.8. Different Scenarios considered

For the current project, two scenarios were considered for district heating network setup. From literature it has been evident that research has been oscillating between a Central heat pump system and distributed heat pump system for low temperature district heating networks. Here, in the following sections these two scenarios are discussed separately describing their setup and base setup as was modelled in SIM-VICUS software.

For both the cases the research postulates consistent temperature levels of the heat source. Should the temperature fluctuate throughout the year, it would influence the system in dual manners. Initially, it would alter the Coefficient of Performance (COP) of the heat pumps across various scenarios; furthermore, it would result in a notable effect on the capacity of the distribution grid.

- DHN with a central heat pump
- DHN with decentralised heat pump system

The following section will elaborate on each of the above and will discuss their setup in detail.

3.9. SCENARIO 1: DHN with a central heat pump system

An initial backbone for the AM5 district heating network is setup using a central heat pump used to upgrade the waste heat recovered from the SOURCE. The network is comprised of a substation at the SOURCE side and a distributed network of substations on the SINK side. As per the Amsterdam heat guide [3], a temperature of 50°C is considered sufficient for space heating for buildings and housings with good insulation. Thus the heat pump is set up to upgrade the incoming working fluid stream from the source at 30°C (Shown by the graph of recovery temperature in APPENDIX 1) to 51°C. This was then distributed further in the network.

3.9.1. Modelled Substations

To incorporate a working model in SIM-VICUS software, the various components to be incorporated in the district heating network are appropriately coupled together to form meaningful substations. These substations work as a unit and can be modified independently as per the iterations during the simulations suggest overtime. In the present section the modelling process of the various substations will be discussed step by step.

1. SOURCE substation: To model the source for the current network, a central circulation pump and heat pump were attached in series starting at the heat recovery from the SOURCE to the heat upgradation and initiation of the distribution of the working fluid. This substation is as depicted by the schematic in Figure 3.9 below.

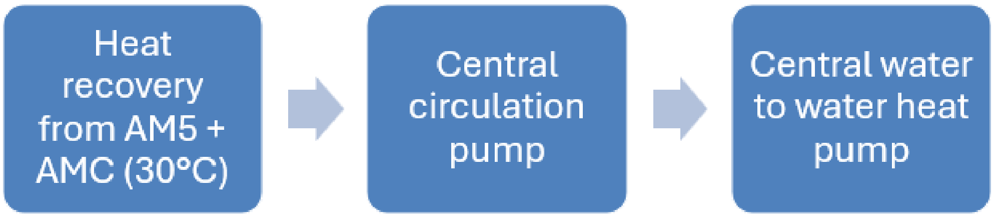

Figure 3.9: Schematic of SOURCE substation – scenario 1

2. SINK substation: At the side of the SINKS each pipe end was modelled as a substation for heat delivery and exchange to the SINK. To develop this station, a heat exchanger is allotted to each SINK corresponding to the peak space heating demand over the year. As the working fluid is already heated at the central substation, the SINK points only were used to exchange the required heat as per the energy demand. This is shown by Figure 3.10.

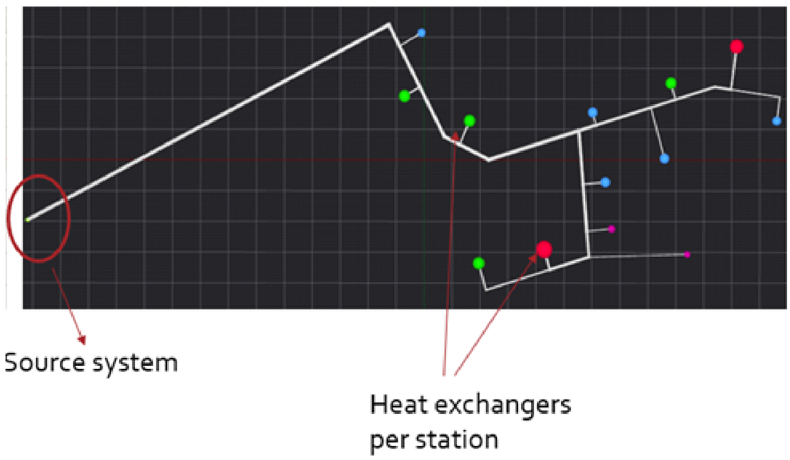

Figure 3.10: System layout – scenario 1

3.9.2. Heat exchange type for each component

1. Central Heat pump: The heat exchange for the central heat pump was given as an hourly heat exchange profile for the condenser. This profile is in correspondence to the yearly space heating demand in Kw, as a collection of hourly data for over a year. The graph is included in APPENDIX 1 for further reference.
2. Heat recovery: The heat recovery corresponds to the total lump sum heat recovered from the data-centre and the AMC hospital. To simplify the working the recovered heat is provided as a constant heat supply in the form of working fluid at 30°C over the year.

3. Pipes: With a lack of appropriate soil data information availability for the considered area in Amsterdam and also to create a first estimation with the maximum capacity of the network, the distribution pipe-lines were considered closely adiabatic in nature (exceptionally effective insulation).

As we are using a central Heat pump to upgrade the recovered heat to 51°C and then supply it to the SINK points. Each SINK point is modelled with a heat exchanger at the substation, to exchange the heat appropriately to meet the space heating demand as per the hourly fluctuations. The sizing of the heat exchanger hydraulic diameter was done as mentioned previously in the report. The various heat exchangers defined and fed in the software are as listed below in Table 3.1:

Table 3.1: Heat exchangers used in scenario 1 setup

Heat exchanger name	Hydraulic diameter (mm)
HE 260	260
HE187	187
HE154	154
HE120	120

3.9.3. Climate and location data

Climate and geographical data play a fundamental role in the examination of a DHN. Various factors include:

- Climate and geographical data play a fundamental role in the examination of a DHN. Various factors include:
- Analysis of heating demand: Climate data, encompassing factors like temperature, humidity, and solar radiation, aid in approximating the heating demand within a district. This data is pivotal in determining the size of the heating system, enhancing energy production, and forecasting energy consumption.
- Calculation of heat loss: Geographical data, incorporating details on building insulation, window positioning, and the impact of urban heat islands, are employed in computing heat losses within the network. This process aids in pinpointing areas where heat wastage occurs and in optimizing the insulation and pipe dimensions of the system.
- Sizing and routing of pipes: Climate and geographical data are pivotal in establishing the most suitable pipe dimensions and layout for the district heating network. This guarantees that the pipes are appropriately sized to manage the anticipated heat demand and flow rates effectively.
- Management of peak demand: Geographical data assists in recognizing regions with substantial heating demand, thereby enabling the application of targeted strategies for managing peak demand, like load shifting or demand response initiatives.
- Planning for network expansion: Climate and geographical data aid in the identification of areas experiencing escalating heating demand, facilitating proactive planning for the expansion and enhancement of the network.
- Evaluation of risks and planning maintenance: Climate data are employed to evaluate the likelihood of pipe failures, corrosion, and other maintenance challenges, thus allowing for proactive maintenance scheduling and minimizing downtime.
- Optimization of energy storage: Climate data are utilized to enhance energy storage systems, such as thermal energy storage, to maximize efficiency and curtail energy wastage effectively.
- Reduction of carbon emissions: Through the analysis of climate and geographical data, district heating networks can refine their operations to diminish carbon emissions and achieve sustainability objectives. The climate data used as input to the software is as shown in Figure 3.11.

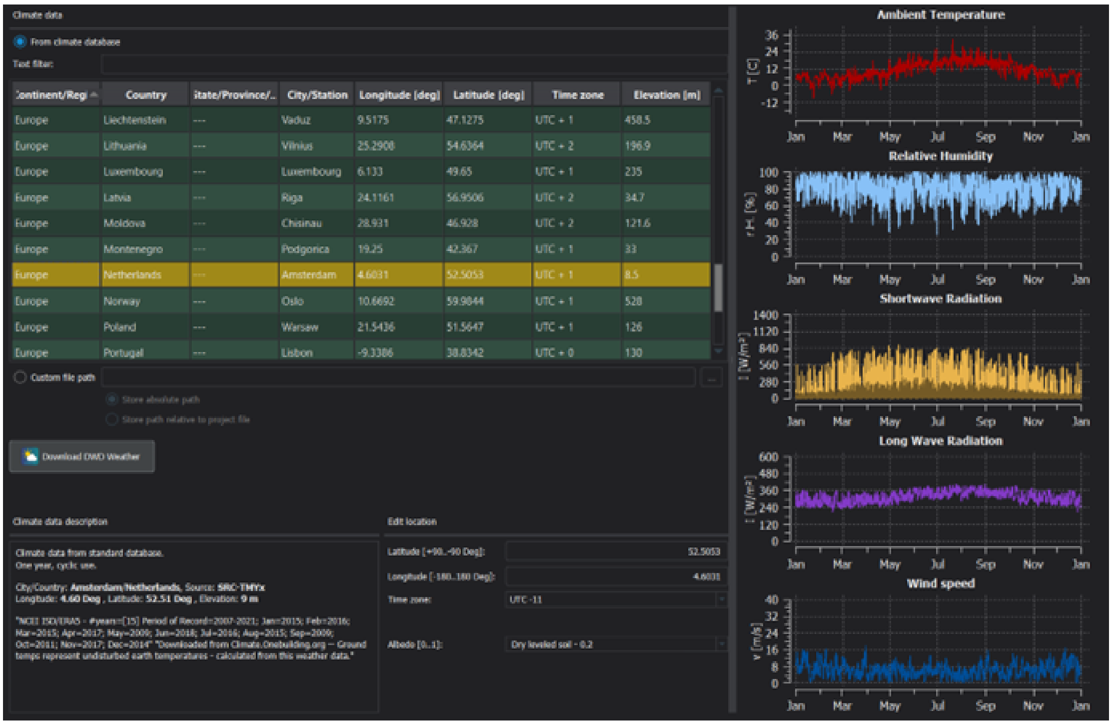

Figure 3.11: Climate data used for analysis

3.10. SCENARIO 2: DHN with decentralised heat pump system

There has been a recent transition towards the utilization of distributed heat pumps in low-temperature district heating networks for various reasons. One significant factor is the growing emphasis on carbon emissions reduction and energy efficiency attainment. Distributed heat pumps present a decentralized and adaptable approach to heat distribution, enabling improved alignment between heat supply and demand. Also, distributed heat pumps can nicely function at lower temperatures, which is an advantage for low-temperature DHN systems. This capability comes from their capacity to harness waste heat or sustainable energy sources like ambient heat from the ground or air for heating provision. This strategy diminishes the necessity for high-temperature heat sources such as fossil fuels, consequently resulting in substantial energy conservation.

A further benefit of distributed heat pumps is their dual functionality in providing both heating and cooling, rendering them a versatile alternative for district heating networks. They can also be configured to operate alongside other heat sources such as biomass or solar thermal systems to establish a hybrid heating mechanism. Moreover, distributed heat pumps aid in mitigating the pressure drop across the circulation pump, a prevalent challenge in conventional district heating networks. Through the decentralization of heat generation and distribution, the pressure drop is lessened, leading to decreased energy wastage and heightened overall efficiency. In essence, the adoption of distributed heat pumps in low-temperature district heating networks is steered by the imperative for more effective, adaptable, and sustainable heat distribution systems geared towards curbing carbon emissions and fulfilling energy efficiency objectives.

As per the Case Study [19]: The Bluestone Organization implemented a distributed heating and cooling system at Norman Towers, a 101-unit building in Jamaica, Queens, NY. Each apartment has its own heat pump, with external components located on the roof and at ground level in a covered carport. It concluded reduction in operation costs, thus over the time benefit. In summary, distributed heat pump systems offer several advantages over central heat pump systems for low-temperature district heating networks, including improved resilience, increased efficiency, greater control, sub-metering, and cost-effectiveness. Thus, considering the current results of the Central heat pump scenario for the low temperature district heating network, it is worthwhile to investigate a model for the distributed heat pump scenario for the same. This section will elaborate on the setup developed for the same.

In a second scenario, an initial framework for the district heating network in AM5 is established by employing a distributed heat pump system to enhance the waste heat extracted from the SOURCE. The network consists of a substation located at the SOURCE end and a dispersed array of substations on the SINK end. According to the heat guidelines of Amsterdam, a temperature of 40 - 50°C is deemed adequate for heating spaces in buildings and residences with effective insulation. Consequently, the heat pumps are installed to elevate the temperature of the incoming flow from the source at 30°C to 51°C, now at each SINK substation instead of a centralized system. Following this, the thermal energy was subsequently distributed throughout the network.

3.10.1. Modelled substations

In order to integrate a functional model into SIM-VICUS software, the diverse elements intended for integration into the district heating network are interconnected in a suitable manner to create coherent substations. These substations operate collectively and have the flexibility to be adjusted autonomously in accordance with the revisions indicated by the simulations over time. Within this specific section, a detailed exploration of the modeling procedure for the different substations will be presented sequentially.

1. SOURCE substation: To model the SOURCE substation for the distributed heat pump system, the Central circulation pump and the was coupled in series with the heat recovery system from the SOURCE. This substation is as depicted by the schematic in Figure 3.12 below.

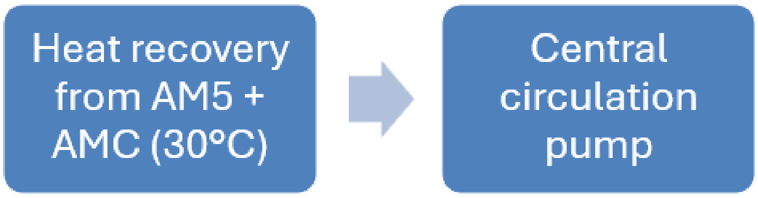

Figure 3.12: Schematic of SOURCE substation – scenario 2

2. SINK substation: As for the distributed heat pump system the heat is not upgraded at the SOURCE, small heat pumps are allotted at each SINK point to up-level the heat to 51°C from the receiving end temperature. This was done by modelling the SINK points as depicted by Figure 3.13 below.

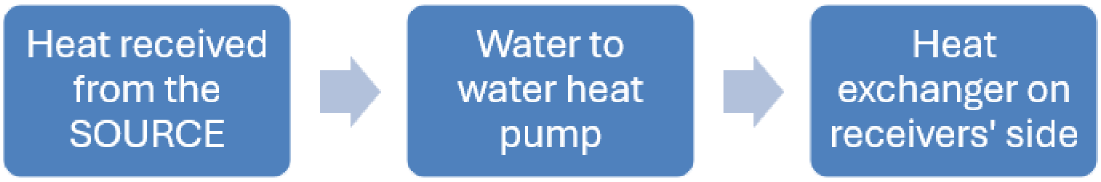

Figure 3.13: Schematic of SINK substation – scenario 2

The following Figure 3.14 shows the setup of the distributed heat pump system DHN network in the SIM-VICUS software, with the Source and SINKs pictorially marked. Where the source heat recovery is considered as one primary point. The size of the SINK points vary relatively as per the maximum peak space heating demand over the year. The color of the SINK varies, as they are provided with a suitable kind of heat pump as per the peak load.

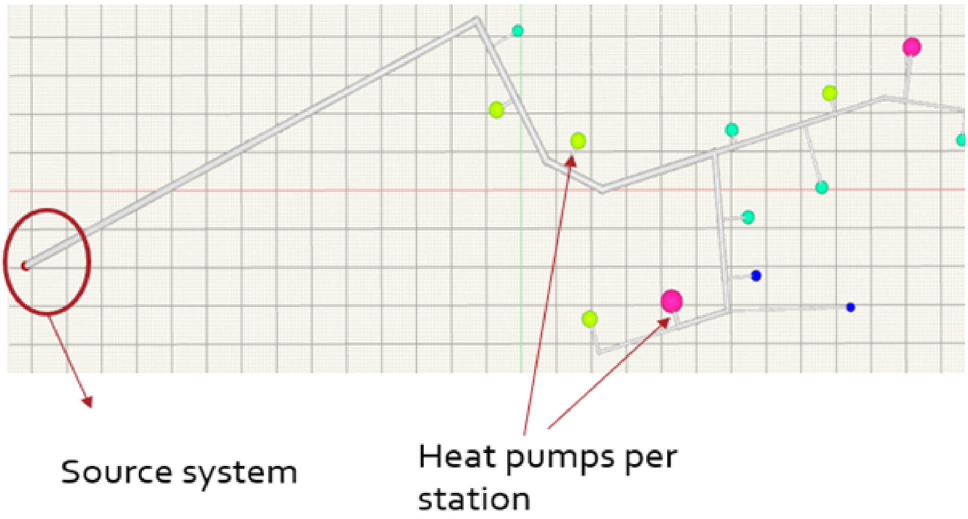

Figure 3.14: System layout – scenario 2

3.10.2. Heat exchange type for each component

1. Distributed Heat pump: The heat exchange for the distributed heat pump was given as an hourly heat exchange profile for each condenser used. To each SINK point substation a heat loss spline condenser using the hourly data over a year was allotted as each SINK substation has a heat pump. The graphs are included in APPENDIX 1 for further reference. Heat pumps used in the model setup are listed further in this section.
2. Heat recovery: The heat recovery corresponds to the total lump sum heat recovered from the data-centre and the AMC hospital. To simplify the working the recovered heat is provided as a constant heat supply in the form of working fluid at 30°C, over the year.
3. Pipes: Due to insufficient soil data available for the specified area in Amsterdam, and in order to establish an initial assessment of the network's maximum capacity, the distribution pipelines were assumed to exhibit close to adiabatic characteristics (exceptionally effective insulation).

As we are using distributed Heat pump system to upgrade the recovered heat to 51°C as a supply to SINK points. Each SINK point is modelled with a heat pump at the substation. Thus to provide the upgraded heat appropriately to meet the space heating demand as per the hourly fluctuations, the sizing of the heat exchanger hydraulic diameter was done as mentioned previously in the report. The various heat pumps defined and modelled in the software are as listed by Table 3.2 below.

Table 3.2: Heat pumps used in scenario 2 setup

Heat pump name	Hydraulic diameter (mm)
HP 260	260
HP187	187
HP154	154
HP120	120

Climate and location data: The climate data used for simulating scenario 2 is same as described in the previous section.

3.11. Pressure head calculation - Central circulation PUMP

To account for a starting head value for the central circulation pump, a manual calculation is carried out. The Darcy-Weisbach equation represents a foundational expression within the field of fluid mechanics, employed for the determination of pressure decline or loss of head resulting from friction within a conduit. Factors considered in this equation encompass the dimensions of the conduit such as length and diameter, the velocity of flow, the roughness of the conduit, and the viscosity of the fluid. This formula finds wide-ranging utility across diverse fluid flow scenarios within conduits, irrespective of whether the flow exhibits laminar or turbulent characteristics. The Darcy-Weisbach equation for head loss h_f due to friction in a pipe is given by:

$$h_f = f\frac{L}{D}\frac{V^2}{2g} \tag{3.5}$$

where:

h_f : Head loss due to friction (meters of fluid)
f : Darcy friction factor (dimensionless)
L : Length of the pipe (meters)
D : Diameter of the pipe (meters)
V : Flow velocity of the fluid (meters per second)
g : Acceleration due to gravity (9.81 meters per second squared)

The pressure drop ΔP can be related to the head loss h_f by:

$$\Delta P = \rho g h_f \tag{3.6}$$

where ρ is the fluid density (kilograms per cubic meter). Thus, the pressure drop is:

$$\Delta P = f\frac{L}{D}\frac{\rho V^2}{2} \tag{3.7}$$

The Darcy friction factor f for laminar flow (Reynolds number Re < 2000) is given by:

$$f = \frac{64}{\text{Re}} \tag{3.8}$$

For turbulent flow (Reynolds number Re > 4000), the friction factor is determined using the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right) \tag{3.9}$$

where ε is the roughness height of the pipe (meters). For PE pipe value used here refer to APPENDIX A.

The Reynolds number Re is defined as:

$$\text{Re} = \frac{\rho V D}{\mu} \tag{3.10}$$

where μ is the dynamic viscosity of the fluid (pascal-seconds). Moody chart is frequently utilized as a substitute to solving Colebrook-White equation due to the implicit nature of the Colebrook-White equation, which necessitates iterative techniques or numerical methods to determine the Darcy friction factor f. By offering a visual depiction of the Darcy friction factor in relation to the Reynolds number and the relative roughness of the conduit, the Moody chart emerges as a practical instrument for engineers to promptly approximate the friction factor without getting into intricate computations. This is shown by the Figure 3.15 below:

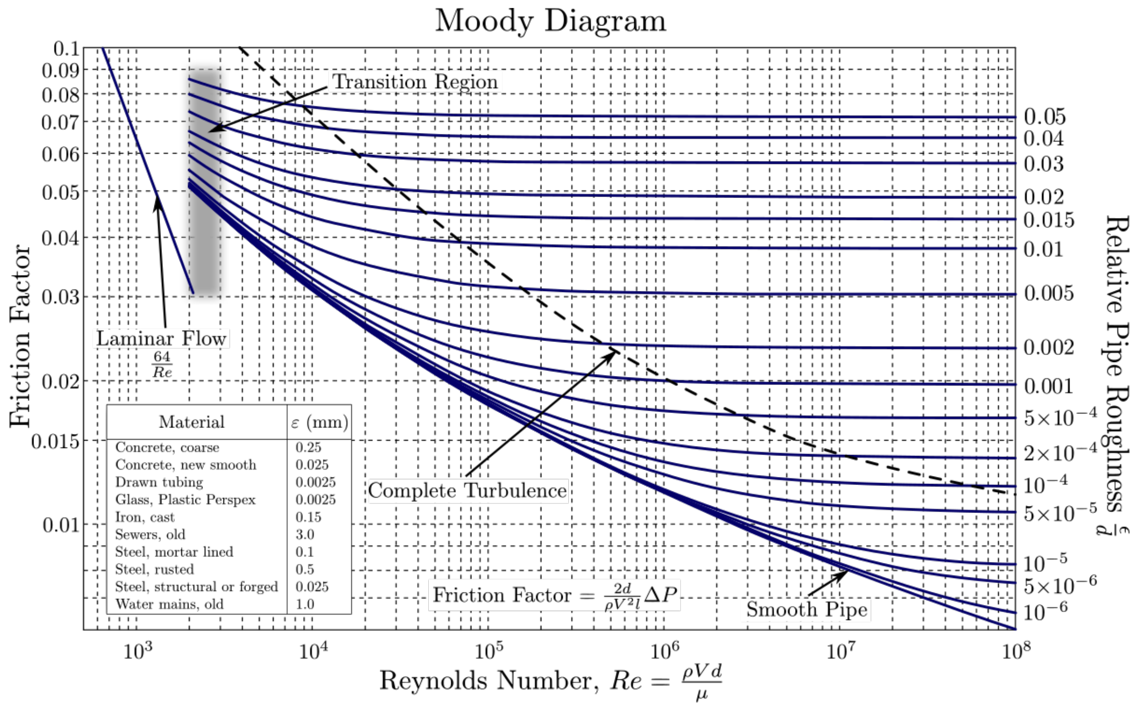

Figure 3.15: Moody Chart

The Moody chart illustrates the relationship between the Darcy friction factor f and the Reynolds number Re across different values of relative roughness ε/D. It encompasses both the laminar and turbulent flow domains. This calculation led us to a pressure drop of 3.9 bar in the network if a maximum velocity of 1.5 m/s is considered through all pipelines. Thus the starting value for the head provided by the central circulation pump was taken to be 5 bar. This also helps to have an account of pressure drop across components used mentioned in section 3.7.

4

Results and Discussions

4.1. CENTRAL HEAT PUMP SYSTEM

4.1.1. Sized pipe network

The following figure (Figure 4.1 below) shows the result of applying pipe sizing algorithm to Scenario 1, where each colour depicts a different pipe diameter discussed earlier in the report. Pipelines within district heating networks typically exhibit an initial increase in diameter followed by a decrease further downstream for several reasons:

- Flow Rate Reduction: Commencing from the network origin, the pipeline is required to facilitate the total flow rate necessary to cater to all downstream consumers. Consequently, a larger diameter is adopted to accommodate the substantial volume of water or steam. As the pipeline progresses downstream, the flow rate experiences a decline due to the dissipation of thermal energy to users along the route. Consequently, smaller diameters become adequate to convey the reduced flow.
- Pressure Drop Considerations: Incorporating larger diameters at the commencement assists in minimizing the pressure drop over extended distances, thereby ensuring the presence of adequate pressure to propel the flow throughout the network. With an increase in distance and a decrease in the number of users, the pressure prerequisites diminish, allowing for the utilization of smaller diameter pipes without significant pressure reduction.
- Cost Efficiency: Larger pipes incur higher expenses in terms of both material and installation costs. Employing smaller pipes in areas with lower flow demands aids in optimizing the overall network cost. The design strategy guarantees that pipe sizes align with the actual flow demands at each network juncture, thereby preventing unnecessary expenditure on oversized pipes.
- Heat Loss Minimization: Smaller diameter pipes possess a reduced surface area relative to their volume, leading to a decrease in heat loss per unit volume of transported fluid. This feature proves advantageous in network segments characterized by reduced flow rates. By implementing smaller pipes in downstream sections, the system can enhance its efficiency in preserving heat within the network.
- System Balancing: Proper sizing of pipe diameters plays a pivotal role in ensuring a uniform flow distribution across the network. This contributes to maintaining consistent thermal provision to all users. Achieving hydraulic balance is crucial for the effective functioning of district heating systems, with varying pipe diameters playing a key role in attaining this equilibrium.

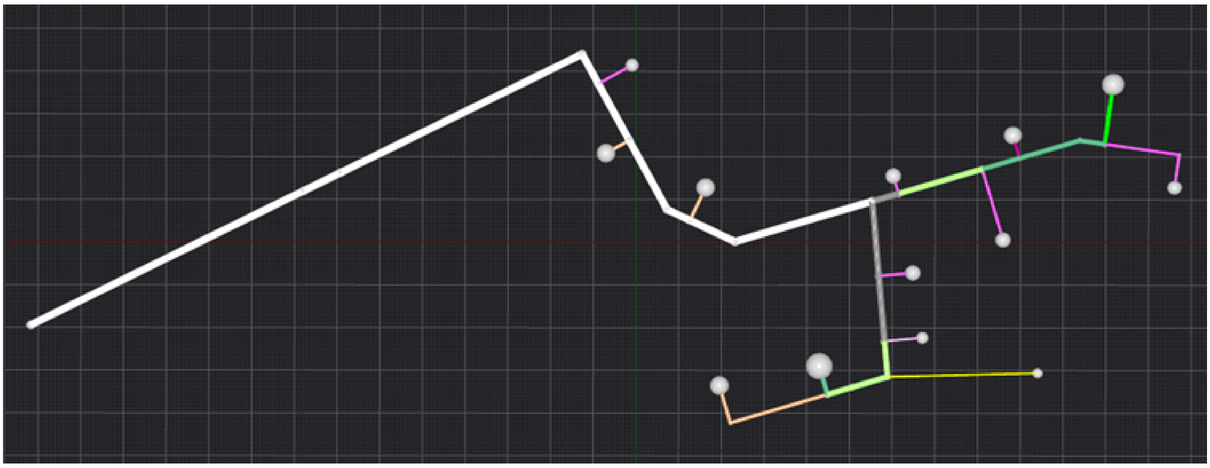

Figure 4.1: Results after pipe sizing for the DHN – Scenario 1

4.1.2. Maintained flow

Based on the findings of previous studies, an appropriate mass flow rate of approximately 60-140 kg/s is considered suitable [18] for a low temperature district heating system to circulate heated working fluid, as indicated in a corresponding figure. These fluctuations in mass flow rate during simulations are expected to be adjustable through iterative processes. The graph in Figure 4.2 shows the relationship between the mass flow rate of heated fluid supplied to a district heating system and the load rate of the system. In the context of a district heating system, the load rate refers to the percentage of the system's maximum capacity that is currently being utilized. As you can see, the mass flow rate decreases as the load rate increases. This is because the system requires less heated working fluid to meet the demand when the load rate is lower. The graph starts at the point (40, 137.5) which indicates that at 40% load rate, the system requires 137.5 kg/s of heated working fluid. As the load rate increases, the mass flow rate decreases, with a steep decline at the beginning and flattening out towards the higher load rates.

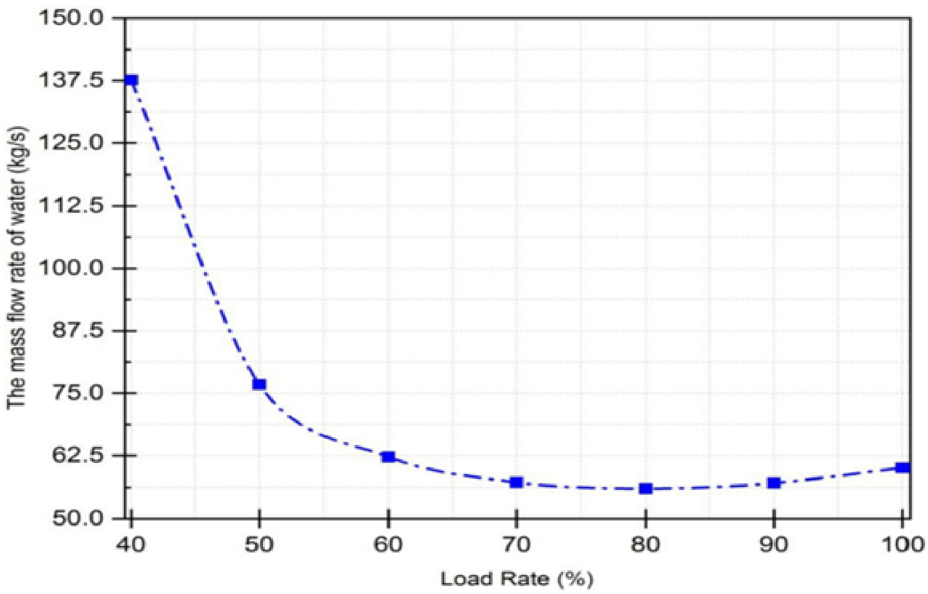

Figure 4.2: Mass flow rate of heated water supplied to the district heating system [18]

At first glance, it might seem counterintuitive that the mass flow rate of heated water decreases as the load rate increases. However, there's a scientific reason behind this phenomenon. In a district heating system, the mass flow rate of heated water is directly related to the heat transfer rate required to meet the heating demand. When the load rate increases, the system needs to provide more heat to the buildings to maintain a comfortable temperature.

As we can see the Figure 4.3 here the mass flow rates ranges from 140 to 50 kg/s (yellow depicting the supply pipe), whereas the lower values corresponds to the return pipe flow rate. This was used as an initial starting condition to aid the iterative process of flow analysis.

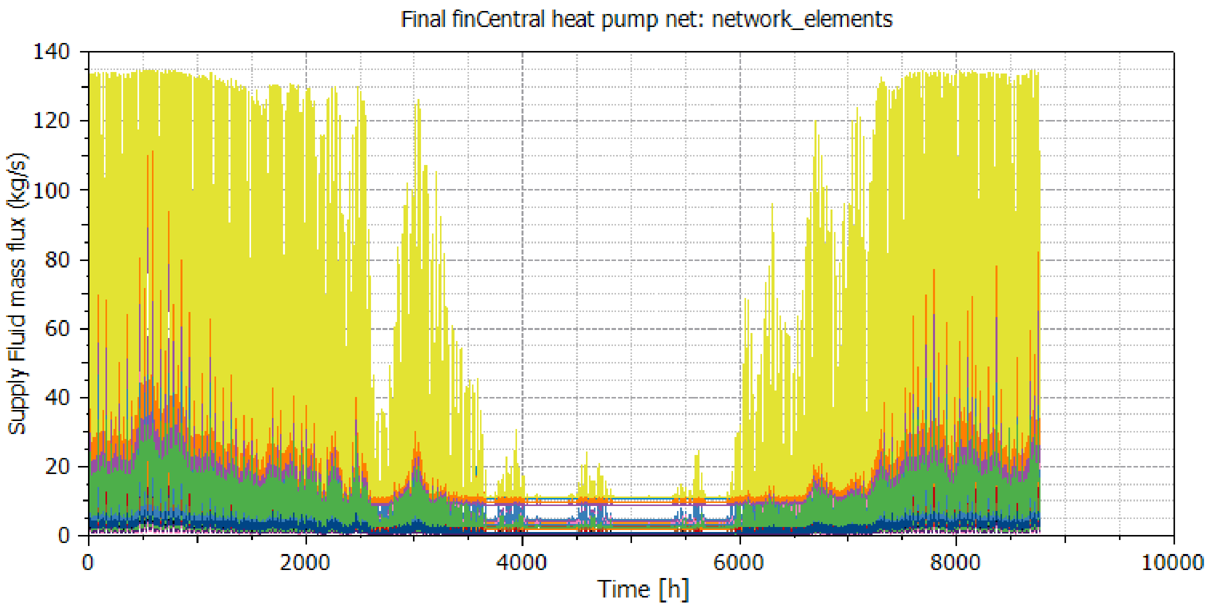

Figure 4.3: Scenario 1: mass flow rate (kg/s) of heated working fluid supplied to the district heating system (current project)

Considering the daily fluctuations in the graph, the mass flow rate increases as the demand is recognized. This flow rate is then reduced and adjusted as the heating demand peaks, to allow better heat exchange at the SINK. The flow rates drops highly when the space heating demands are really low for the houses/establishments. For the months experiencing summer the space heating demand touches the bar to almost negligible, this can also be seen translated to the obtained graphs as the mass flow rates of the network are negligible for that period of time. Thereby the corresponding heated working fluid supply velocities does not exceed 1.6 m/s, as can be seen from the figure 4.4 below. The lower velocities in the bottom represent the return pipe velocities.

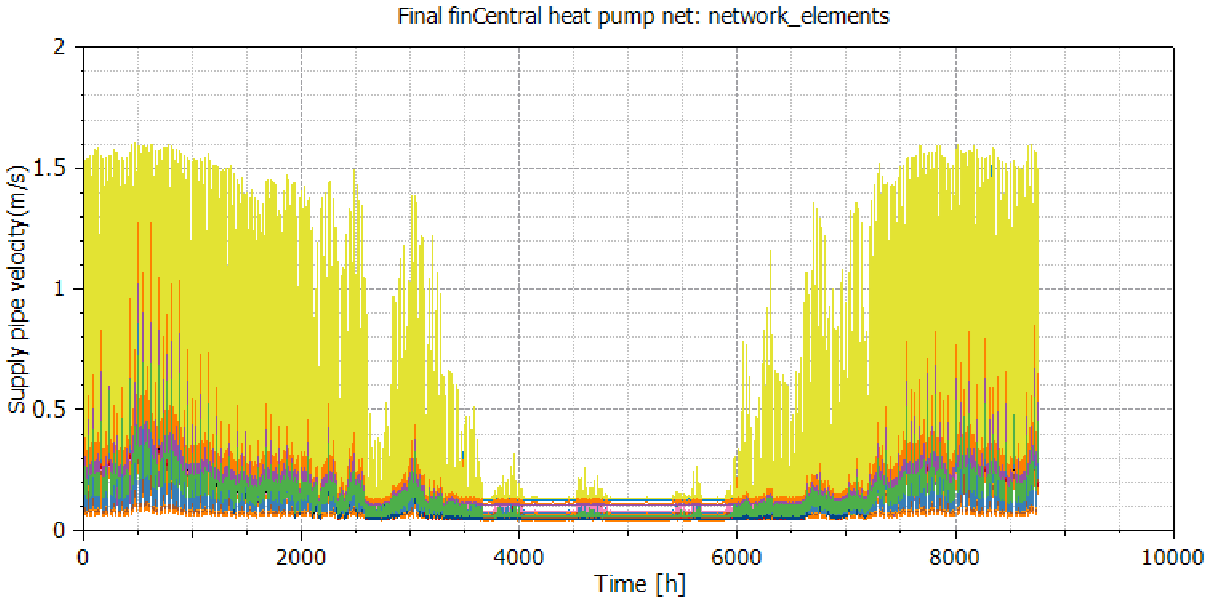

Figure 4.4: Scenario 1: flow velocity (m/s) of heated working fluid supplied to the district heating system (current project)

4.1.3. Pressure drop/difference

Measurement of pressure differences plays a pivotal role in the development and enhancement of Low Temperature District Heating (LTDH) networks. Through a comprehensive grasp of the pressure differentials across the pipeline, designers are empowered to engage in well-informed decision-making processes concerning various aspects such as pipe dimensions, pump choices, valve and fitting selections, network configuration, heat exchanger design, insulation strategies, leak identification, and system equilibrium. This, in turn, culminates in the establishment of a more effective, dependable, and economically viable LTDH network. Considering the Pressure losses at various components as per the data collected from the initial iterative processes for the central heat pump system, the outlet node pressure for the SOURCE was kept to be around 5 bar as shown in the figure 4.5 below.

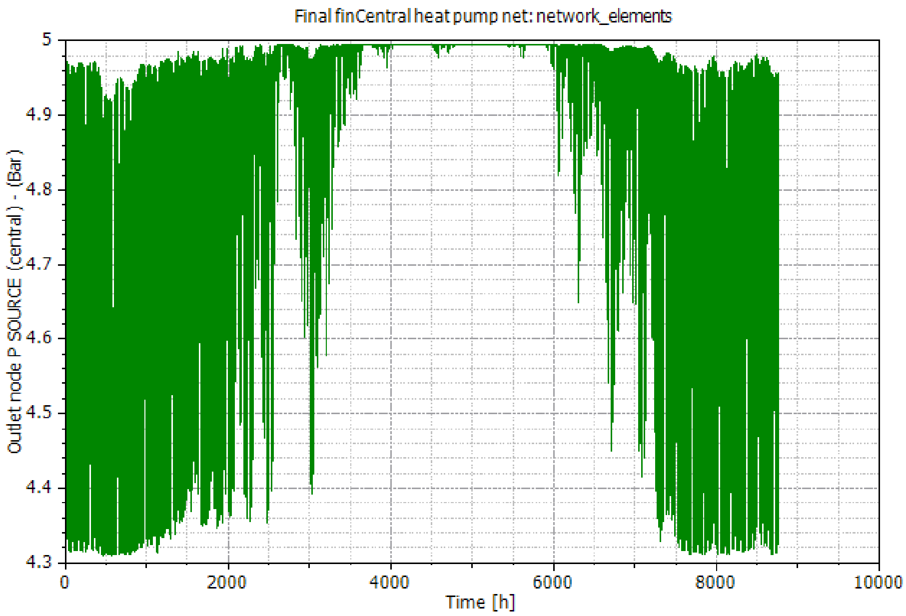

Figure 4.5: Scenario 1: Outlet node pressure Source (Bar) (current project)

The Figure 4.6 below shows the pressure loss at various pipe elements when the supply pipeline delivers the heated fluid to the SINK. As depicted from the obtained graph it is clear that the pressure loss per major element does not exceed a maximum od 0.4 bar.

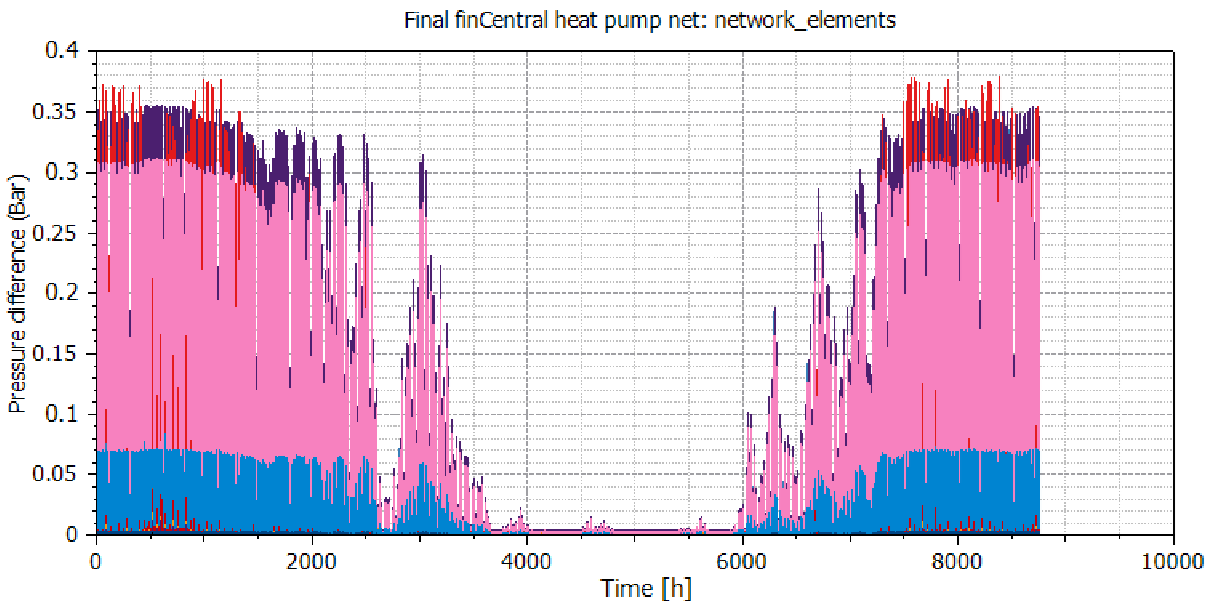

Figure 4.6: Scenario 1: Pipeline supply and return element Pressure difference (Bar)

It can be seen from the graph, that if focused on a few day cycle the pressure drop going down (if we zoom it into a small time interval) corresponds to reduced flow. This is directly related to the minimised space heating demand during those instances.

To get a much clear idea of the total pressure drop as the fluid travels from the SOURCE point to the SINK and is fed back to the network from the SINK after heat exchange, we will look at the outlet node pressure for the supply and the return. This result further helps us to adjust with the provided head for the central circulation pump after going through various simulations. We will look at Figure 4.7 for the above mentioned.

As demonstrated in the Figure 4.7 below, the lighter hues correspond to the supply pipe outlet node pressure, while the darker tones on the graph signify the return pipe outlet node pressure. The overall head loss can be readily construed to be approximately 3 to 3.5 bar (indicated by the red arrow) as the simulation spans a year with hourly data interpolation. Here the outlet node pressure ranges from 5 to 3.5 bar for the supply side whereas for the return pipeline the outlet node pressure ranges from 2 to 1.3 bar.

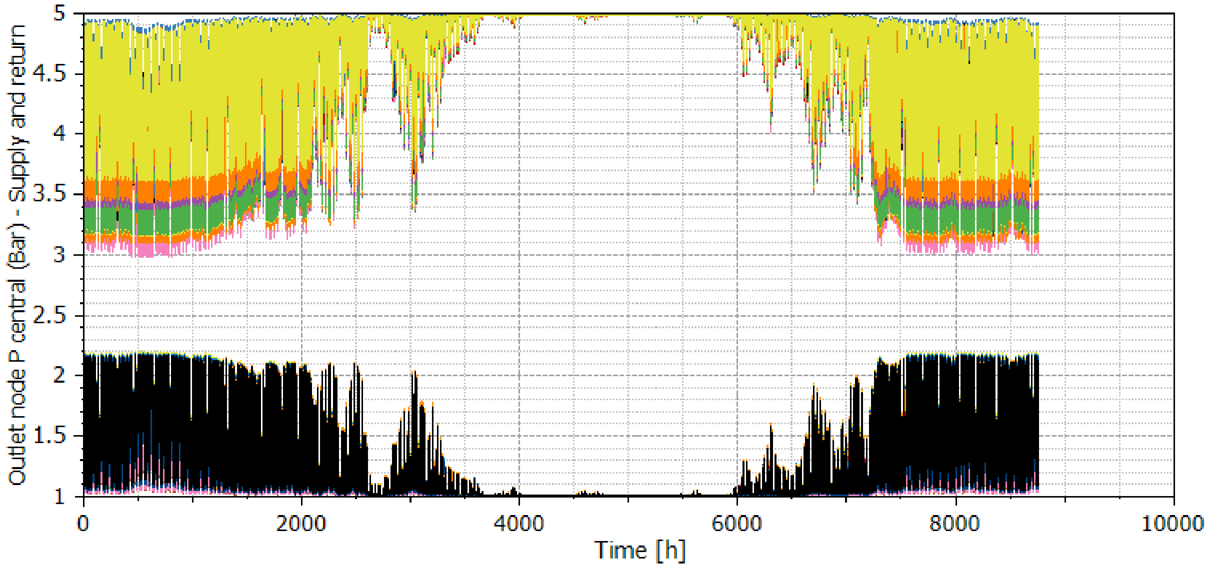

Figure 4.7: Scenario 1: Pipeline supply and return outlet node Pressure (Bar)

If we closely look at the graph shown in Figure 4.7, the topmost yellow colour represents the initial backbone of the network whereas the orange and the green colour represents the extended branches further down stream in the network. The fluctuations in the outlet nodes vary on a daily basis as per demand and mass flow rates. Similarly for the return pipes the pressure of 2.2 bar represents the initial fed in pressure to the return whereas the lower pressures of faint pink shows the return pipe pressure further downstream of the network.

The total pressure drop over the central heat pump system – SOURCE is around 0.7 bar which matches with the data of commercially available [30] components corresponding to the ones used in the simulation at the start of the heated working fluid supply system. This is represented by the graph shown in the figure 4.8 below.

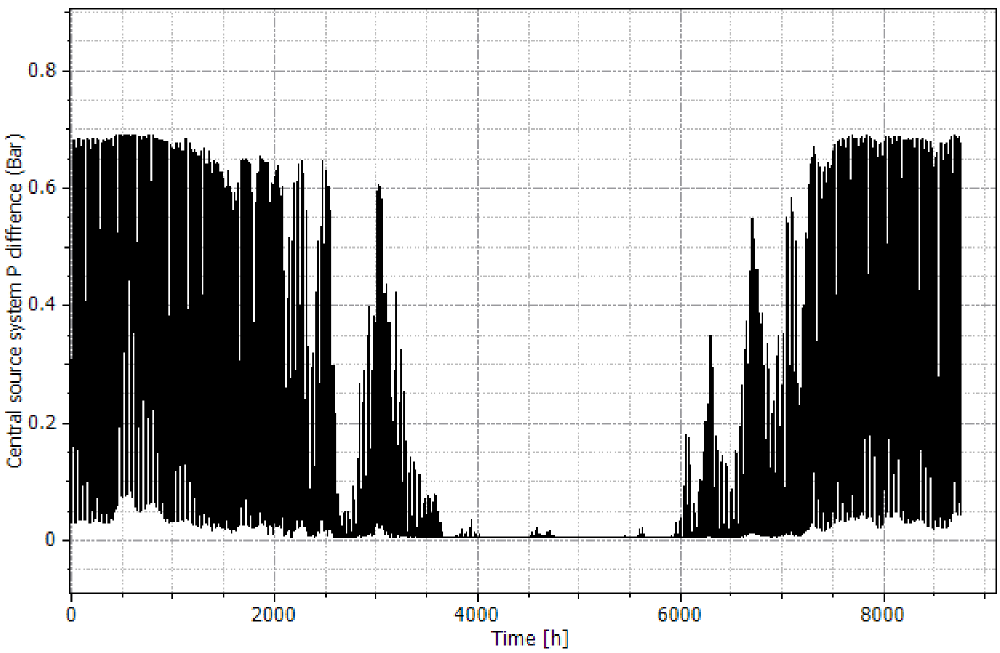

Figure 4.8: Scenario 1: Central source system pressure drop (Bar)

4.1.4. Temperature and temperature difference

The graph in Figure 4.9 below shows the temperature of the heat pump outlet over time. The temperature is relatively constant at around 51°C, with a few spikes up to 52 degrees Celsius. This suggests that the heat pump is operating normally. The absurd spikes in the graph during summer months are due to simulation gap of the current project which will be discussed later in conclusions.

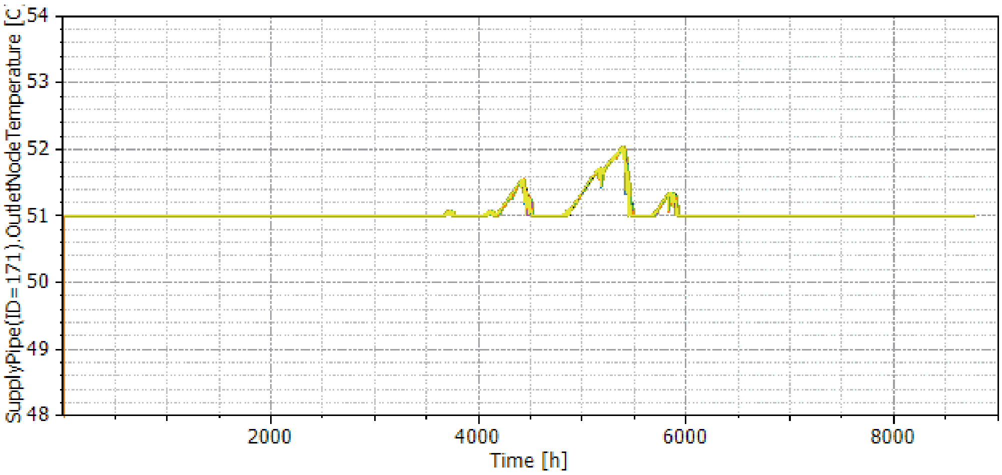

Figure 4.9: Scenario 1: Supply pipe – outlet node temperature (°C)

This graph in Figure 4.10 shows the temperature of the return pipe elements in a district heating network over time. The return pipe is the pipe that carries the working fluid back to the heat source after it has circulated through the network and heated the buildings. The graph shows that the return pipe temperature varies significantly over time, ranging from about 32°C to 47°C, (ignoring the summer months when space heating demands are negligible). As expected the temperature is lowest during the early morning hours and highest during the evening hours. Similarly, the temperature is lowest when the space heating demand is at peak and high otherwise. The temperature drop in this graph is typically between 10 - 18°C during day peak demand for space heating and around 3 - 5°C during off peak hours.

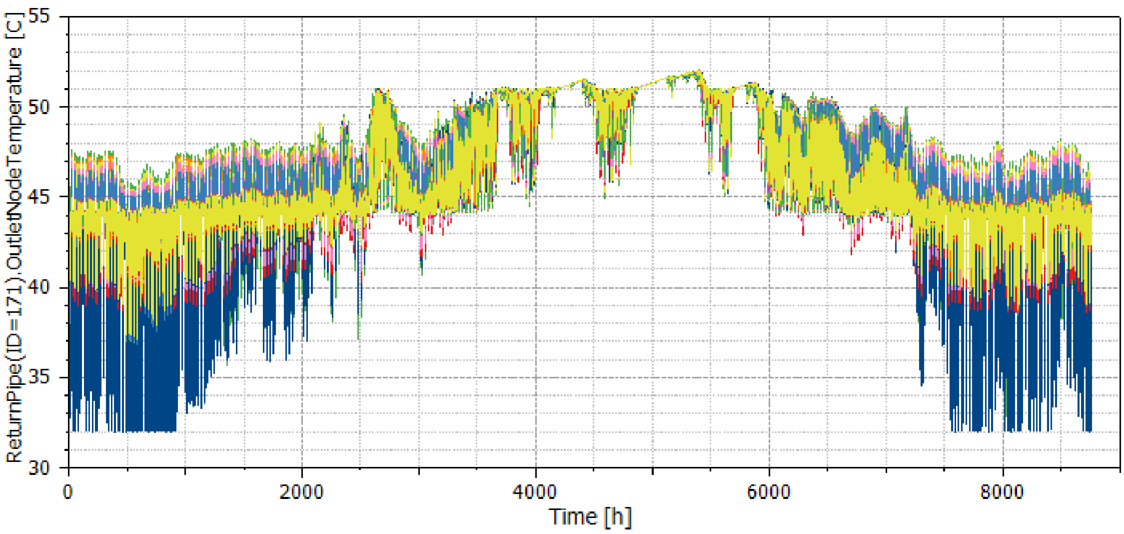

Figure 4.10: Scenario 1: Return pipe – outlet node temperature (°C)

The graph in Figure 4.11 given below shows the temperature difference at the condenser side of the heat pump. The supply temperature to the district heating network is 51°C, and the return pipe temperature varies between 35°C and 47°C.

Also the graph 4.11 below shows that the temperature difference at the condenser side of the heat pump is between 7°C and 14°C. In other words, the heat pump is rejecting heat from the condenser side to the district heating network at a temperature difference of 7°C to 14°C. This temperature difference is a key parameter in determining the performance of the heat pump, as it affects the coefficient of performance (COP) and the overall efficiency of the system.

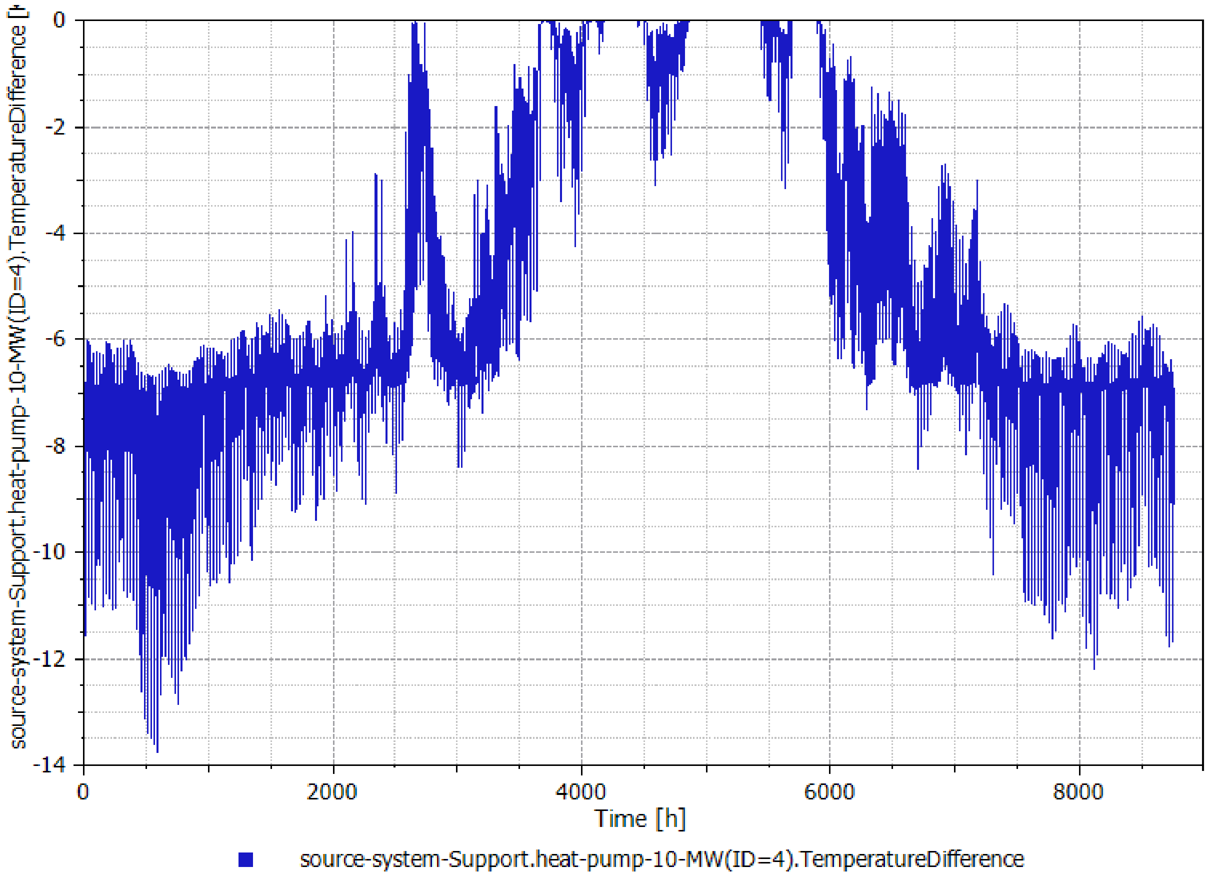

Figure 4.11: Scenario 1: Condenser temperature difference – Central heat pump (°C)

The graph in Figure 4.12 below shows the temperature difference across different heat exchangers in a district heating network over a year's time. The temperature difference is the difference between the inlet and outlet temperature of each heat exchanger. This can tell us about the amount of heat being transferred in each part of the system, and how the system responds to changes in demand over time. For the different colored lines, each color represents a different heat exchanger (HE) in the network, each labeled with its ID.

Heat exchangers HE-154 (ID=28), HE-187 (ID=43), and HE-260 (ID=42) have a high temperature difference in the beginning of the year, indicating they were transferring a lot of heat. This is likely due to the colder weather during the winter months. As the year progresses, the temperature difference decreases, indicating reduced heat transfer. This could be due to warmer weather and less demand for heating. Overall, this graph can be used to understand how the district heating network performs over a year, identifying potential areas for improvement in efficiency and performance.

In the following graph shown by Figure 4.12 the daily cycle shows a higher value of temperature difference for certain hours of the day. This is in correspondence to the higher heat exchange rate during the peak load hours when the space heating demand is high. Whereas the temperature difference shows lower values for the lower demand hours thus indicating lower heat exchange requirements during those hours of the day.

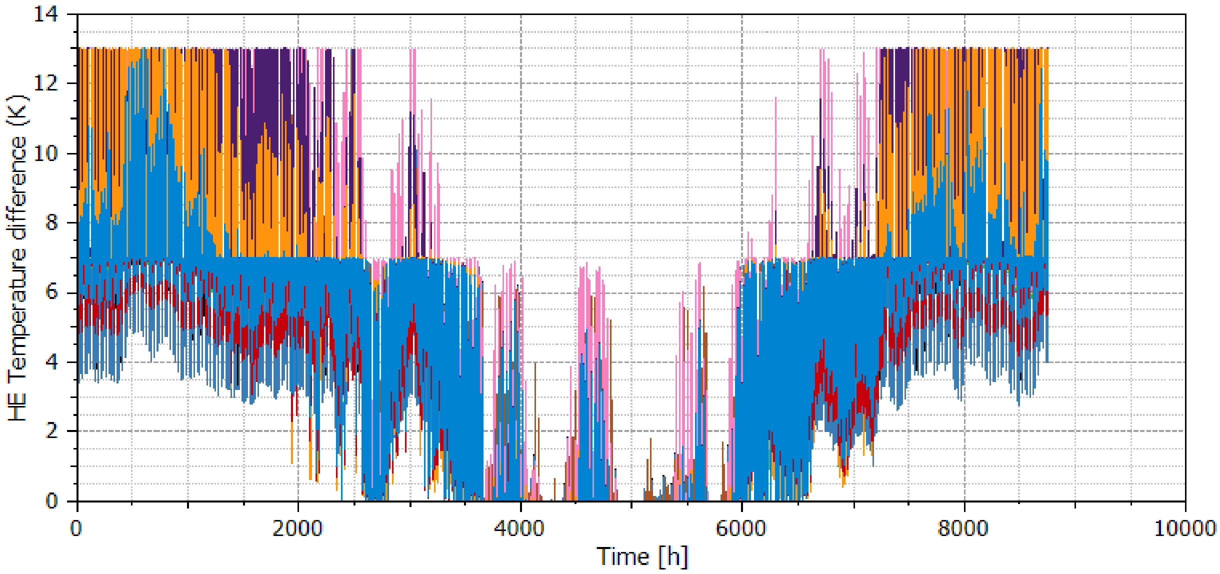

Figure 4.12: Scenario 1: Various Heat exchangers' temperature difference (°C)

4.1.5. Heat load and Electrical power input

The graph here shown by Figure 4.13 shows the total space heating demand over a year for the district heating network. The demand is highest in the winter months (December-February) and lowest in the summer months (June-August). If we now closely look at the daily cycle we observe that the demand peaks in the early morning hours and late evening hours.

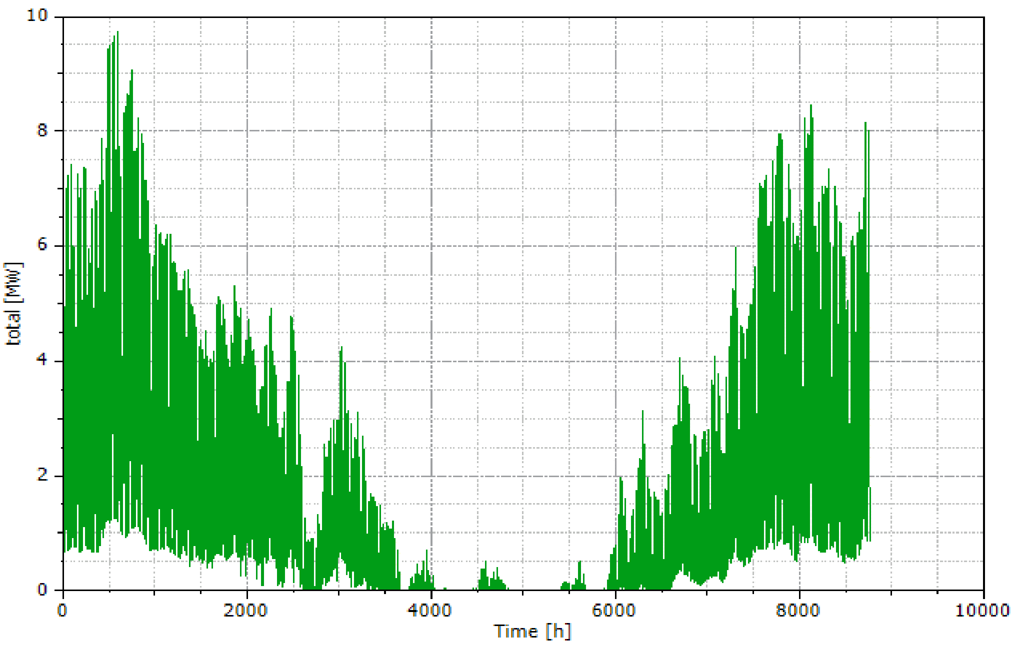

Figure 4.13: Scenario 1: Total space heating load (MW)

Heat pumps and circulation pumps require electricity to operate. In fact, all pumps run on electricity, and they are highly efficient because of this. The electricity powers the heat pump's compressor, fan, and valve, which work together to transfer thermal energy from one location to another. In this section the amount of electricity input required for the current setup is discussed. As we can see in the graph below, the amount of electric power required for the central circulation pump uninterrupted operation throughout the year, sums to around 79kW. This is shown by the graph in Figure 4.14(a). Although, as depicted in graph shown by Figure 4.14(b) the amount of electric power required for the central heat pump is 0.8MW or 800kW (maximum).

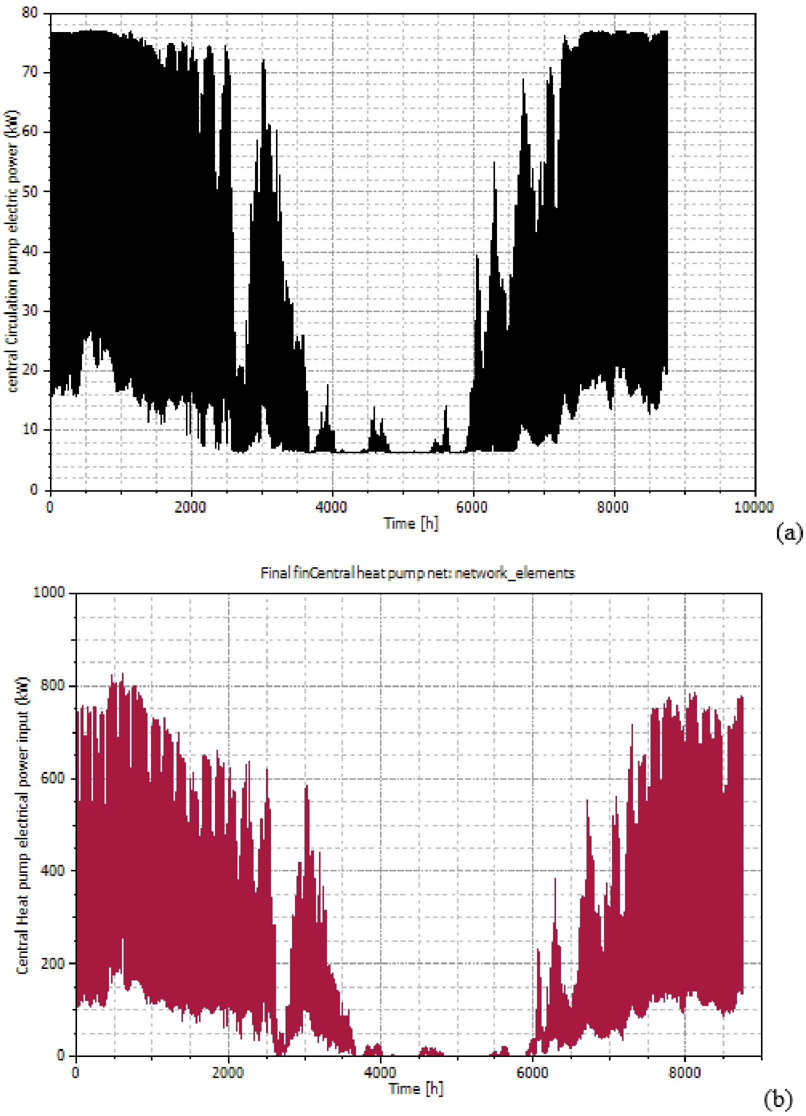

Figure 4.14: Scenario 1: Electrical power input (a)Central circulation pump, (b)Heat pump

4.2. DISTRIBUTED HEAT PUMP SYSTEM

4.2.1. Sized pipe network

The following figure (Figure 4.15 below) shows the result of applying pipe sizing algorithm to Scenario 2, where each colour depicts a different pipe diameter discussed earlier in the report.

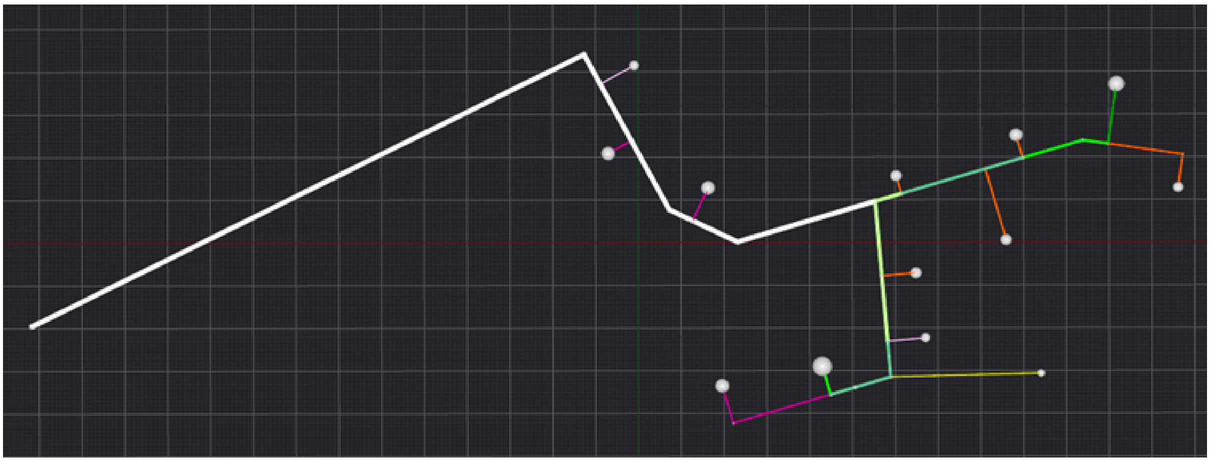

Figure 4.15: Results after pipe sizing for the DHN – Scenario 2

4.2.2. Maintained flow

The maintained flow requirement initial conditions were provided as described above by Graph in Figure 4.16. As the iterative process was moved through after simulating the network, it was realised that a lower flow rate is required for the current setup of the distributed heat pump system (explained in the methodology). As we can see from the graph the supply velocities range from 0.5 to 1.2 m/s as simulated over the year with hourly heat load profile. Whereas the return velocities are lower to around 0.4 m/s if taken as an average. This difference in the velocity requirement from the central heat pump system (scenario 1) is further discussed in conclusions section later.

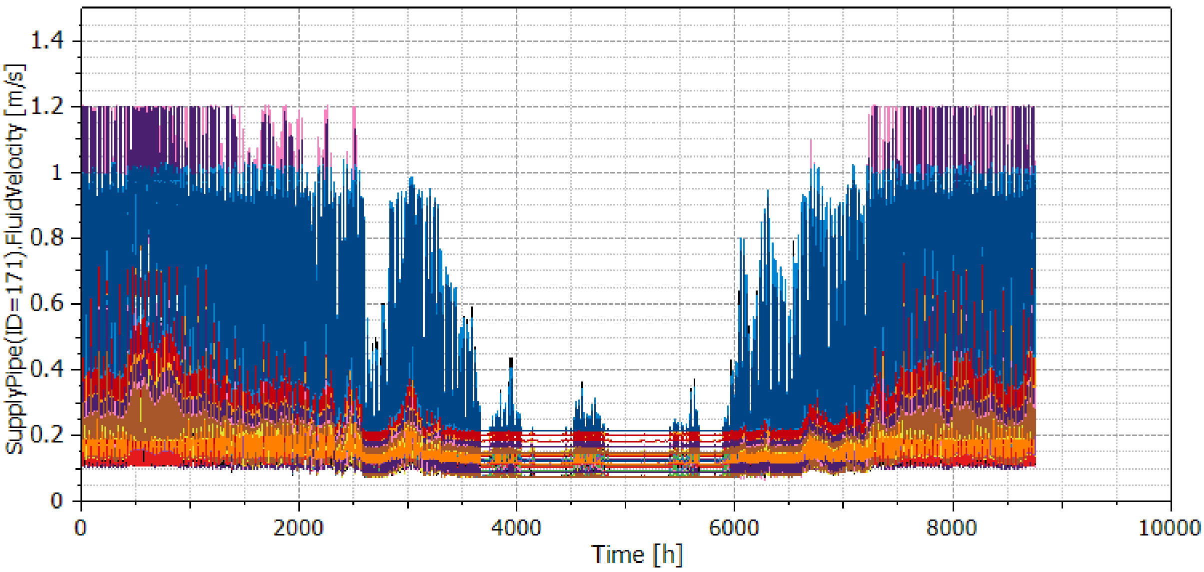

Figure 4.16: Scenario 2: flow velocity (m/s) of heated working fluid supplied to the DHN

Analyzing the daily variations depicted in the graph reveals that the mass flow rate escalates upon the identification of demand. Subsequently, this flow rate undergoes a reduction and modification when the heating demand reaches its peak, facilitating enhanced heat transfer at the SINK point. A significant decrease in flow rates occurs when the space heating requirements diminish considerably in residential and commercial structures. During the summer months, the space heating demand dwindles to nearly negligible levels, a trend that is also reflected in the graphical representation showing minimal mass flow rates within the network during this specific timeframe.

As already mentioned the velocities the following graph in Figure 4.17 represents the mass flow rates of the supply and the return pipes for the current distributed heat pump system scenario. As we can see here the top band ranging from 40 kg/s to around 85 kg/s depicts the supply pipeline flow. On the other hand the lower band ranging from 10 kg/s to around 40 kg/s shows the return pipe flow. These values are considerably lower than the results accumulated in the Scenario 1 - Central heat pump system.

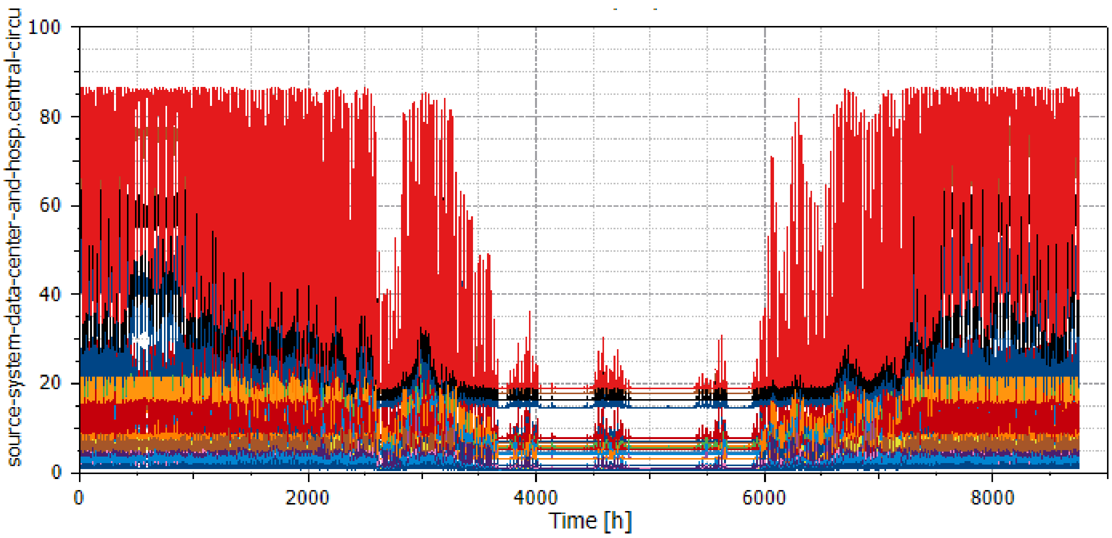

Figure 4.17: Scenario 2: Mass flow rate (kg/s) of heated working fluid supplied to the DHN

4.2.3. Pressure drop/difference

As already explained before, the measurement of pressure variations plays a crucial role in the advancement and improvement of Low Temperature District Heating (LTDH) systems. By obtaining a thorough understanding of the pressure variances along the pipeline, designers are enabled to participate in well-informed decision-making procedures relating to various factors such as pipe sizes, pump selections, valve and fitting choices, network layout, heat exchanger planning, insulation approaches, leak detection, and system balance. Consequently, this leads to the establishment of a more efficient, reliable, and financially feasible LTDH network.

To account for a better one-on-one comparison of the two scenarios for the current setup, , the outlet node pressure for the SOURCE was kept to be around 5 bar after considering the Pressure losses at various components as per the data collected from the initial iterative processes for the network setup. The graph below shows the pressure losses at various pipe elements considering both supply and return pipeline network respectively. The graph in Figure 4.18 clearly depicts the pressure differences ranges from 0.05 bar to 0.2 bar for the supply side. Whereas this difference reduces much for the return pipelines. This lower pressure loss can be partially attributed to the lower values of velocity/flow required by the distributed heat pump setup for the low temperature district heating network.

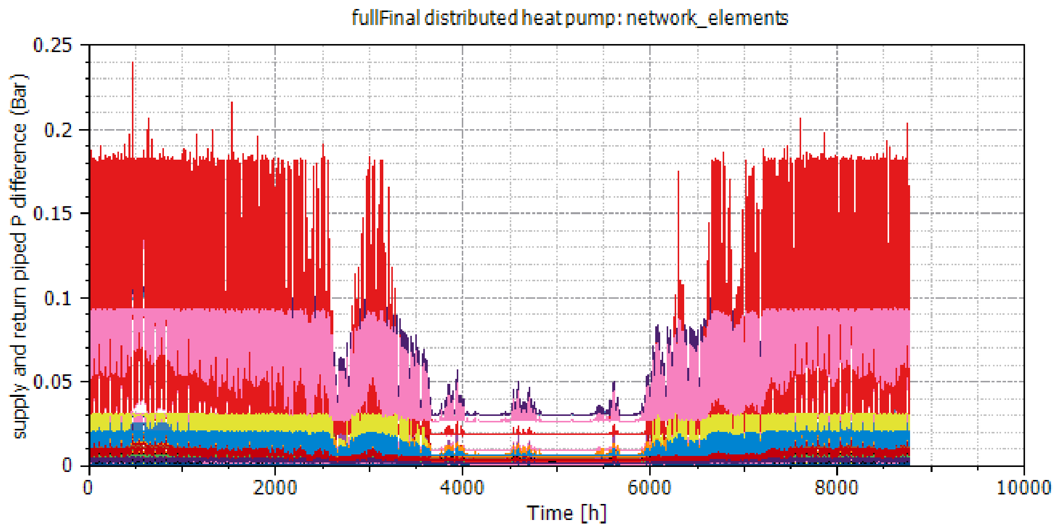

Figure 4.18: Scenario 2: Pipeline supply and return element Pressure difference (Bar)

Though as per the simulation results the total pressure loss across the network was around 2 bar to 3 bar. Thus the maximum of 3 Bar was considered for any further calculations in the simulations. The same can be clearly seen from the graph in Figure 4.19 below, as the lighter colour band corresponds to the supply pipe outlet node pressures, while the darker tones below on the graph (2 Bar – 2.5 Bar) signify the return pipe outlet node pressures. This overall Pressure drop seems higher than individual pipeline pressure drops as it also accounts for the heat pump pressure loss as the heated supply side working fluid provides the heat to the SINK points and returns back to the return pipeline network, with one heat pump present at each SINK point for the current setup.

It is evident from the graph that when focusing on a short-term cycle, the decrease in pressure (when examining a narrow time frame) corresponds to a decrease in flow rate. This phenomenon is closely linked to the decrease in demand for space heating during those specific time periods.

In order to gain a clearer understanding of the overall pressure drop as the fluid moves from the SOURCE to the SINK and is returned to the network from the SINK post heat exchange, an analysis of the outlet node pressure at the supply and return points is necessary. This outcome further aids in the adjustment of the head provided for the central circulation pump following multiple simulations.

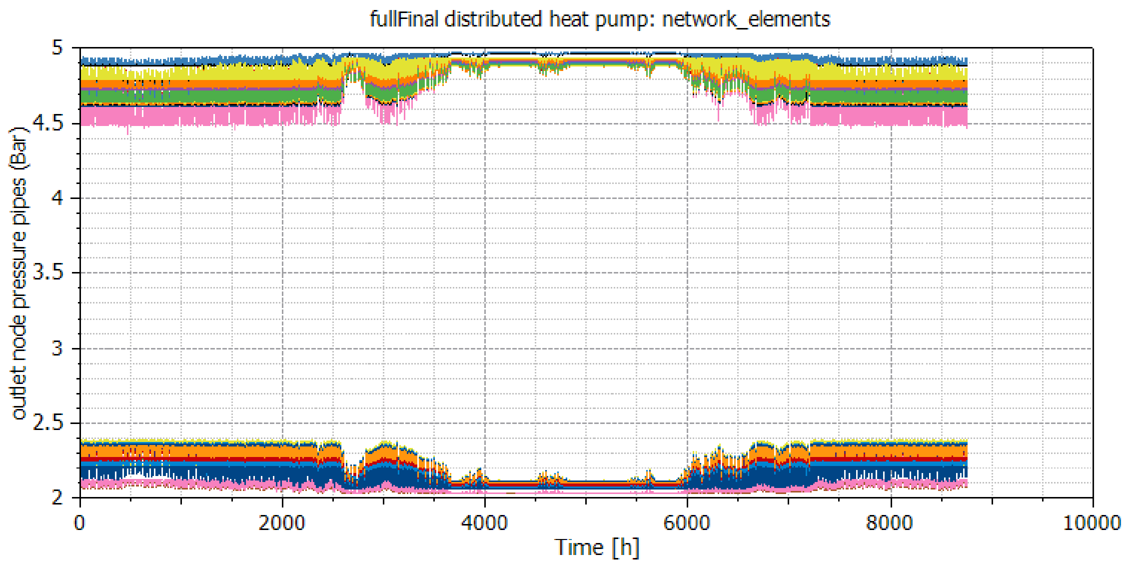

Figure 4.19: Scenario 2: Pipeline supply and return outlet node Pressure (Bar)

If we closely look at the graph shown in Figure 4.19 , the topmost blue and yellow colours represent the initial backbone of the network whereas the orange, green and pink colours represents the expanded branches further downstream in the network. The fluctuations in the outlet nodes vary on a daily basis as per demand and mass flow rates adjusted accordingly. Similarly for the return pipes the pressure of 2.4 bar represents the initial fed in pressure to the return network, whereas the lower pressures of blue and faint pink shows the return pipe pressure further downstream of the network.

4.2.4. Temperature and temperature difference

To account for the working of the complete distributed heat pump district heating network setup, it is important to look into how the temperatures are varying at the various substations set-up modelled and fed in the SIM-VIICUS software. In the present network the heat is circulated as soon as it is recovered from the SOURCE. This recovered heat, as previously mentioned in the report is available at 30°C which is a combination of primary waste heat from datacentre AM5 and a part of waste heat from AMC hospital.

As for the present simulation the focus was to estimate the maximum capacity and working efficiency of the proposed network, the distribution pipes are considered to be with high effective insulation (minimum heat exchange with the environment).

In the graph shown below (Figure 4.20), it is clearly depicted how the available pipe temperatures (depicted by the colourful band ranging from 24°C to 30°C is up-levelled to the required temperature of 51°C needed for space heating. This shows a proper working of the heat pumps at each available substation.

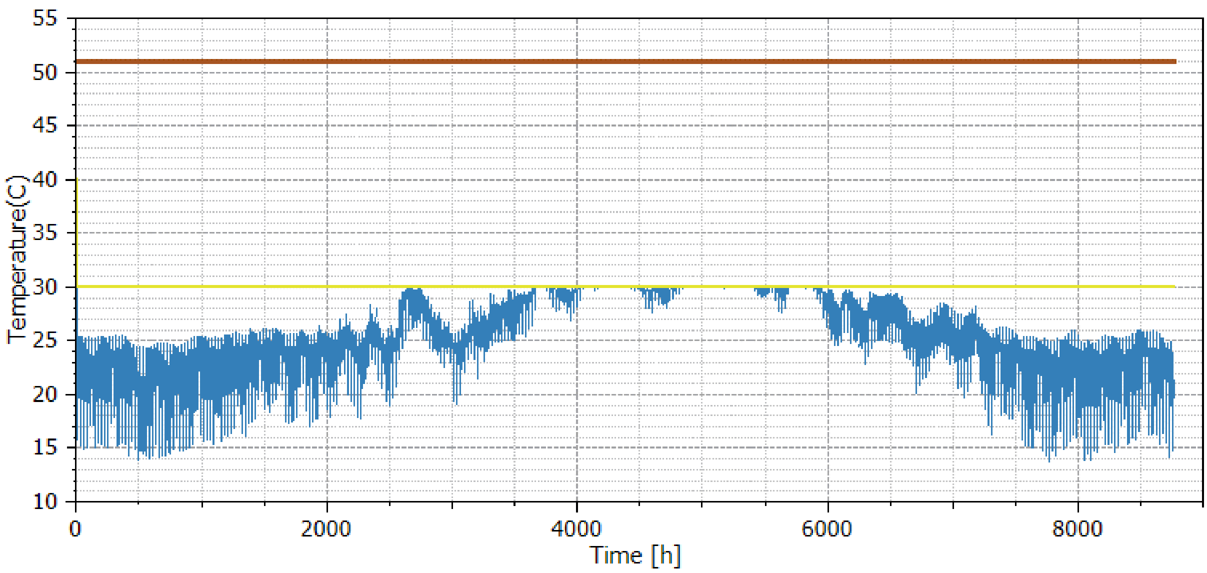

Figure 4.20: Scenario 2: red – HP outlet node temperature (°C), yellow – Datacentre recovery temperature(°C) and Blue – Supply pipe refed stream temperature(°C)

As already discussed above, that the heat is circulated as soon as it is recovered from the SOURCE which is available at 30°C. This heat is not upgraded until it reaches the SINK substations, where the heat pumps are installed. This heated working fluid reaching to the SINK ranges in temperature from 29°C to 30°C because of the presence of exceptionally effective insulation (already discussed assumption previously in the report).

As the temperature of the working fluid is upgraded by the heat pump and supplied to the SINK, the next graph shown by Figure 4.21 accounts for the return pipe temperatures as the working fluid flows back to into the pipe network. As interpreted from the graph below, the return pipe temperatures ranges from 25°C to 28°C considering when the network is working with an acceptably higher loads (not considering the band representing the summer months with negligible space heating demands.

As expected the temperature is lowest during the early morning hours and highest during the evening hours. Similarly, the temperature is lowest when the space heating demand is at peak and high otherwise. The temperature in this graph is typically around 5 - 10°C during day peak demand for space heating and around 27 - 25°C during off peak hours.

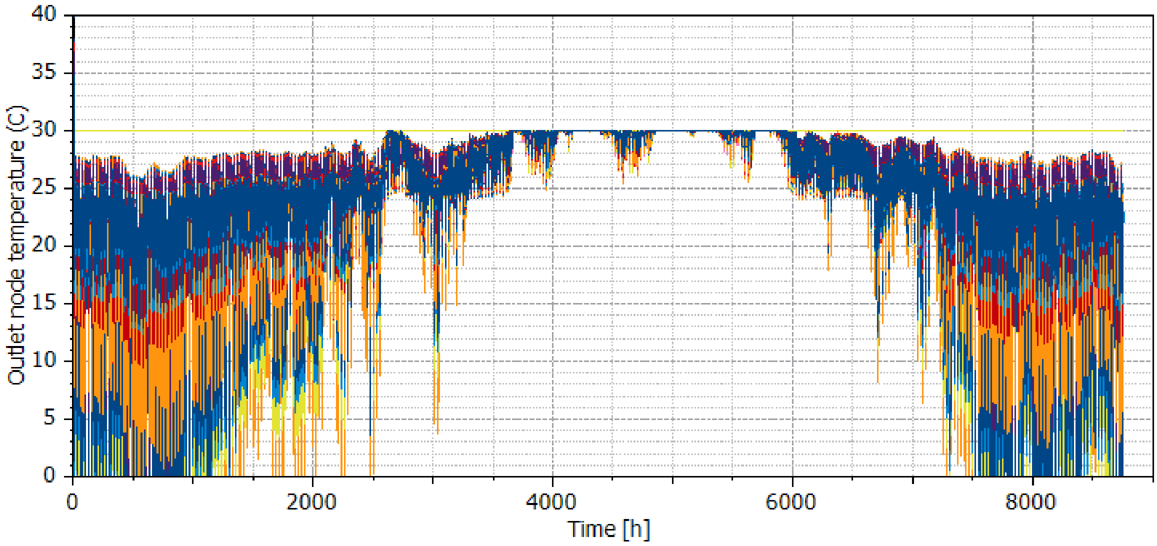

Figure 4.21: Scenario 2: Return pipe – outlet node temperature (°C)

4.2.5. Heat load and Electrical power needed

Heat pumps and circulation pumps rely on electricity as the primary energy source for their functioning. An example of this is seen in heat pump system that combines waste heat and electricity to elevate the temperature by using electricity externally to boost the pressure of low-pressure vapor and a dilute solution of a working fluid, thus improving the efficiency of waste heat utilization. Likewise, in the context of a heating system, a circulation pump is powered by an electric motor, with the stator positioned in a motor casing that is linked to the pump casing, underscoring the dependence on electricity for the operation of the pump. To sum up, electricity plays a pivotal role in driving both heat pumps and circulation pumps, thereby enabling their operation in diverse settings.

Thus now we will look into the amount of electric power that is needed for the smooth operation of the current setup – Distributed heat pump system for a low temperature district heating network.

The first to focus on is the central circulation pump integrated in the SOURCE system. As clearly interpreted from the graph shown in Figure 4.22 below, the electric power needed for the circulation pump utilised in the current setup is 26.5kW. Again the lower values attribute to the requirement of lower velocities partially and also the fact that a heat pump is setup at each SINK site, as it typically covered by the Heat pump provided at each SINK site. This reasoning and great difference in operation conditions is further discussed in the section conclusions of the report later.

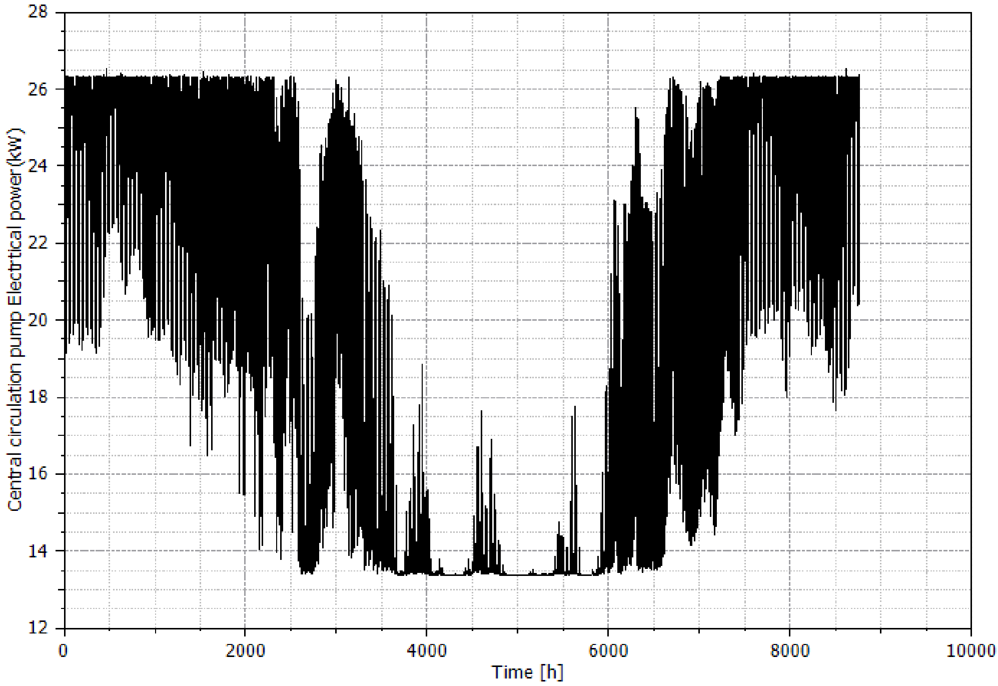

Figure 4.22: Scenario 2: Electrical power input - Central circulation pump

As for the Scenario 2 – distributed heat pump system, the heat pumps are present at each SINK point, thus the electric energy required is presented separately for the heat pumps.

HP - 260, peak load 500 kW

In the graph presented by Figure 4.23 below we can see how the electrical input varies for a day cycle. The peak corresponds to the peak hours, whereas the non-peak region corresponds to the hours of the day when space heating demands are low. Also as per the complete simulation of a year, the maximum needed electrical input for the heat pump is around 500kW.

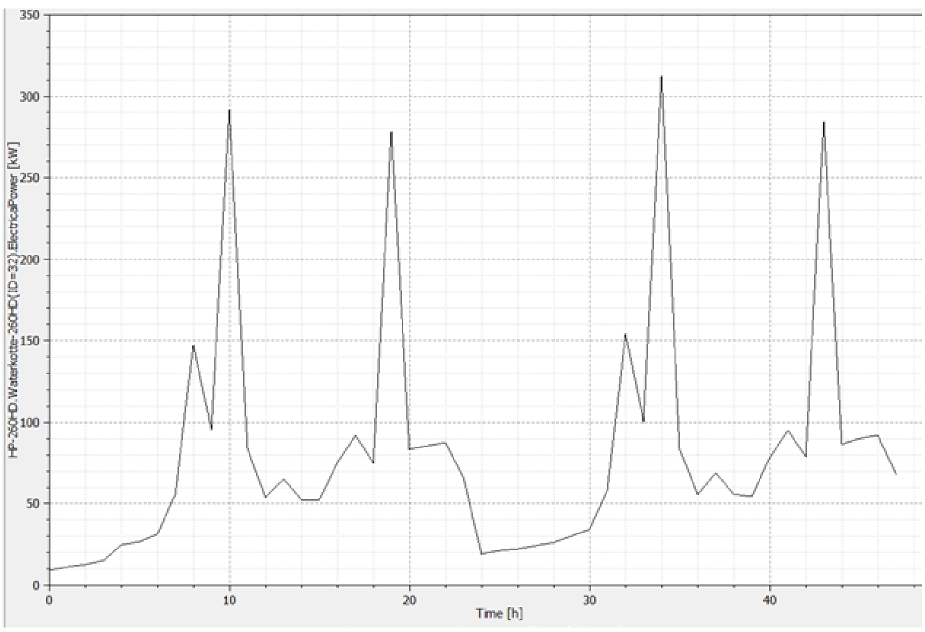

Figure 4.23: Scenario 2: Electrical power input – HP260

HP - 187, peak load 250 kW

The graph depicted by Figure 4.24 below shows the electrical energy input cycle closely for HP – 187. The peak on the graph aligns with the peak hours, while the off-peak zone corresponds to the periods of the day characterized by reduced space heating requirements. Furthermore, based on the comprehensive year-long simulation, the highest necessary electrical power input for the heat pump is approximately 250kW. Which occurs for a week in the time slot of 3 weeks period of February, being the coldest month of the year in the Netherlands.

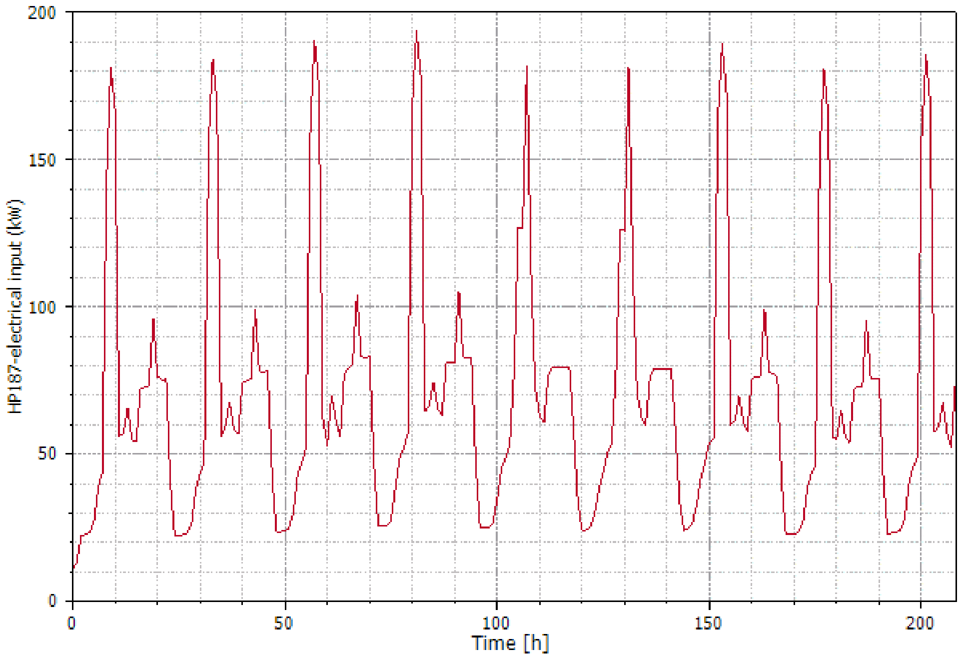

Figure 4.24: Scenario 2: Electrical power input – HP187

Similarly we can see the graphs shown bby Figure 4.25 and 4.26 below, for the heat pumps – HP154 and HP120 and interpret the electricity input needed as a data sheet of hourly values for over the year.

HP - 154, peak load 220 kW

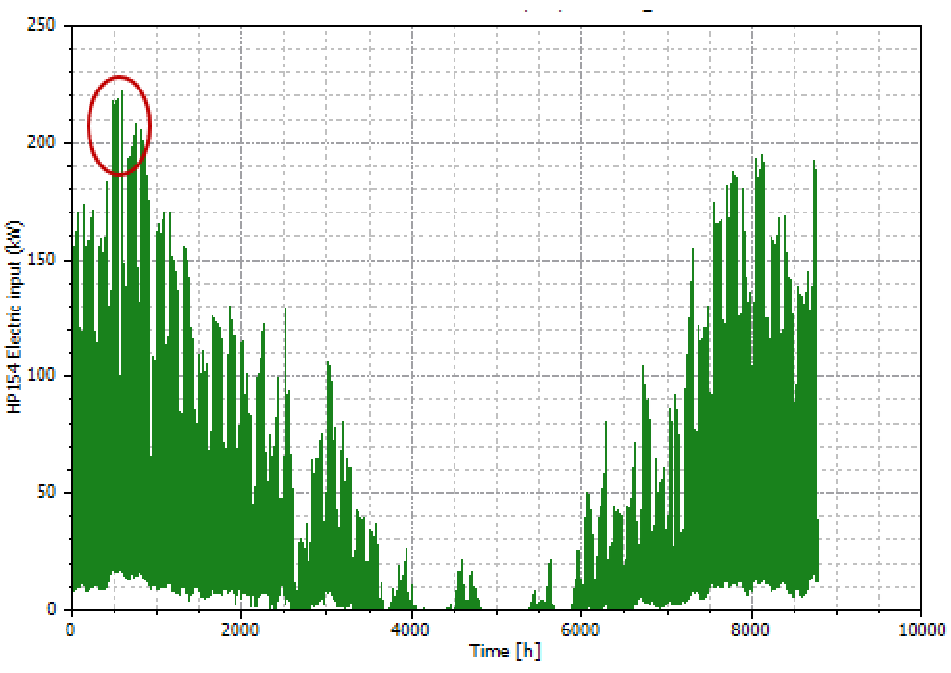

Figure 4.25: Scenario 2: Electrical power input – HP154

HP - 120, peak load 110 kW

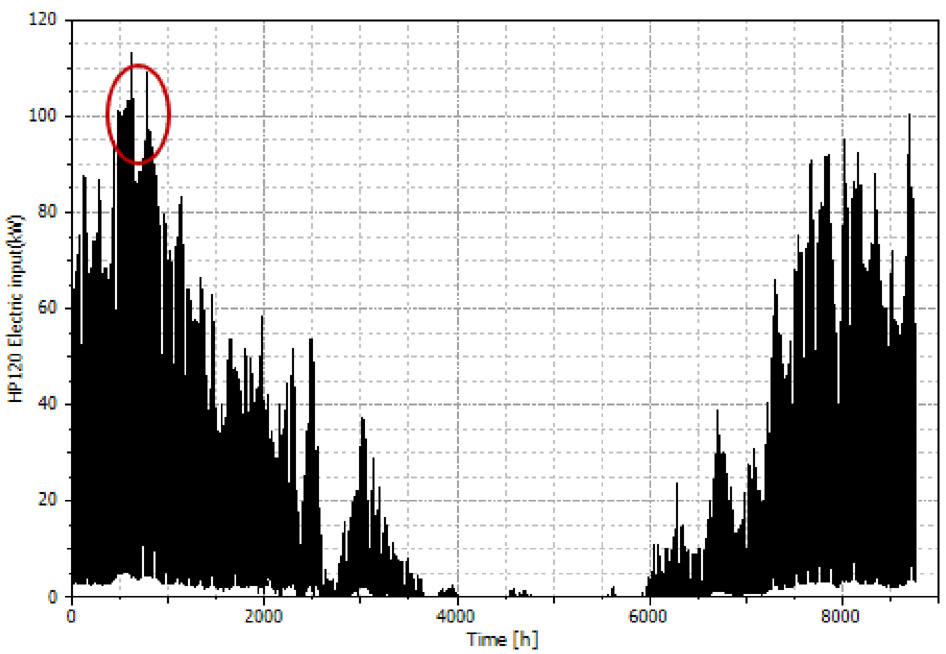

Figure 4.26: Scenario 2: Electrical power input – HP120

From the heat pump graphs (as the data observation is made on a complete year as time interval), it is well evident that the peak electrical energy input is usually higher than the average electrical energy input. This suggests that the network is working with peak loads for 1 or 1.5 months where the electricity requirement is much high but overall the electricity input is considerably in acceptable range and can be covered by renewables in a combined system.

During a week within the three-week period of February, which is considered the coldest month of the year in Netherlands, these peaking demand phenomenon takes place. January, and February are identified as the coldest months of the year in the Netherlands. The average temperatures on the chilliest days range from 0ºC (33ºF) to 5ºC (42ºF) and 6ºC (43ºF). In the event of a winter visit to the city, encountering snowfall is highly likely [8].

4.2.6. Heat load per Heat pump and COP

The heat load is the amount of heat energy required to meet the building's heating or cooling demand. It's typically measured in kilowatts (kW) whereas the COP is a dimensionless value that represents the ratio of the heat output to the electrical energy input. It's defined as:

$$COP = \frac{Q}{W} \tag{4.1}$$

where W is the electrical power input to the heat pump.

As we gathered the values of heat load and the COP of the heat pumps also shown herewith by Figure 4.27, we see that the values correspond to the above relationship. Thus ensuring the heat pump model is working correctly.

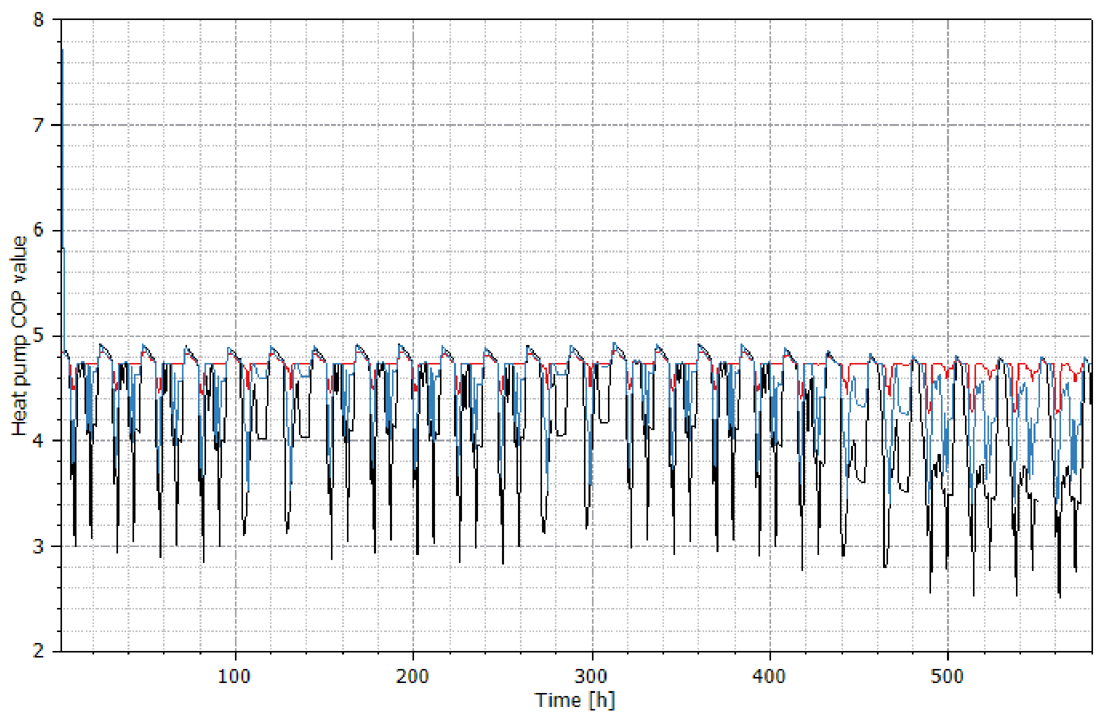

Figure 4.27: Scenario 2: Heat pumps COP value

The peak corresponds to the heat pump working on a peak demand on a daily basis and thus has a higher COP value during that period. The lower points correspond to lower demands where the heat pumps are working with much lower temperature differences and thus cannot perform to their full potential. Operating a heat pump under part-load conditions signifies that the system is not achieving its maximum capacity, but rather generating a reduced level of heating or cooling, which occurs when the building's demand for heating or cooling is below the heat pump's maximum capacity.

The heat load is discussed and shown by Figure 4.28 herewith. As discussed earlier we can clearly see the correspondence and relation that the COP holds with the heat load experienced by each Heat pump and the electrical input required by each heat pump separately.

The heat load depicted in Figure 4.28 is specifically shown by a negative axis. The downward peaks corresponds to the higher heat loads whereas the upward peaks represents partial load hours on the heat pump. This is complementing the daily heat demand cycle when the space heating demands are higher and lower. The graph in Figure 4.28 shown below was generated for 280 hours to have a much clear idea of each heat pump behaviour as the load varies over the day on a hourly basis, also requiring the heat pumps to efficiently work with partial loads.

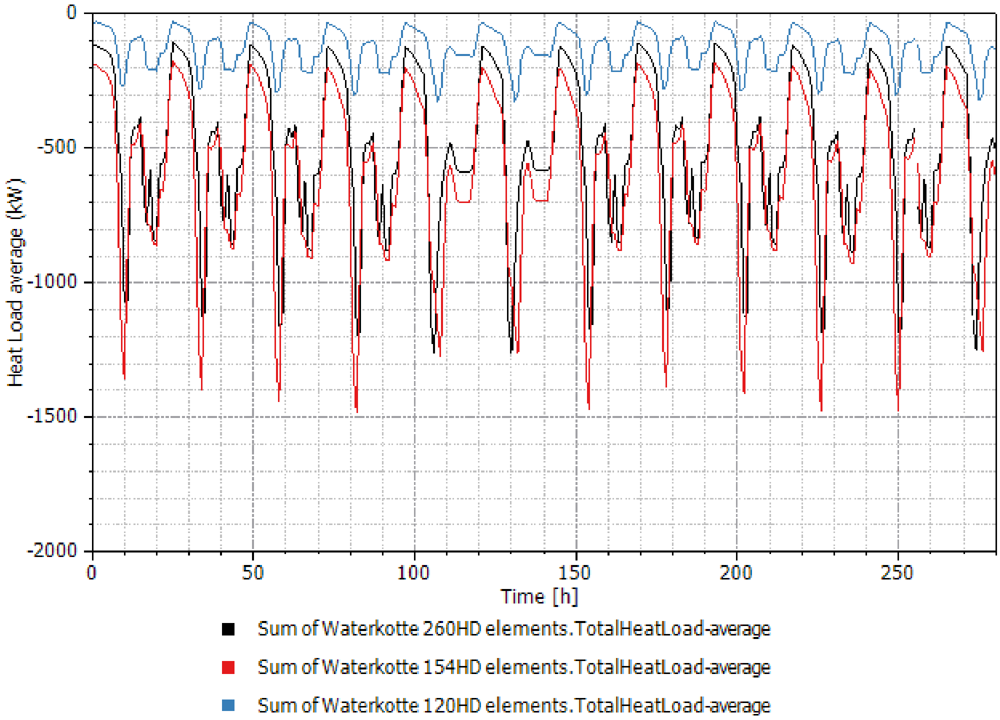

Figure 4.28: Scenario 2: Heat load average – heat pumps

Also as very evident from the graph shown by Figure 4.28 we can see that the heat load experienced by different heat pumps are varying. This is an obvious result of working with different heat loads. Lower the peak downwards, more is the heat load experienced by the heat pumps per hour.

5

Qualitative study on Financial aspects

When examining the financial implications of a decentralized heat pump system versus a centralized heat pump system for low-temperature district heating networks, it is essential to take into account the subsequent factors:

Installation Expenses: Typically, decentralized heat pump systems entail greater installation expenses compared to centralized heat pump systems. This is attributed to the additional infrastructure, such as piping and duct work, that is necessary to be implemented in each building.

Operating Costs: Decentralized heat pump systems have the potential to exhibit higher energy efficiency than centralized heat pump systems, leading to reduced operational costs. This is due to the decentralized systems focusing on heating or cooling only the spaces in use, rather than the entire building, thereby enhancing climate control efficiency.

Maintenance Expenditure: The maintenance costs associated with decentralized heat pump systems might be lower than those of centralized heat pump systems. This is because decentralized systems feature fewer components that are susceptible to failure, and maintenance can be conducted on individual units rather than the entire system.

Resilience: Decentralized systems demonstrate greater resilience to flood damage as a majority of the equipment is situated above the basement level, diminishing the likelihood of flood-related harm. Consequently, this can lead to decreased expenses pertaining to repairs and replacements over time.

Sub-Metering Capability: Decentralized systems allow for the sub-metering of heating and cooling energy, offering advantages in specific scenarios. This capability can culminate in enhanced precision in billing and cost distribution.

Table 5.1: Scenario comparison – Qualitative financial aspects

Factor	Distributed Heat pump System	Central Heat Pump System
Installation Costs	Higher	Lower
Operational Costs	Lower	Higher
Maintenance Costs	Lower	Higher
Resilience	Higher	Lower
Sub-Metering	Possible	Not possible
Summary	More Favourable	Less Favourable

In conclusion, decentralized heat pump systems may entail higher costs in terms of installation, operation, maintenance, and repairs as opposed to centralized heat pump systems designed for low-temperature district heating networks. Furthermore, decentralized systems can facilitate more precise billing and cost distribution through sub-metering. This conclusion is also represented by the Figure 5.1 as an overview shown below.

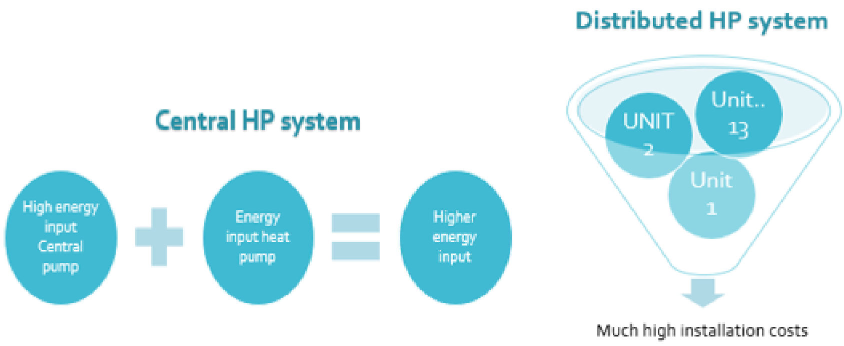

Figure 5.1: Schematic - Qualitative aspects of the 2 scenarios considered in the project

6

Conclusions and future scope

6.1. Pipe network sizing

The significance of pipe sizing within low-temperature district heating (LTDH) networks is rooted in its influence on the overall effectiveness and cost-efficiency of the system. The proper sizing of pipes is essential for the minimization of heat dissipation, reduction of pressure fluctuations, and enhancement of the system's operational efficiency.

Within LTDH networks, pipes are commonly dimensioned according to a specified pressure drop target per unit length of the pipe. Nonetheless, this method can result in the installation of excessively large pipes, leading to heightened heat losses, particularly evident during periods of low heating demand and in pipes with smaller diameters. Conversely, the utilization of undersized pipes may culminate in escalated electricity consumption required for flow circulation, especially when facing elevated demands and larger pipe diameters.

The pipe sizes allotted using the pipe sizing algorithm were found to be almost similar for both the cases. If looked closely, the pipe sizes received as a result of the simulation for distributed heat pump system (scenario 1) were still a bit lower than the central heat pump system (scenario 2). This can be justified with the presence of heat pumps at each SINK station to maintain and suffice the demand at each time interval. The same is depicted in the Figure 6.1 below. As a summary the optimal pipe sizing can assist in addressing these challenges through the following:

Decreasing thermal losses: By careful selection of the appropriate pipe diameter, thermal losses can be mitigated, resulting in energy efficiency and decreased emissions of greenhouse gases.

Minimizing pressure variations: Adequate pipe sizing can mitigate pressure fluctuations, thereby reducing energy consumption for pumping and decreasing operational expenditures.

Enhancing system efficiency: Optimal pipe sizing can contribute to maintaining the system's operation within the specified temperature parameters, lowering the risk of Legionella contamination, and enhancing the overall reliability of the system.

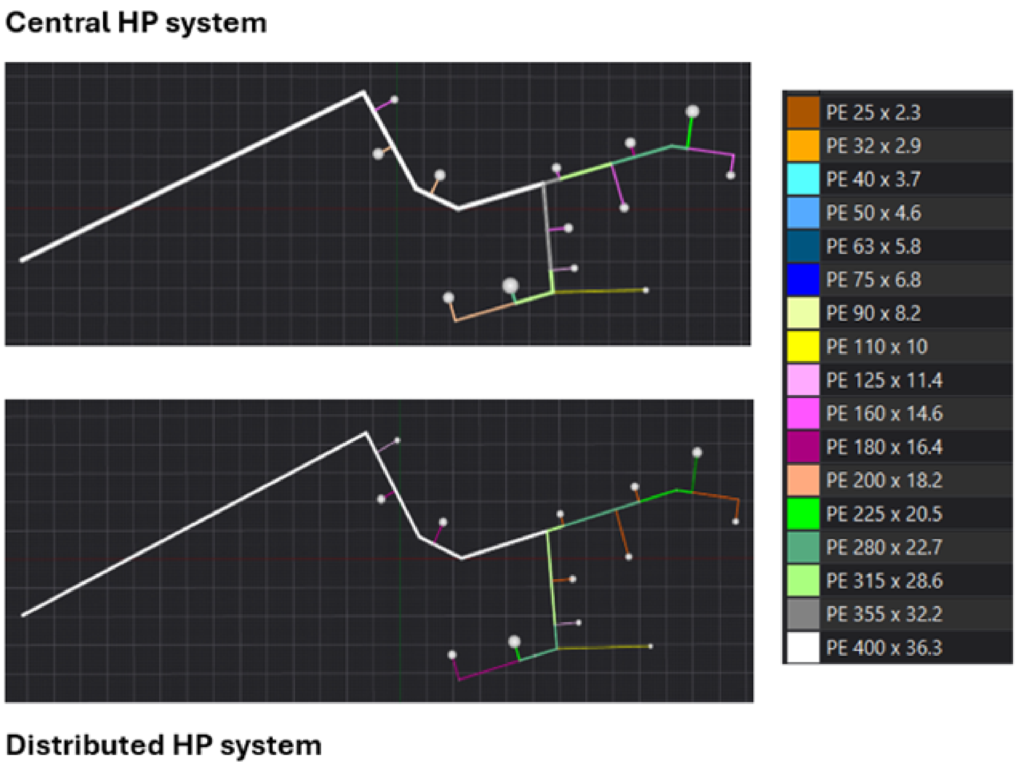

Figure 6.1: Pipe sizing comparison for both scenarios

6.2. Maintained velocity

As it can be interpreted from the graphs shown by Figure 6.2 below, that the working velocity for the central Heat pump system (1.5 m/s) is much higher than the 0.75 m/s for the distributed heat pump system. This can be attributed to the following factors:

- Presence of Heat pumps at each SINK substation to cover for the required pressure difference needed
- working with a lower temperature in the whole pipe network until the working fluid reaches the heat pumps at SINK
- Different modules/substations adjusting with the heat demands when needed independently.

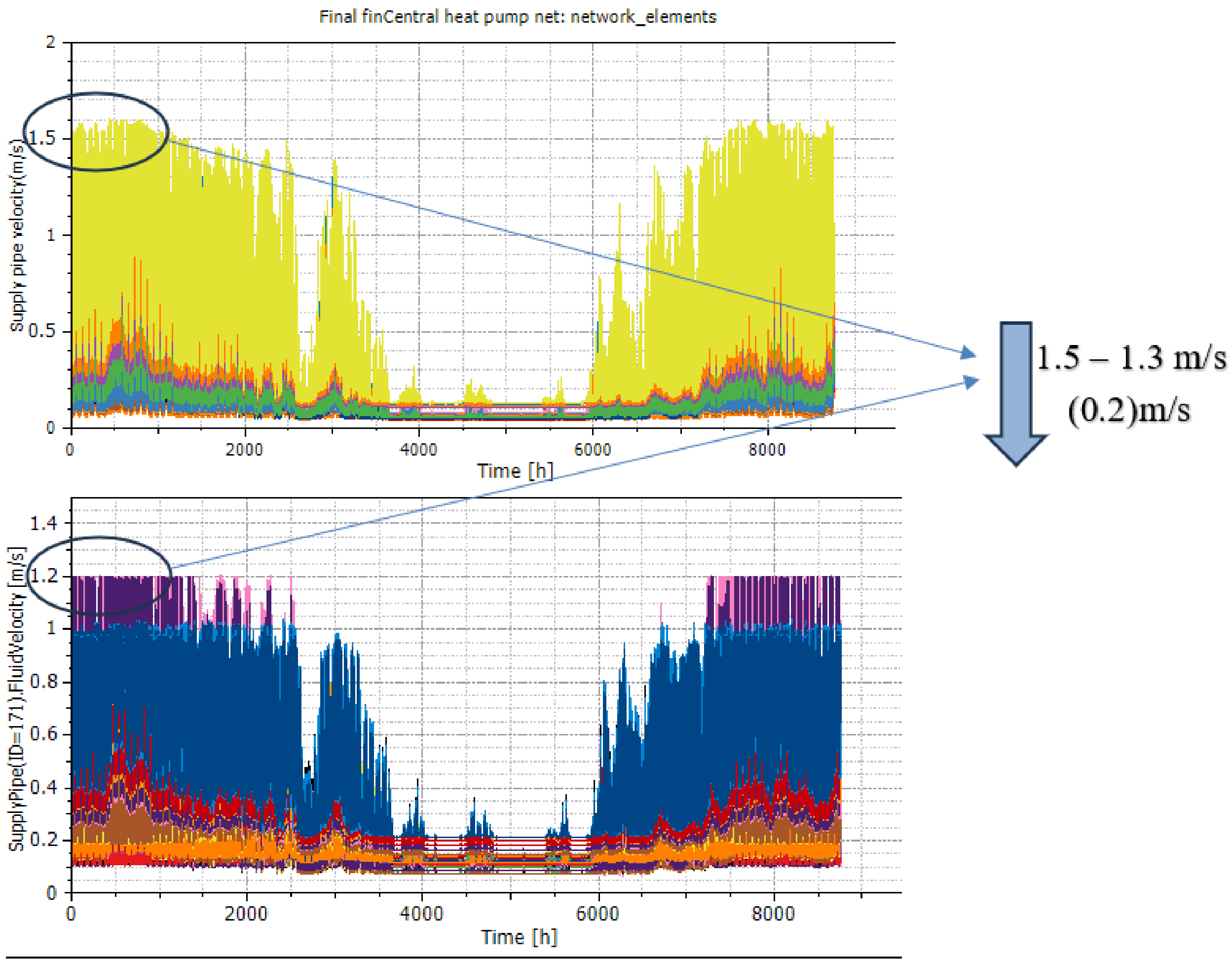

Figure 6.2: Minimum needed velocity comparison for both scenarios

Lower velocities in low-temperature district heating (LTDH) networks may offer advantages compared to higher velocity for multiple reasons:

- Reduced Thermal Losses: Lower velocities lead to decreased heat losses by diminishing turbulence and friction within the pipes, ultimately enhancing system efficiency and reducing energy consumption.
- Minimized Pressure Fluctuations: Lower velocities help in minimizing pressure drops, thereby lowering the energy needed for pumping fluid through the network. This leads to decreased operational expenses and enhanced system dependability.
- Extended Pipe Durability: Lower velocities mitigate the likelihood of pipe erosion and corrosion, consequently prolonging the pipes' lifespan and reducing maintenance expenditures.
- Enhanced System Regulation: Lower velocities facilitate improved system regulation, as the flow rate becomes more consistent and manageable. This, in turn, allows for more precise temperature regulation and enhanced system operation.
- Diminished Noise and Vibrations: Lower velocities contribute to reducing noise and vibrations within the pipes, creating a more comfortable system for users and decreasing the likelihood of pipe impairment.

6.3. Pressure drop

From the graph comparison represented by Figure 6.3 below, it is very evident that the pressure drop in the pipelines for the supply and the return is much lower for the distributed heat pump system (scenario 2), when compared to the central heat pump system.

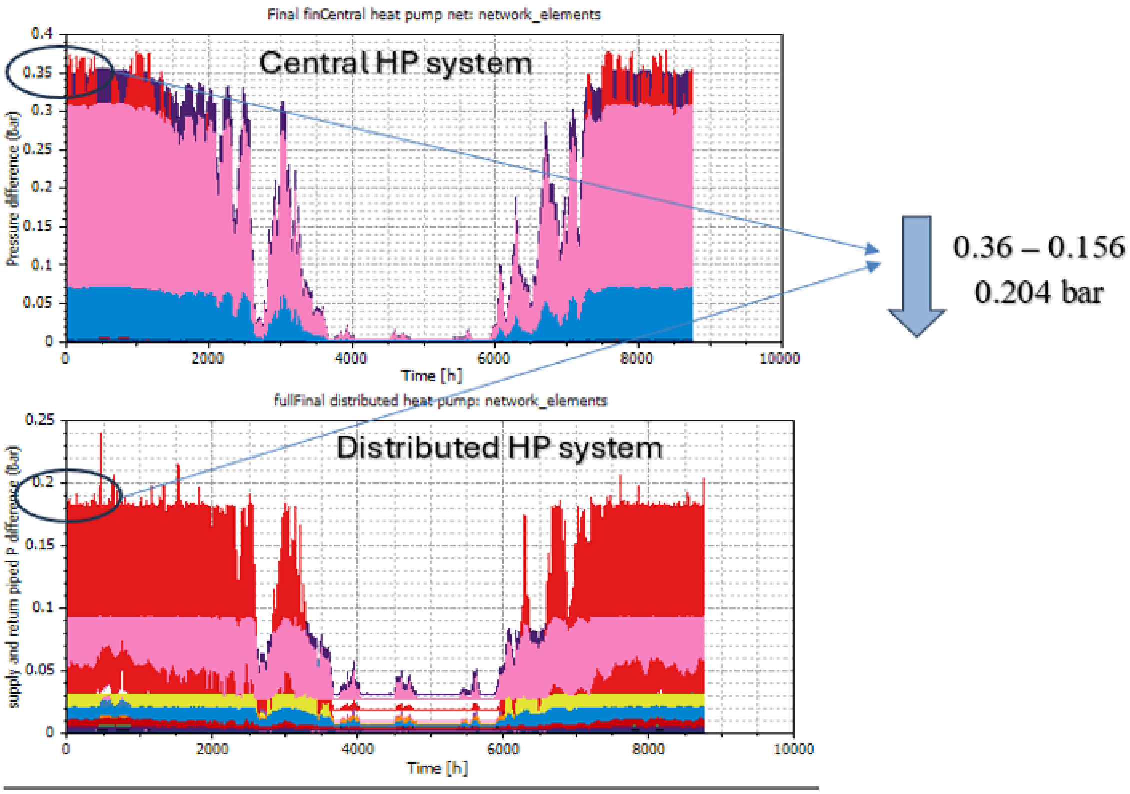

Figure 6.3: Supply and return pipe pressure difference comparison for both scenarios

The reduced pressure drop in a hydraulic network with lower fluid velocity is attributed primarily to the diminished friction between the fluid and the pipe walls. Within the realm of fluid dynamics, the pressure drop is intricately linked to both the velocity of the fluid and the level of friction encountered during its passage through the pipe.

When working fluid traverses a pipe, it encounters opposition from the pipe walls, resulting in the generation of friction. This friction is responsible for the decline in pressure along the length of the pipe. Greater velocity corresponds to heightened frictional forces, consequently leading to an increased pressure drop. The Darcy-Weisbach equation, a cornerstone equation in fluid dynamics, delineates the connection between pressure drop, fluid velocity, and friction. Figure 6.4 ddescribes the Darcy-Weisbach equation.

Here, the friction factor (f) is influenced by the flow regime (whether laminar or turbulent) and the relative roughness of the pipe. In the case of laminar flow, it is determined by the expression f=64/Re, where Re denotes the Reynolds number. However, for turbulent flow, the value of friction factor is commonly obtained through empirical relationships or by referencing the Moody chart. This formula is widely utilized for estimating pressure losses in round pipes for both laminar and turbulent flows, playing a crucial role in the planning and evaluation of piping networks. The Darcy-Weisbach equation, by quantifying the friction-induced energy dissipation, facilitates the creation of effective piping systems, guaranteeing that pumps and other elements are suitably dimensioned to sustain desired flow rates.

Darcy Weisbach Equation

hf = (f × L × V^2) / (2 × g × D)

Symbol	Parameter	Metric Unit	Imperial Unit
hf	Head loss due to friction	meters (m)	feet (ft)
f	Darcy friction factor	dimensionless	dimensionless
L	Pipe length	meters (m)	feet (ft)
V	Flow velocity	m/s	feet per second (fps)
g	Earth's gravitational acceleration	m/s^2	feet per second squared (fps^2)
D	Pipe diameter	meters (m)	inches (in)

Figure 6.4: Darcy-Weisbach equation

The head loss due to friction (hf) is directly proportional to the square of the fluid velocity (V^2), as the equation illustrates. Because of the decreased frictional forces, a lower velocity causes a smaller pressure drop.

Although this lower pressure drop as the heated working fluid is distributed over the network length might not effect the overall pressure drop of the two systems considred in scenario 1 and scenario 2, as both the vaules when computed are comparable to each other. This can be explained as the number of heat pumps increase additionally to other components in a distributed heat pump system and thus covering up the lower distribution losses.

6.4. Return pipe outlet node temperature

As clearly demonstrated from the graphs shown by Figure 6.5 below, the return pipe temperatures for the scenario 2 – distributed heat pump system (25°C – 28°C) were lower compared to the scenario 1 - central heat pump system (32°C - 47°C).

Lower return temperatures are typically more favorable than higher return temperatures in the context of a district heating network. The advantages of lower return temperatures encompass enhanced energy efficiency, diminished heat losses, and enhanced operational efficacy.

Various renewable energy sources and waste heat sources demonstrate higher efficiency levels or are only viable at lower temperatures. Through the operation of the district heating system at reduced return temperatures, these sources can be more effectively utilized, thereby decreasing dependency on fossil fuels and elevating the overall efficiency of the system.

When the return pipe temperature decreases, there is a rise in the temperature differential (ΔT) between the supply and return pipes. This heightened ΔT facilitates a more effective heat transfer process, enabling the heat exchanger to extract a greater amount of heat from the supply pipe and convey it to the heating system.

Also, lower return temperatures have the potential to decrease the necessary pumping energy. With lower return temperatures, the system can function with a reduced flow rate for the same heat transfer, thereby lowering the energy required for pumping and improving the overall operational efficiency of the network.

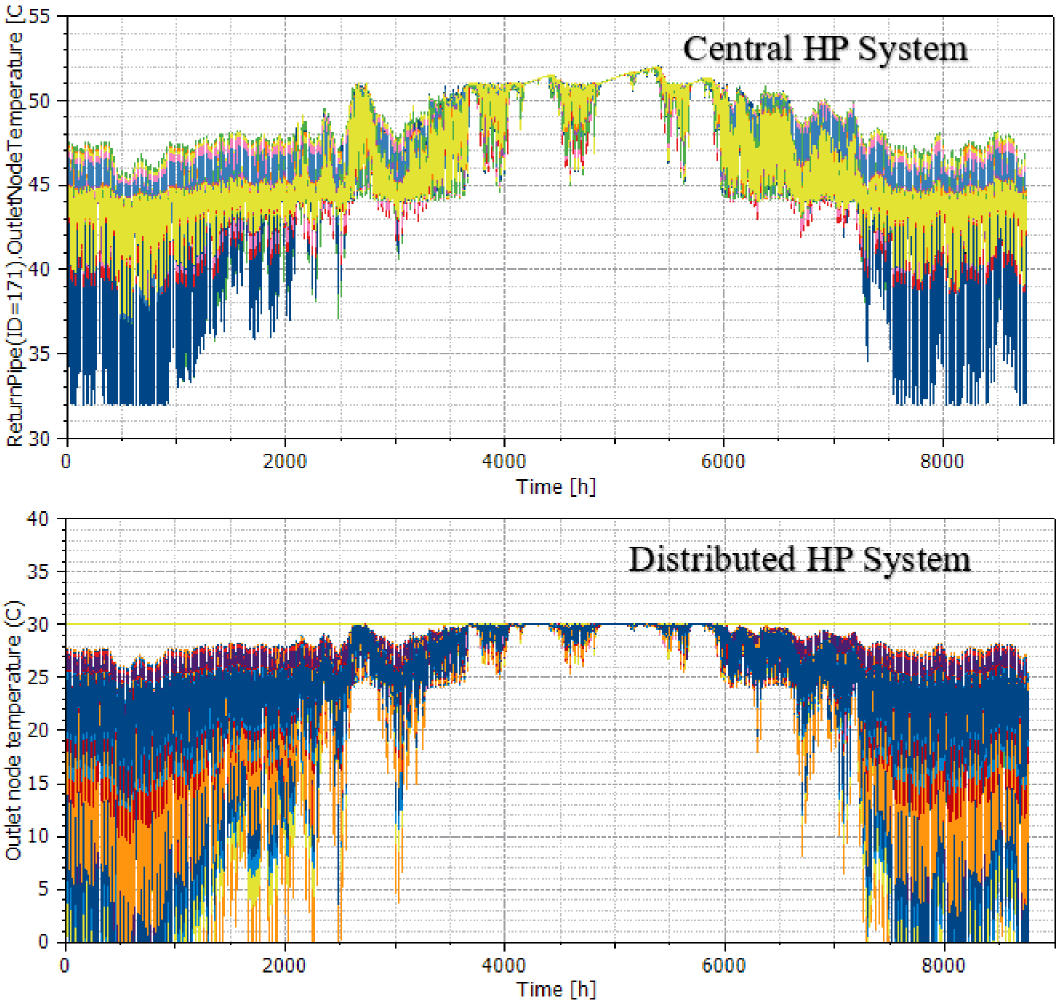

Figure 6.5: Return pipe outlet node temperature (°C) comparison for both scenarios

Moreover, lower return temperatures play a role in curbing heat losses within the distribution network. Heat losses exhibit a direct correlation with the temperature differential between the pipe and its surrounding. By decreasing the return temperature, the temperature differential diminishes, consequently leading to reduced heat losses.

Additionally, lower return temperatures aid in mitigating the likelihood of buildings connected to the district heating network overheating. Overheating scenarios may transpire when the return temperature surpasses a certain threshold, prompting the heating system to dispense excessive heat. Lower return temperatures contribute to sustaining a more equitable and pleasant indoor climate.

To recapitulate, lower return pipe temperatures within district heating networks can engender escalated energy efficiency, minimized heat losses, and heightened system functionality.

6.5. Central circulation pump – Electrical power

A clear representation of the electric power capacity required for the smooth working of the central circulation pump for both the scenarios is given by the graph comparison shown by Figure 6.6 below.

As it is clear from the graphs here the electric power capacity is much higher for the scenario 1 (78 - 79Kw) compared to a 26.5 kW needed for the distributed heat pump system.

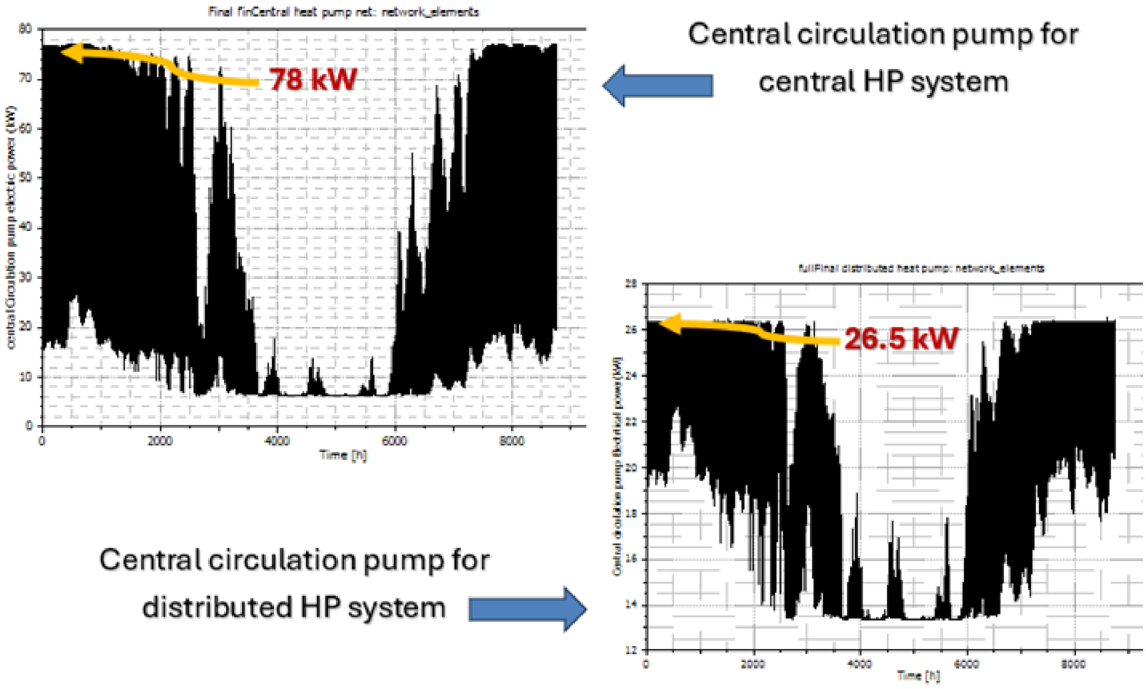

Figure 6.6: Electrical power input – central circulation pump(kW) comparison for both scenarios

From a scholarly standpoint, the pump power needed to facilitate fluid flow in a low-temperature district heating (LTDH) network is intricately linked to the pressure loss within the system. This decrease in pressure is instigated by the frictional hindrance caused by the pipes, connectors, and other elements present in the network. Further the decrease in supply temperature results in a decline in fluid density, thereby causing a reduction in pressure loss within the system. Consequently, the pump is required to combat lower pressure levels in order to circulate the fluid, consequently diminishing the necessary pump power.

The installation cost will be significantly higher due to the larger pump size and potential complexities in the installation process. A rough estimate for the installation cost of an 80kW the circulation pump could be in the range of $10,000 to $20,000 [13] or more, depending on factors such as the complexity of the installation, labor costs, and materials required. However, this is a very rough estimate and should be taken as a ballpark figure.

6.6. COP of heat pumps used

A water source heat pump with a Coefficient of Performance (COP) of 9 is deemed to be of exceptional quality. Generally, a COP ranging from 3 to 4 is classified as satisfactory, whereas a COP of 5-6 is regarded as highly commendable. We can see this for the values obtained for Heat pumps in the second scenario with a distributed heat pump system. Pictorially shown by Figure 6.7 below.

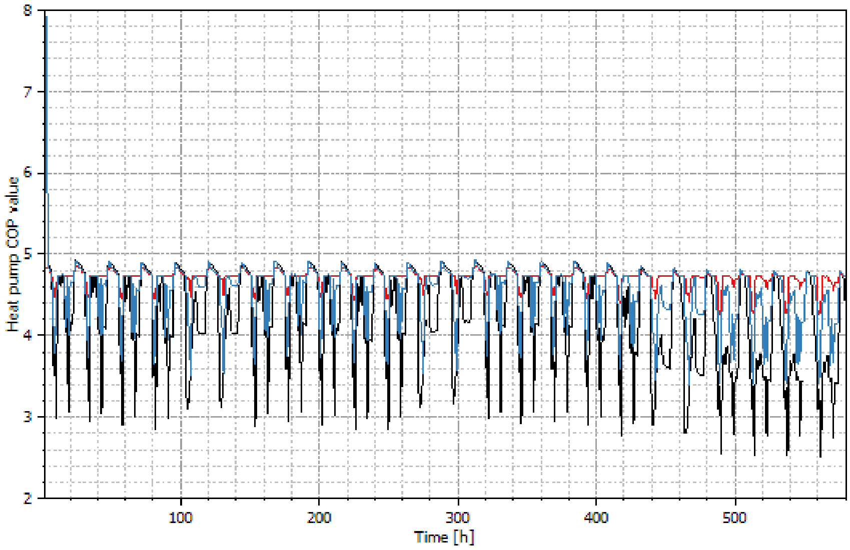

Figure 6.7: Scenario 2 –Distributed HP COP

On the other hand The COP of 9 significantly surpasses the average, indicating the heat pump's exceedingly efficient operation. This is in reference to Figure 6.8 below.

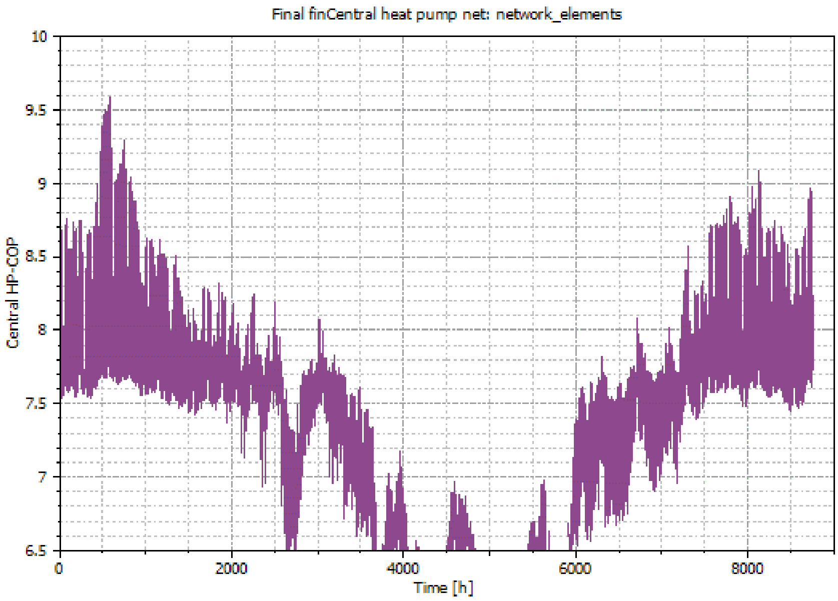

Figure 6.8: Scenario 1 – Central HP COP

In perspective, a COP of 9 signifies that for each unit of electricity consumed, the heat pump has the ability to generate 9 units of heat energy. This level of efficiency is noteworthy, particularly when compared to traditional heating systems dependent on fossil fuels, which typically exhibit a COP of approximately 0.8-1.0. A COP as elevated as 9 offers advantages by leading to decreased energy expenses, diminished greenhouse gas emissions, and an environmentally sustainable heating system.

Although a COP of 9 is theoretically attainable, it is highly improbable to achieve in a practical heat pump setup. Theoretical COP values are derived from idealized circumstances, assuming flawless heat transfer, absence of losses, and optimum component performance. Nevertheless, real-world heat pumps are susceptible to numerous inefficiencies and losses, including:

1. Heat exchanger inefficiencies: Heat exchangers do not operate at full efficiency, resulting in losses due to temperature differentials, flow rates, and other variables.
2. Losses from compressors and pumps: The compressor and pump in a heat pump system consume energy and release heat, thereby diminishing overall efficiency.
3. Losses through pipes: Heat dissipation occurs through pipes during transmission, particularly if they lack proper insulation.
4. Defrosting losses: Defrosting cycles in air-source heat pumps can diminish efficiency.
5. Inefficiencies in components: Real-world components like compressors, pumps, and valves do not perform at 100% efficiency.

Taking into account these inefficiencies, a more realistic COP for a high-efficiency water-source heat pump may fall within the range of 4-6. Even the most advanced heat pumps available in the market typically exhibit COPs in the vicinity of 5-6.

In a conclusion the coefficient of performance for a central heat pump is higher than that of heat pumps used in distributed heat pump system. The peak and drop in the COP over few hours each time during simulation can be justified by the nature of the heat pump not optimised for part load function. Operating a heat pump under part-load conditions signifies that the system is not achieving its maximum capacity, but rather generating a reduced level of heating or cooling, which occurs when the building's demand for heating or cooling is below the heat pump's maximum capacity. There are several factors that can result in a decrease in the Coefficient of Performance (COP) when a heat pump is operating at part-load conditions:

- Compressor inefficiency: When operating at part-load, the compressor may not be functioning at its peak efficiency level, as compressors are typically designed for optimal efficiency near their maximum capacity. Hence, a reduction in load may prevent the compressor from reaching its optimal operating point, leading to reduced efficiency.
- Increased compression ratio: Under part-load conditions, the compressor might need to work at a higher compression ratio to maintain the necessary pressure difference between the evaporator and condenser. This situation can escalate energy consumption and lower COP.
- Reduced refrigerant flow rate: At part-load, the refrigerant flow rate may decrease to align with the diminished heating or cooling demand. However, this adjustment can result in diminished heat transfer rates in the evaporator and condenser, diminishing the overall system efficiency.
- Increased pressure drops: Part-load operation can cause an increase in pressure drops within the system due to decreased refrigerant flow rate, leading to escalated energy consumption and reduced COP.
- Defrosting challenges: With air-source heat pumps, operating at part-load can trigger defrosting issues, particularly when the outdoor coil struggles to defrost adequately at lower loads. Such issues can lower COP and escalate energy usage.
- Fan and pump inefficiencies: When operating under part-load conditions, the fan and pump motors may not be functioning at their optimal efficiency levels, resulting in heightened energy consumption and reduced COP.
- Control system limitations: Inadequate optimization of the control system for part-load operation can lead to decreased efficiency and COP.

6.7. Heat pump – Electrical power input

Using a distributed heat pump system helps us to reduce the size of individual heat pumps used in the network. This also help to introduce modularity to the system which comes with further benefits. As expected we can see from the obtained graph comparison shown in Figure 6.9 below, that the electric power capacity required for the system heat pump to work for a central heat pump system is much higher, thus attributing to a larger heat pump requirement.

Whereas for the scenario 2 although we need smaller heat pumps to suffice the job, in total 13 units of such heat pump are required to be installed at each station. This brings us to a total of approximately 180kW (13.5 * 13) of electrical capacity requirement for the scenario 2 as a total for all the required heat pumps installed at the SINK substations in the District heating network.

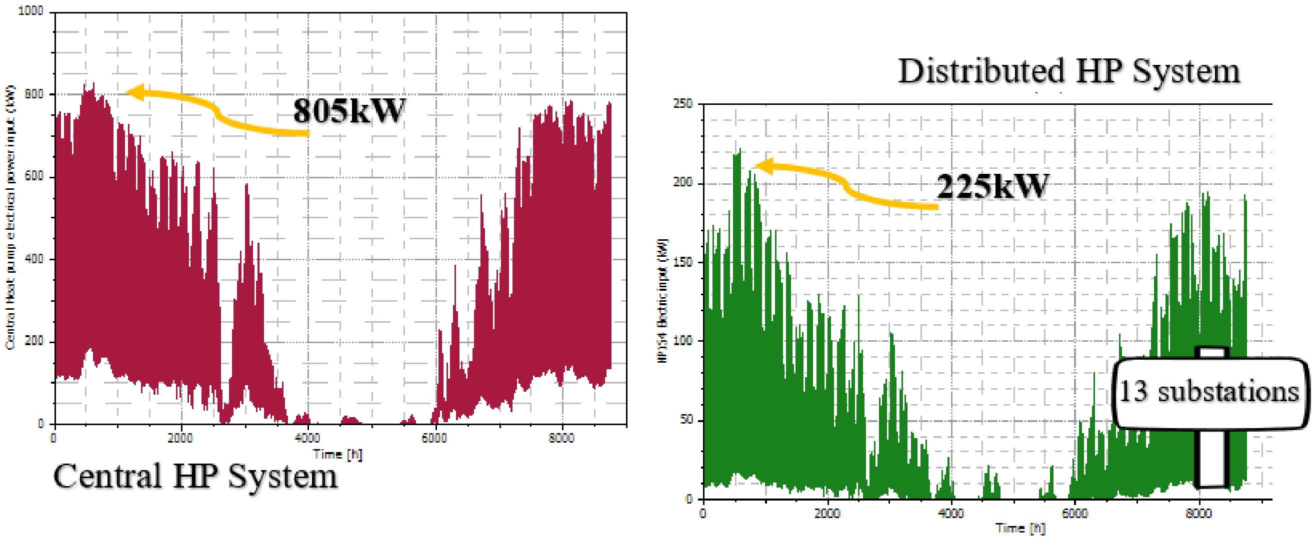

Figure 6.9: Electrical power input – Heat pump(kW) comparison for both scenarios

The benefits of utilizing a smaller electrical capacity heat pump in comparison to larger heat pumps within a low-temperature district heating network include the following:

- Lower initial expenses: Generally, smaller heat pumps are more cost-effective to purchase and set up, a factor advantageous for smaller structures or residences with lower heating requirements.
- Enhanced effectiveness: Smaller heat pumps can achieve higher efficiencies compared to larger ones (considering the real case scenario with the heat pumps – not theoretical COP values), particularly under partial loads, a circumstance frequently encountered in district heating networks. This is due to the ability of smaller heat pumps to sustain a more consistent operating temperature, thereby minimizing energy wastage.
- Increased adaptability: Smaller heat pumps can be easily adjusted to cater to fluctuating heating needs, rendering them more appropriate for district heating networks with diverse loads.
- Reduced maintenance: Smaller heat pumps usually possess fewer moving components and are less intricate than their larger counterparts, leading to reduced maintenance expenses and downtimes.

- Ideal for low-temperature networks: Smaller heat pumps are often engineered to function effectively at lower temperatures, making them well-suited for low-temperature district heating networks.

The heat pump graphs clearly indicate that the maximum electrical energy input typically exceeds the average electrical energy input. This observation implies that the system operates under peak loads for a duration of 1 to 1.5 months, during which the electricity demand is significantly high. However, the overall electricity input remains within an acceptable range and could be met by renewable sources in a combined system. These peak is an effect seen in a specific week occurring within the three-week span of February, which is renowned as the coldest month in the Netherlands. We can see this more clearly in graph shown below by Figure 6.10

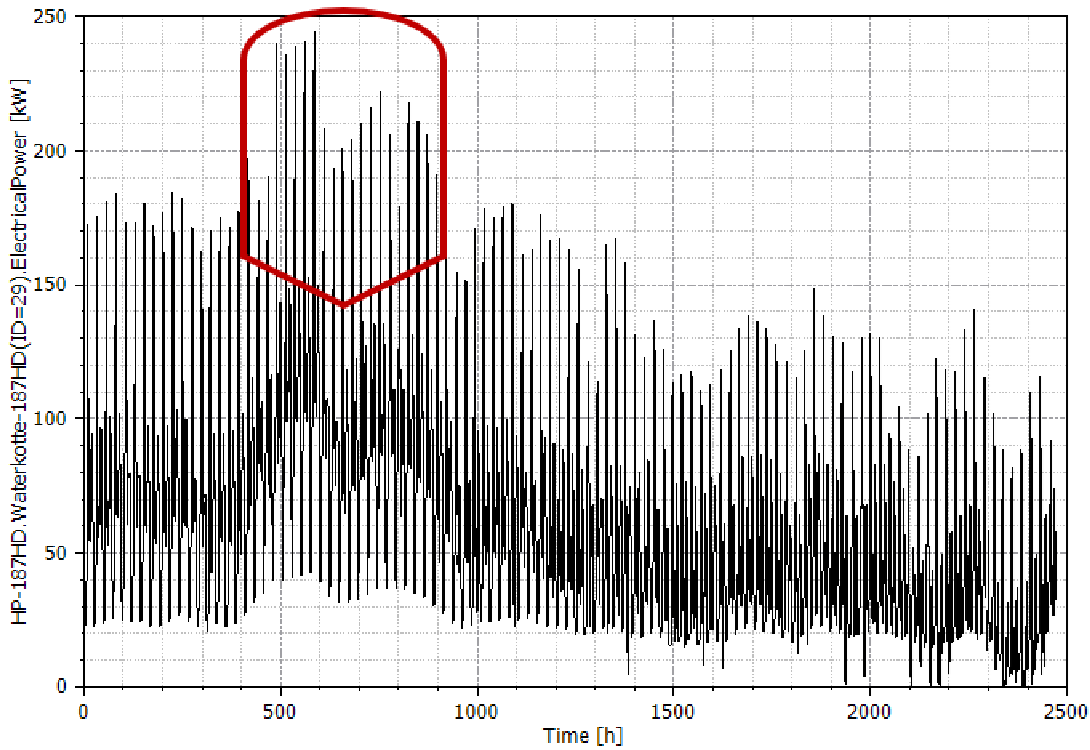

Figure 6.10: Peak value of Electrical power input

6.8. Future scope

As the global community moves towards a more sustainable and effective energy framework, the significance of district heating networks in curbing greenhouse gas emissions and advocating for renewable energy sources grows significantly. Within the realm of low-temperature district heating networks, the strategic planning and configuration of forthcoming systems will play a pivotal role in unleashing the complete capabilities of these networks.

Thus the future investigations should concentrate on the innovation of new arrangements and enhancement strategies for current systems, while also tackling the technological obstacles hindering the incorporation of sustainable heat sources. Furthermore, the creation of top-notch heat maps and the efficient design of communal heating systems will play a crucial role in stimulating the extensive acceptance of these networks. In this particular section we will discuss the future potential that the project holds and the research it can undergo to come forth with a practical solution to the present energy crisis.

6.8.1. Incorporating an ATES system

An Aquifer Thermal Energy Storage (ATES) system represents an innovative and sustainable technological approach that leverages subterranean aquifers for purpose of thermal energy storage and regulation. This system functions through a dual-well configuration, comprising both warm and cold wells, enabling the transfer and storage of excess heat from buildings into the warm well during summer, while the cold well facilitates the absorption of heat from buildings by cold groundwater in winter. This cyclic operation enables the seasonal equilibrium of energy requirements by employing heat exchangers and pumps to facilitate the exchange of thermal energy between the building's HVAC system and the aquifer. [36]

The principal advantages associated with ATES encompass heightened energy efficiency, diminished environmental footprint, and substantial financial savings. Through the accumulation of thermal energy during surplus periods and its retrieval during peak demand, ATES systems diminish the dependency on traditional heating and cooling methodologies, consequently leading to reduced greenhouse gas emissions and operational expenses. Particularly beneficial in densely populated areas with elevated heating and cooling needs, such as commercial infrastructures, medical facilities, and residential complexes, these systems, despite their considerable initial installation expenses and prerequisites for geological appropriateness and regulatory consent, offer a compelling resolution for sustainable energy administration.

The utilization of the Aquifer Thermal Energy Storage (ATES) system is of paramount importance within a low-temperature district heating network due to its capability to offer a promising and efficient solution for balancing the supply and demand of renewable energy across different seasons. Specifically tailored for low-temperature district heating networks, the ATES system plays a key role in storing thermal energy in the aquifer during warmer months and extracting it during the colder months, consequently mitigating the peak demand on the heating infrastructure. This functionality yields various advantages, such as enhanced efficiency by diminishing the energy needed for water heating in winter, thereby resulting in decreased energy consumption and cost savings.

Furthermore, by harnessing renewable energy sources and curbing the energy demand for heating purposes, the ATES system aids in lowering greenhouse gas emissions and fostering the development of a more sustainable energy framework. Additionally, the ATES system bolsters the reliability of the overall system by ensuring a stable supply of thermal energy, consequently minimizing the likelihood of system breakdowns and enhancing the dependability of the district heating network.

Within the framework of a low-temperature district heating network, the ATES system emerges as a particularly potent tool for diminishing the energy demand for heating, leveraging the inherent thermal storage capacity of the aquifer. The same is depicted by Figure 6.11 below.

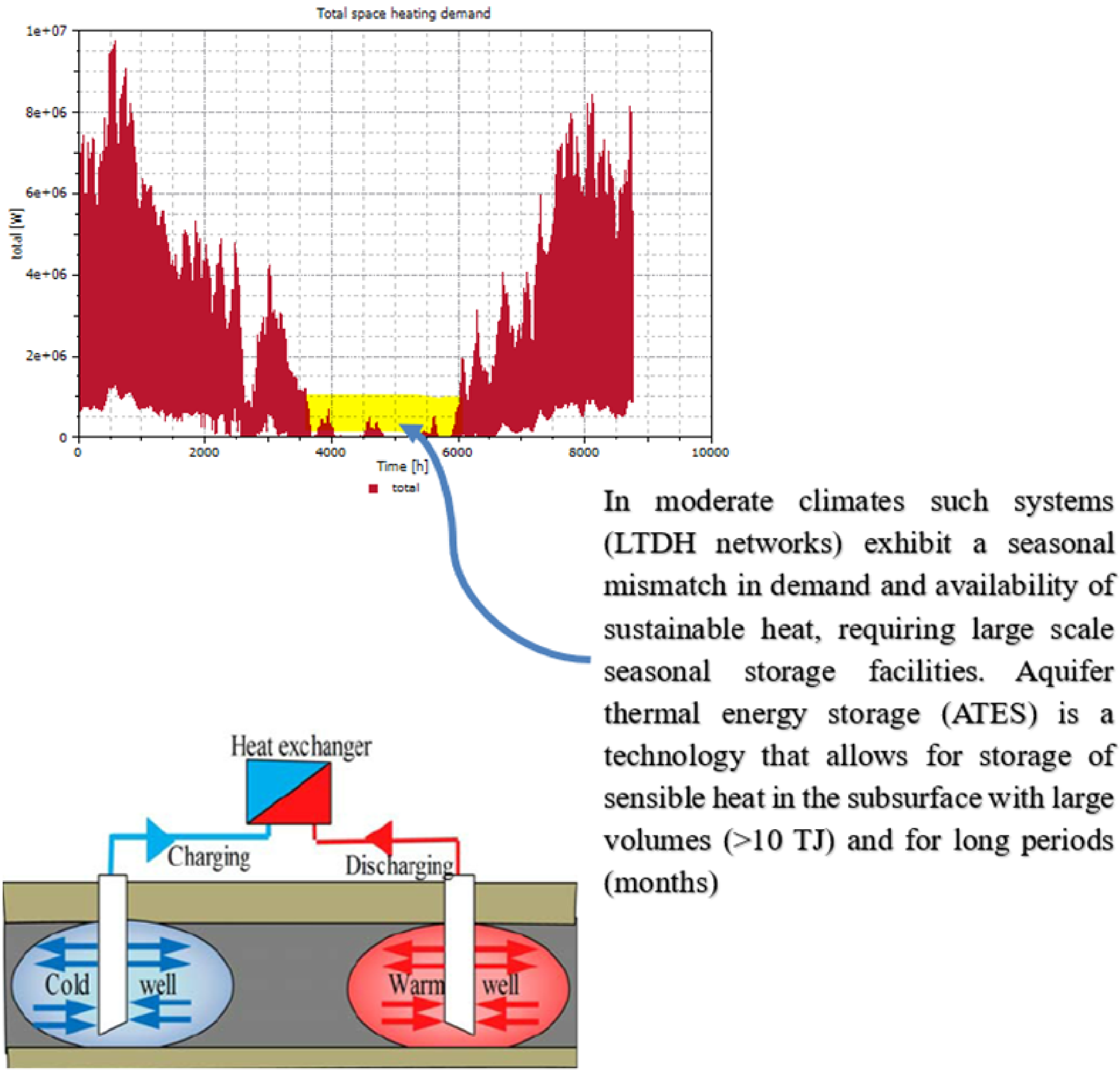

Figure 6.11: ATES system incorporation

6.8.2. Incorporation of other local renewable sources

In a district heating network with low temperatures, renewable sources may be utilized to supply electrical energy for pumps. Among the renewable sources suitable for this purpose are solar power, wind power, and geothermal power. Possibilities considering the present project are discussed herewith.

- Solar power production involves the utilization of photovoltaic (PV) panels, which transform sunlight into electrical energy. The electrical power generated by these panels can then be employed to operate the pumps within the district heating network.
- Wind power generation entails the use of wind turbines, which convert the wind's kinetic energy into electrical power. The electricity produced by these turbines can be harnessed to operate the

pumps in the district heating network.

- Geothermal power generation is achieved through the extraction of heat from the earth's interior, which is then converted into electricity. The electrical energy produced by the geothermal power plant can be used to operate the pumps in the district heating network.

The presence of the available wind energy very close to the Amstel III area (marked by the green circle in the Figure 6.12) is further a promising factor for the AM5 project to get to practical grounds in near future. Here in the figure the yellow marked box shows the AM5 datacentre and the area highlighted in pink is the target audience for the heat distribution for space heating.

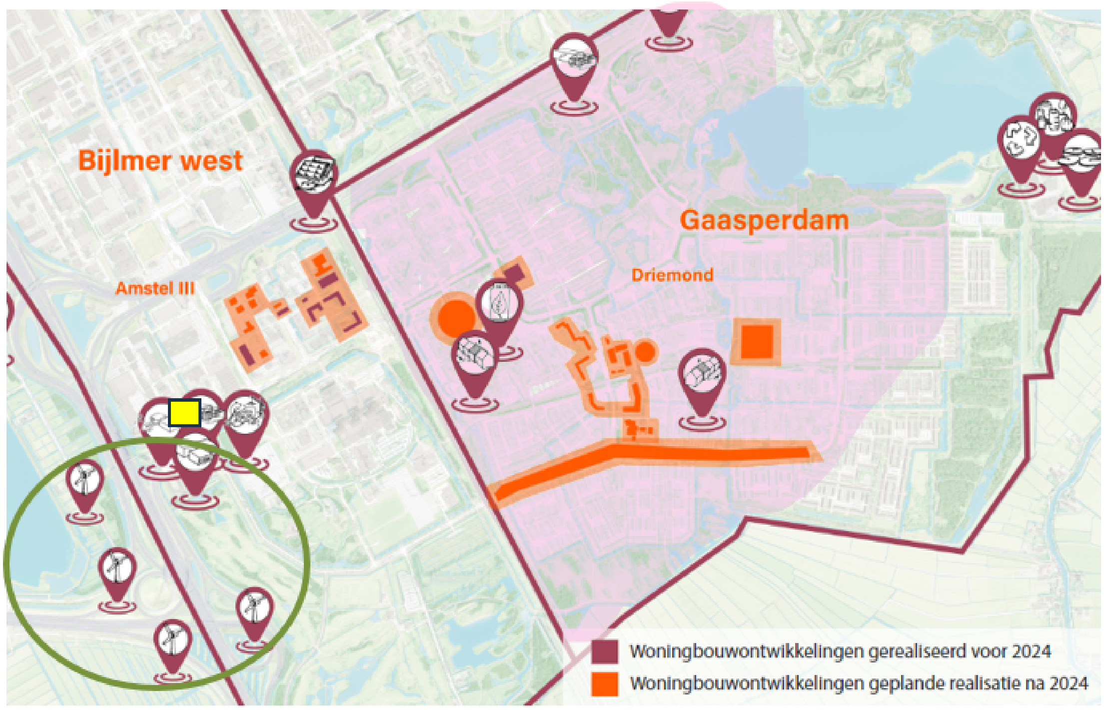

Figure 6.12: Possible renewable energy sites in the vicinity of the area oof interest

This incorporation of the available nearby local renewable energy sources and further boost the overall efficiency of the whole system.

6.8.3. Heat Pumps

To address the issues caused by the necessity of operating the heat pump at part load, manufacturers and designers have the capability to incorporate a range of strategies:

- Utilization of inverter-driven compressors: These compressors possess the ability to regulate their velocity in order to correspond with the fluctuating load, thereby upholding an ideal level of efficiency and COP.
- Employment of multi-stage compressors: These compressors can function at various stages, enabling them to adapt to varying loads and sustain an optimal level of efficiency.
- Integration of load-matching controls: These controls can modify the speed of the compressor, the flow rate of refrigerant, and other variables to align with the changing load, thereby maintaining an ideal level of efficiency and COP.

- Development of part-load optimized system design: The system can be structured to enhance performance under part-load conditions, considering the specific application and load profile.

Through the implementation of these solutions, heat pump manufacturers and designers can enhance the efficiency and COP of their systems, even when operating at part-load conditions.

6.8.4. Some other final recommendations

- Considering non-adiabatic (close to real) environment for the pipes
  It is very important for the network simulation to take a next step further in the current project setup and just focus on the heat exchange between the pipes and surrounding soil. This will require collecting the underground soil temperature data in the target area and a proper model of pipes separately with material specifications. Thus this will rule out the assumption of having minimum heat loss with exceptionally perfect pipe insulation, in the current research.
- More data from Data centre possible recovery and heating demand
  In the present research the data used for simulations was old data manipulated as per the new heating guidelines published and provided by the Gemeente Amsterdam. As procuring hourly space heating demands intrudes in the privacy law setups of the people, there is a need to find out an alternative way to work with real time data which is close to the real values.
- Results with integration of above-mentioned possibilities, ensuring greener future

Low temperature district heating (LTDH) networks are emerging as a promising solution in the effort to decrease carbon emissions and advance towards a more environmentally friendly future. Through their operation at reduced temperatures, LTDH networks have the capability to make use of waste heat, renewable energy sources, and excess heat from different industries, thus diminishing the dependence on fossil fuels and lowering CO2 emissions. Furthermore, LTDH networks have the potential to integrate with other sustainable technologies like heat pumps, biomass boilers, and solar thermal systems to further decrease their carbon footprint. As a summary, the introduction of LTDH networks has the potential to result in substantial reductions in CO2 emissions, particularly in urban areas with high heat demand. By utilizing local renewable energy sources and waste heat, LTDH networks can lessen the requirement for fossil fuels, leading to decreased greenhouse gas emissions. Moreover, LTDH networks can also enhance energy efficiency by minimizing heat losses during the process of transmission and distribution.

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A

Data collected : demand graphs

Total space heating demand:

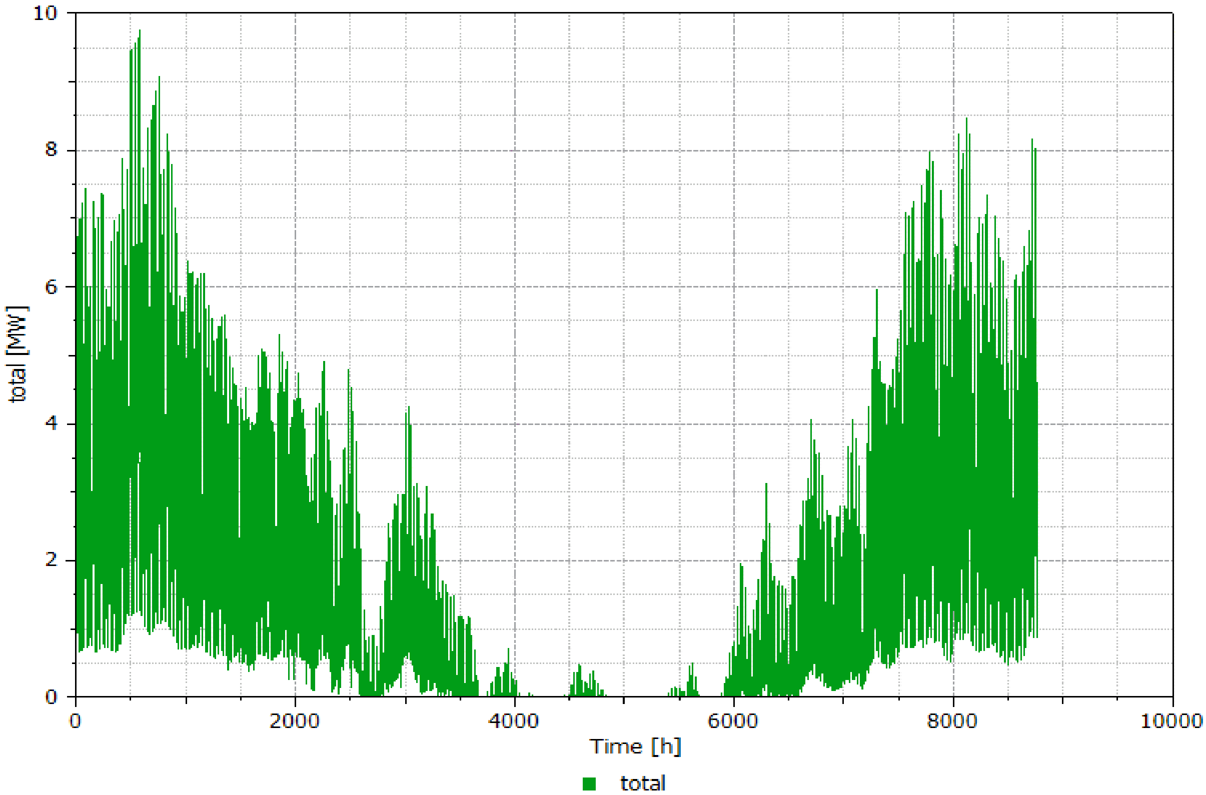


Figure A.1: Total space heating demand curve kW vs hour

Commercially available pipes:[21]

DN	Toleranslar (+) *			SDR 41 PN 4			SDR 33 PN 5			SDR 26 PN 6			SDR 21 PN 8		
mm	A*	B*	O*	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m
16	0,3	0,3	1,2	-	-	-	-	-	-	-	-	-	-	-	-
20	0,3	0,3	1,2	-	-	-	-	-	-	-	-	-	-	-	-
25	0,3	0,3	1,2	-	-	-	-	-	-	-	-	-	-	-	-
32	0,3	0,3	1,3	-	-	-				-	-	-	-	-	-
40	0,4	0,4	1,4	-	-	-							2,0	2,3	0,24
50	0,4	0,4	1,4	-	-	-				2,0	0,3	0,30	2,4	0,3	0,36
63	0,4	0,4	1,5	1,8	0,3	0,36	2,0	0,3	0,39	2,5	0,4	0,47	3,0	0,4	0,57
75	0,4	0,5	1,6	1,9	0,3	0,45	2,3	0,4	0,54	2,9	0,4	0,65	3,6	0,4	0,81
90	0,6	0,6	1,8	2,3	0,3	0,64	2,8	0,4	0,78	3,5	0,5	0,94	4,3	0,5	1,16
110	0,7	0,6	2,2	2,7	0,4	0,93	3,4	0,5	1,16	4,2	0,6	1,38	5,3	0,6	1,74
125	0,8	0,6	2,5	3,1	0,5	1,22	3,9	0,5	1,50	4,8	0,6	1,79	6,0	0,7	2,25
140	0,9	0,9	2,8	3,5	0,5	1,52	4,3	0,6	1,86	5,4	0,7	2,26	6,7	0,8	2,81
160	1,0	1,0	3,2	4,0	0,5	1,97	4,9	0,6	2,40	6,2	0,8	2,96	7,7	0,9	3,69
180	1,1	1,1	3,6	4,4	0,6	2,46	5,5	0,7	3,04	6,9	0,8	3,70	8,6	1,0	4,64
200	1,2	1,2	4,0	4,9	0,6	3,02	6,2	0,8	3,81	7,7	0,9	4,59	9,6	1,1	5,75
225	1,4	1,4	4,5	5,5	0,7	3,82	6,9	0,8	4,74	8,6	1,0	5,77	10,8	1,2	7,26
250	1,5	1,5	5,0	6,2	0,8	4,79	7,7	0,9	5,88	9,6	1,1	7,16	11,9	1,3	8,89
280	1,7	1,7	9,8	6,9	0,8	5,94	8,6	1,0	7,35	10,7	1,2	8,94	13,4	1,4	11,18
315	1,9	1,9	11,1	7,7	0,9	7,46	9,7	1,1	9,32	12,1	1,4	11,37	15,0	1,6	14,10
355	2,2	2,2	12,5	8,7	1,0	9,49	10,9	1,2	11,78	13,6	1,5	14,40	16,9	1,7	17,86
400	2,4	2,4	14,0	9,8	1,1	12,03	12,3	1,4	15,01	15,3	1,7	18,26	19,1	1,9	22,72
450	2,7	2,7	15,6	11,0	1,2	15,17	13,8	1,5	18,90	17,2	1,9	23,09	21,5	2,2	28,81
500	3,0	3,0	17,5	12,3	1,4	18,89	15,3	1,7	23,31	19,1	2,1	28,49	23,9	2,4	35,56
560	3,4	3,4	19,6	13,7	1,5	23,52	17,2	1,9	29,34	21,4	2,3	35,75	26,7	2,7	44,51
630	3,8	3,8	22,1	15,4	1,7	29,75	19,3	2,1	37,01	24,1	2,6	45,29	30,0	3,0	56,24
710	6,4	6,4	24,9	17,4	1,9	37,86	21,8	2,3	47,04	27,2	2,9	57,61	33,9	3,3	71,52
800	7,2	7,2	28,0	19,6	2,1	48,01	24,5	2,6	59,58	30,6	3,2	73,02	38,1	3,7	90,58
900	8,1	8,1	31,5	22,0	2,3	60,55	27,6	2,9	75,47	34,4	3,9	92,35	42,9	4,2	114,77
1000	9,0	9,0	35,0	24,5	2,6	74,98	30,6	3,2	92,96	38,4	4,0	114,55	47,7	4,7	141,83
1200	10,8	10,8	42,0	29,4	3,1	107,93	36,7	3,8	133,73	45,9	4,5	164,30	57,2	5,2	203,39
1400	12,6	12,6	49,0	34,3	3,6	146,87	42,9	4,4	182,28	53,5	5,5	223,43	66,7	5,8	276,21
1600	14,4	14,4	56,0	39,2	4,1	191,80	49,0	5,0	237,89	61,2	6,3	292,10	76,2	6,5	360,37

DN	SDR 17 PN 10			SDR 13,6 PN 12,5			SDR 11 PN 16			SDR 9 PN 20			SDR 7,4 PN 25			SDR 6 PN 32		
mm	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m	S mm	S*	m kg/m
16	-	-	-	-	-	-	-	-	-	2,0	0,3	0,09	2,3	3,0	0,11	3,0	0,4	0,12
20	-	-	-	-	-	-	2,0	0,3	0,11	2,3	0,4	0,13	3,0	0,4	0,16	3,4	0,5	0,18
25	-	-	-	2,0	0,3	0,15	2,3	0,4	0,17	3,0	0,4	0,21	3,5	0,5	0,24	4,2	0,6	0,28
32	2,0	0,3	0,19	2,4	0,4	0,23	3,0	0,4	0,27	3,6	0,5	0,32	4,4	0,6	0,38	5,4	0,7	0,45
40	2,4	0,4	0,29	3,0	0,5	0,36	3,7	0,5	0,42	4,5	0,6	0,50	5,5	0,7	0,60	6,7	0,8	0,70
50	3,0	0,4	0,45	3,7	0,5	0,54	4,6	0,6	0,66	5,6	0,7	0,78	6,9	0,8	0,93	8,3	1,0	1,08
63	3,8	0,5	0,71	4,7	0,6	0,87	5,8	0,7	1,04	7,1	0,9	1,25	8,6	1,0	1,46	10,5	1,2	1,69
75	4,5	0,6	1,01	5,6	0,7	1,23	6,8	0,8	1,46	8,4	1,0	1,75	10,3	1,2	2,08	12,5	1,4	2,43
90	5,4	0,7	1,45	6,7	0,8	1,76	8,2	1,0	2,11	10,1	1,2	2,53	12,3	1,4	2,99	15,0	1,7	3,51
110	6,6	0,8	2,15	8,1	1,0	2,60	10,0	1,1	3,13	12,3	1,4	3,76	15,1	1,7	4,47	18,3	2,0	5,22
125	7,4	0,9	2,74	9,2	1,1	3,35	11,4	1,3	4,06	14,0	1,6	4,87	17,1	1,9	5,76	20,8	2,2	6,74
140	8,3	1,0	3,44	10,3	1,2	4,20	12,7	1,4	5,06	15,7	1,7	6,09	19,2	2,1	7,23	23,3	2,5	8,45
160	9,5	1,1	4,50	11,8	1,3	5,48	14,6	1,6	6,64	17,9	1,9	7,94	21,9	2,3	9,42	26,6	2,8	11,03
180	10,7	1,2	5,69	13,3	1,5	6,96	16,4	1,8	8,40	20,1	2,2	10,04	24,6	2,6	11,91	29,9	3,1	13,94
200	11,9	1,3	7,02	14,7	1,6	8,53	18,2	2,0	10,36	22,4	2,4	12,42	27,4	2,9	14,73	33,2	3,5	17,21
225	13,4	1,5	8,90	16,6	1,8	10,83	20,5	2,2	13,00	25,2	2,7	15,72	30,8	3,2	18,61	37,4	3,9	21,79
250	14,8	1,6	10,91	18,4	2,0	13,34	22,7	2,4	16,12	27,9	2,9	19,32	34,2	3,6	22,98	41,5	4,3	26,87
280	16,6	1,8	13,70	20,6	2,2	16,72	25,4	2,7	20,21	31,3	3,3	24,28	38,3	4,0	28,82	46,5	4,8	33,71
315	18,7	2,0	17,35	23,2	2,5	21,19	28,6	3,0	25,58	35,2	3,7	30,72	43,1	4,5	36,48	52,3	5,4	42,66
355	21,1	2,3	22,09	26,1	2,8	26,87	32,2	3,4	32,47	39,7	4,1	39,01	48,5	5,0	46,25	59,0	6,0	54,19
400	23,7	2,5	27,91	29,4	3,1	34,07	36,3	3,8	41,23	44,7	4,6	49,49	54,7	5,6	58,75			
450	26,7	2,8	35,36	33,1	3,5	43,16	40,9	4,2	52,21	50,3	5,2	62,66	61,5	6,3	74,32			
500	29,7	3,1	[illegible]	[illegible]	[illegible]	[illegible]	45,4	4,7	64,42	55,8	5,7	77,22						
560	33,2	3,5	54,74	41,2	4,3	66,81	50,8	5,2	80,70	62,5	6,3	96,43						
630	37,4	3,9	69,33	46,3	4,8	84,45	57,2	5,9	102,25	70,3	7,2	132,5						
710	42,1	4,4	87,97	52,2	5,4	107,28	64,5	6,7	129,97	79,3	8,1	149,0						
800	47,4	4,9	111,55	58,8	6,0	136,09	72,6	7,4	162,8	89,3	9,1	200,2						
900	53,3	5,5	141,11	66,1	6,7	172,29	81,7	8,3	207,5									
1000	59,3	6,1	174,39	73,4	7,5	212,64	90,8	9,2	261,3									
1200	71,1	6,8	248,56	88,2	9,0	324,0												
1400	83,0	7,6	337,82	102,9	10,4	462,8												
1600	94,8	8,5	440,55	117,5	11,9	616,4												

hdpe-pipes-kuzeyboru

Figure A.2: Commercially available pipes

The PE pipe roughness ε [34] was taken to be - $1.5 * 10^{-6}$

Space heating demand for various SINK substations:

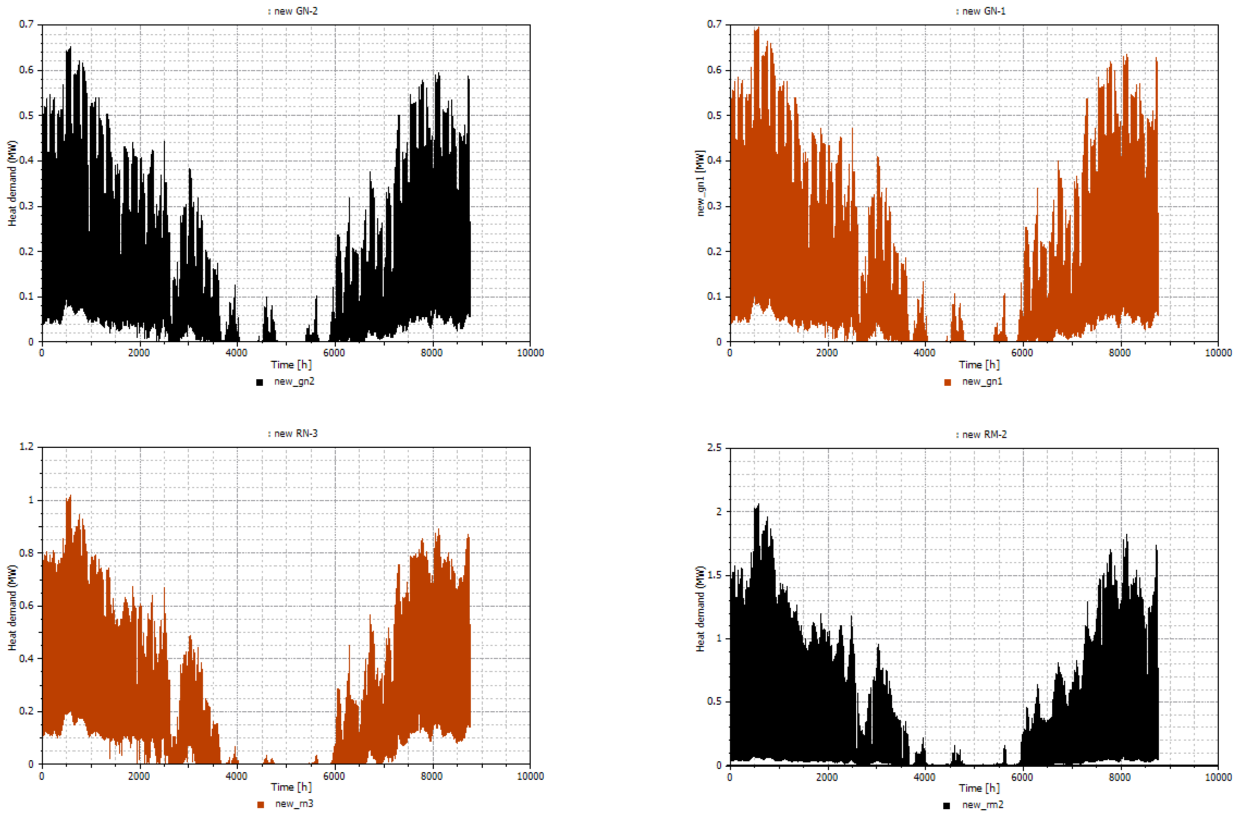
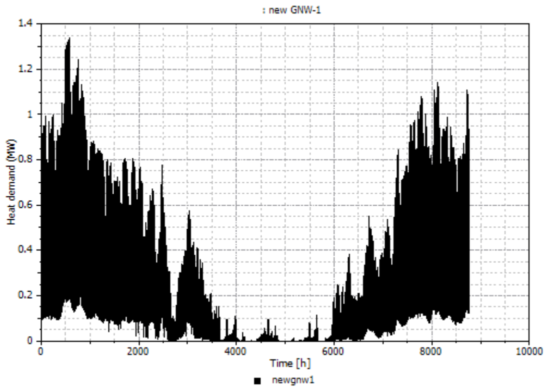
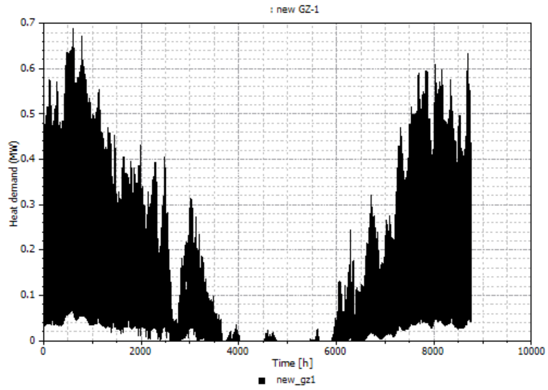
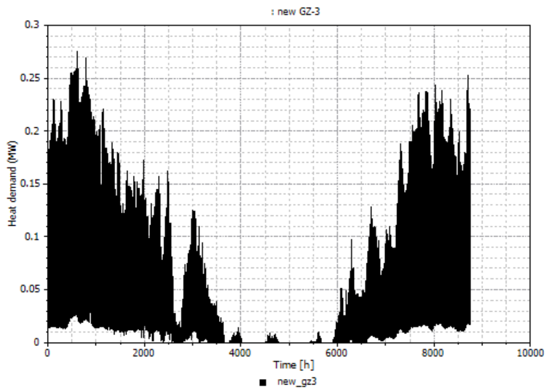
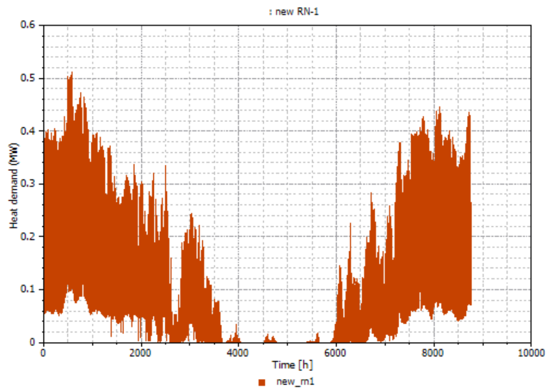


Figure A.3: Per substation demand curve


: new GNW-1
Heat demand (MW)
Time [h]
newgnw1


: new GZ-1
Heat demand (MW)
Time [h]
new_gz1


: new GZ-3
Heat demand (MW)
Time [h]
new_gz3


: new RN-1
Heat demand (MW)
Time [h]
new_rn1

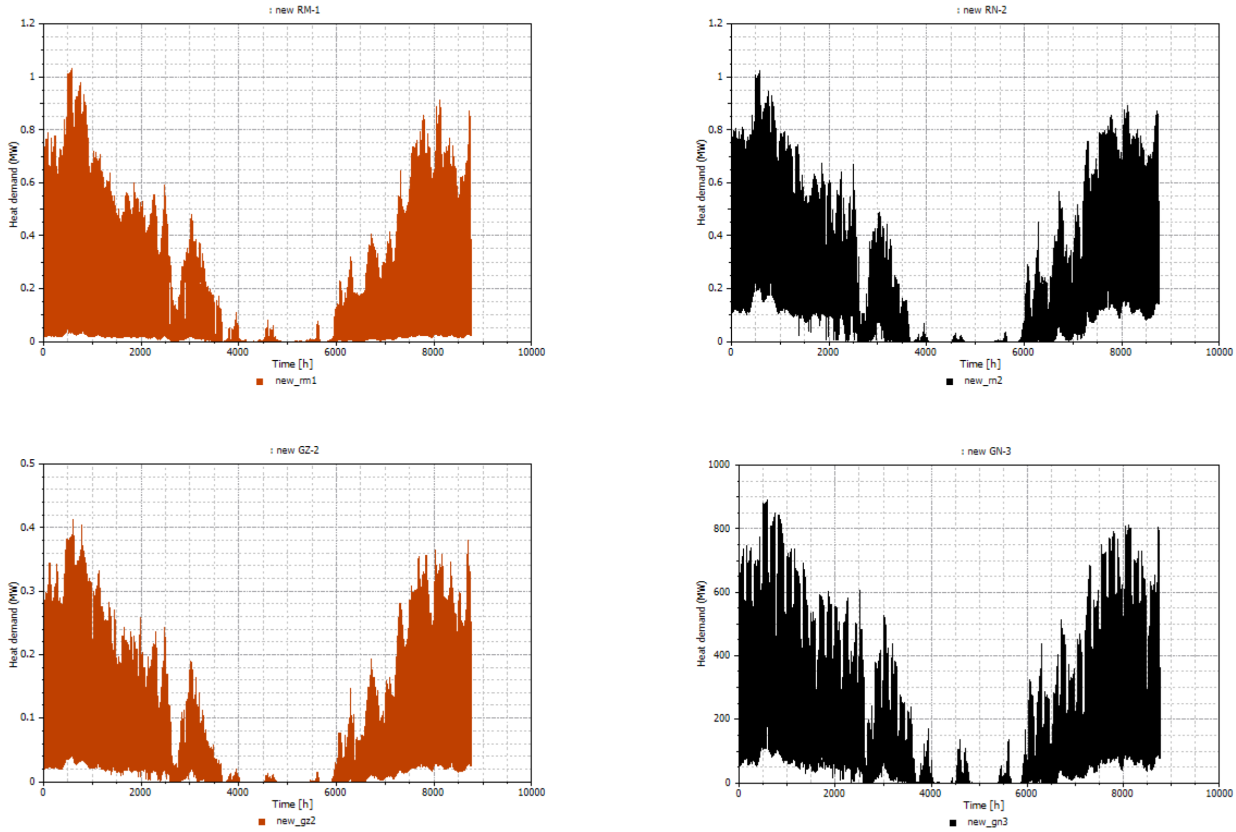


Figure A.4: Per substation demand curve

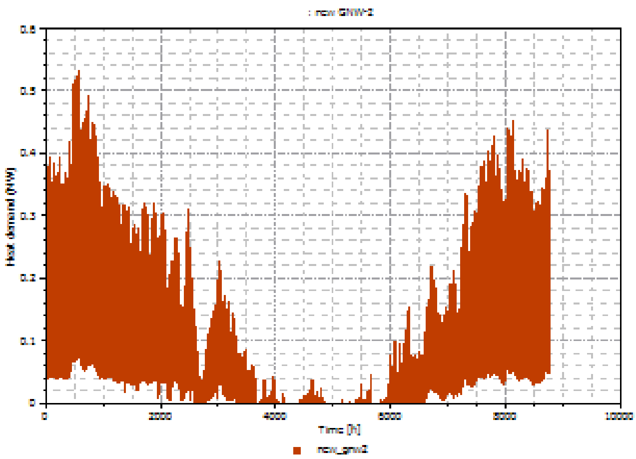


Figure A.5: Per substation demand curve

B

Appendix B

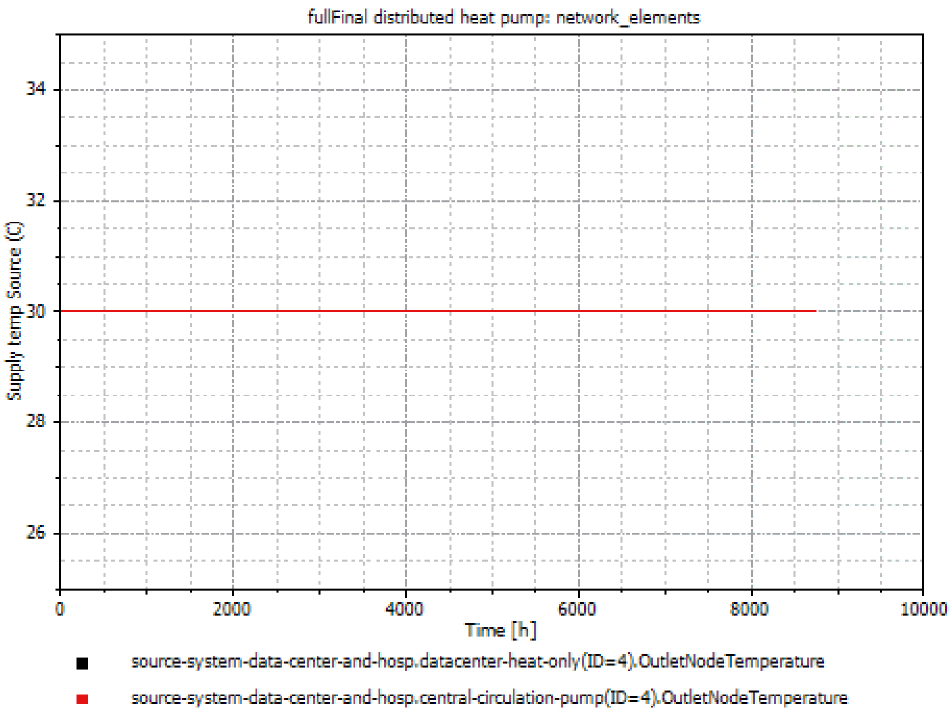


Figure B.1: Recovery source temperature

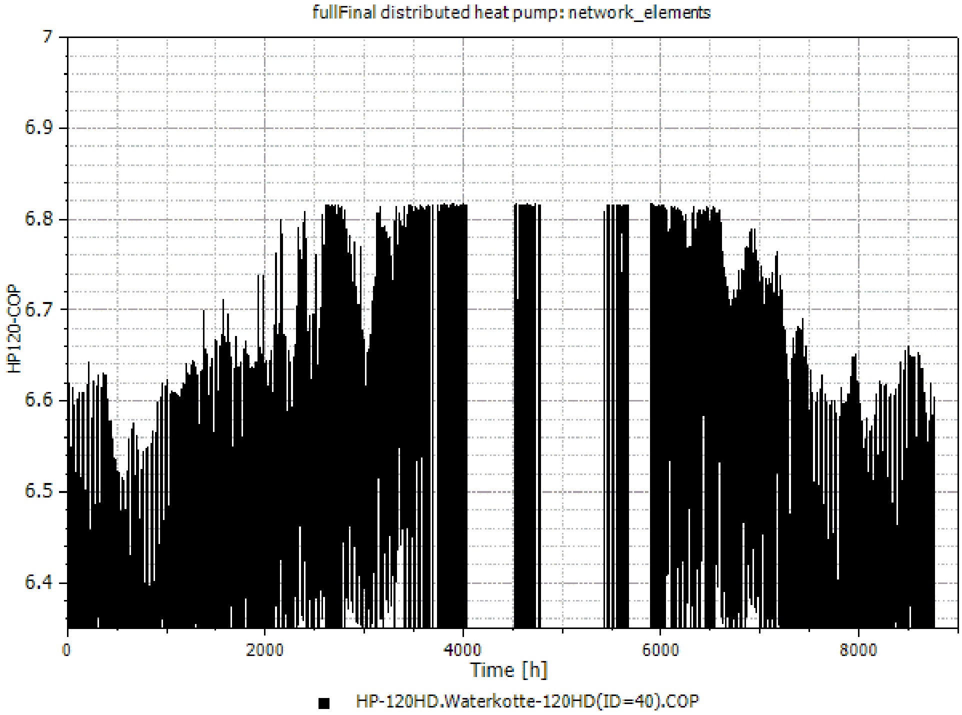


Figure B.2: COP HP-120

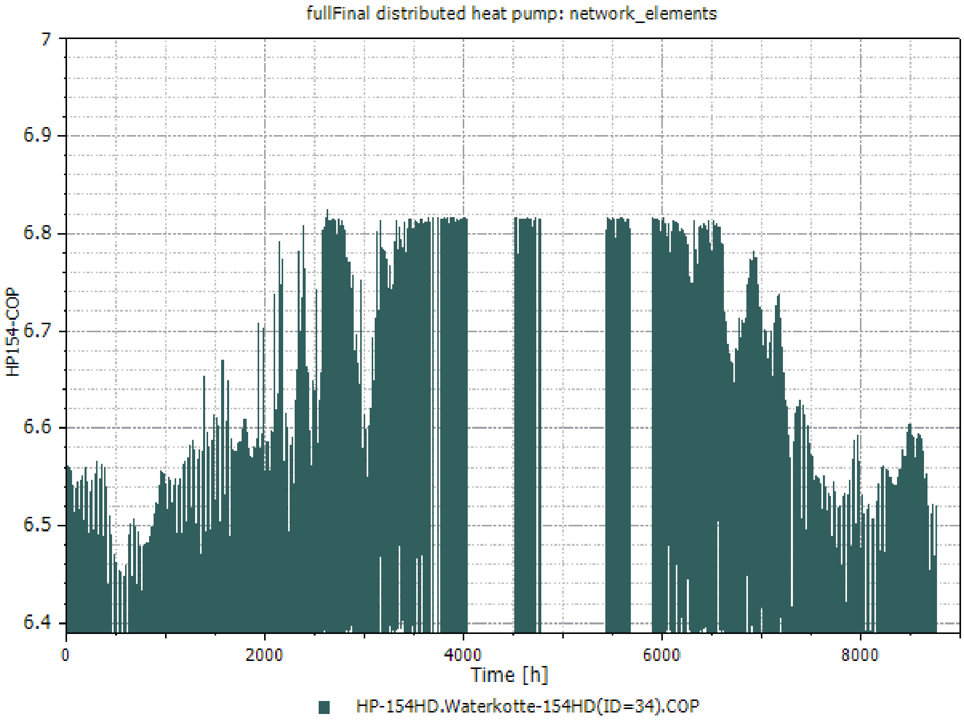


Figure B.3: COP H-154

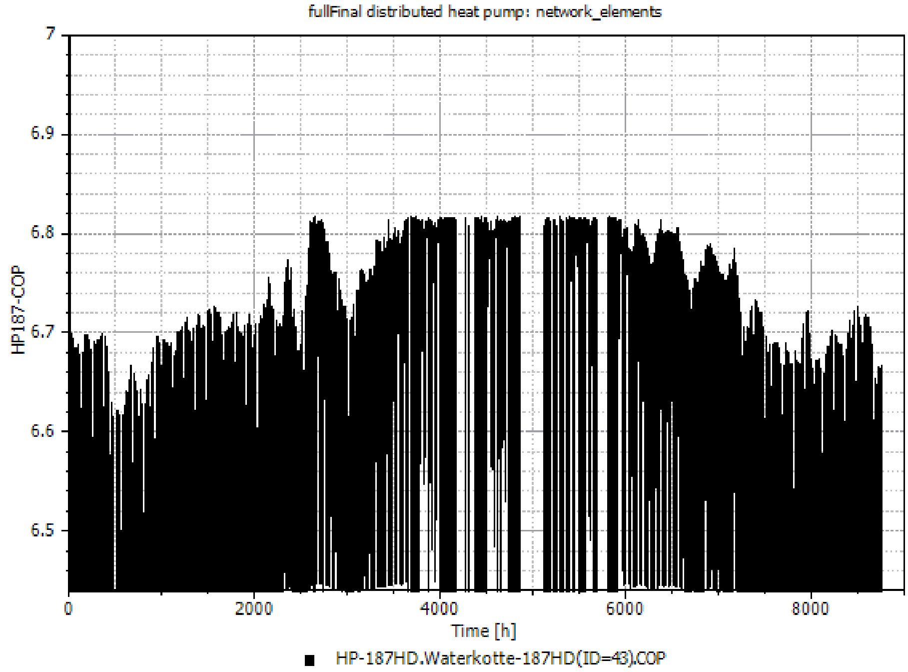


Figure B.4: COP H-187

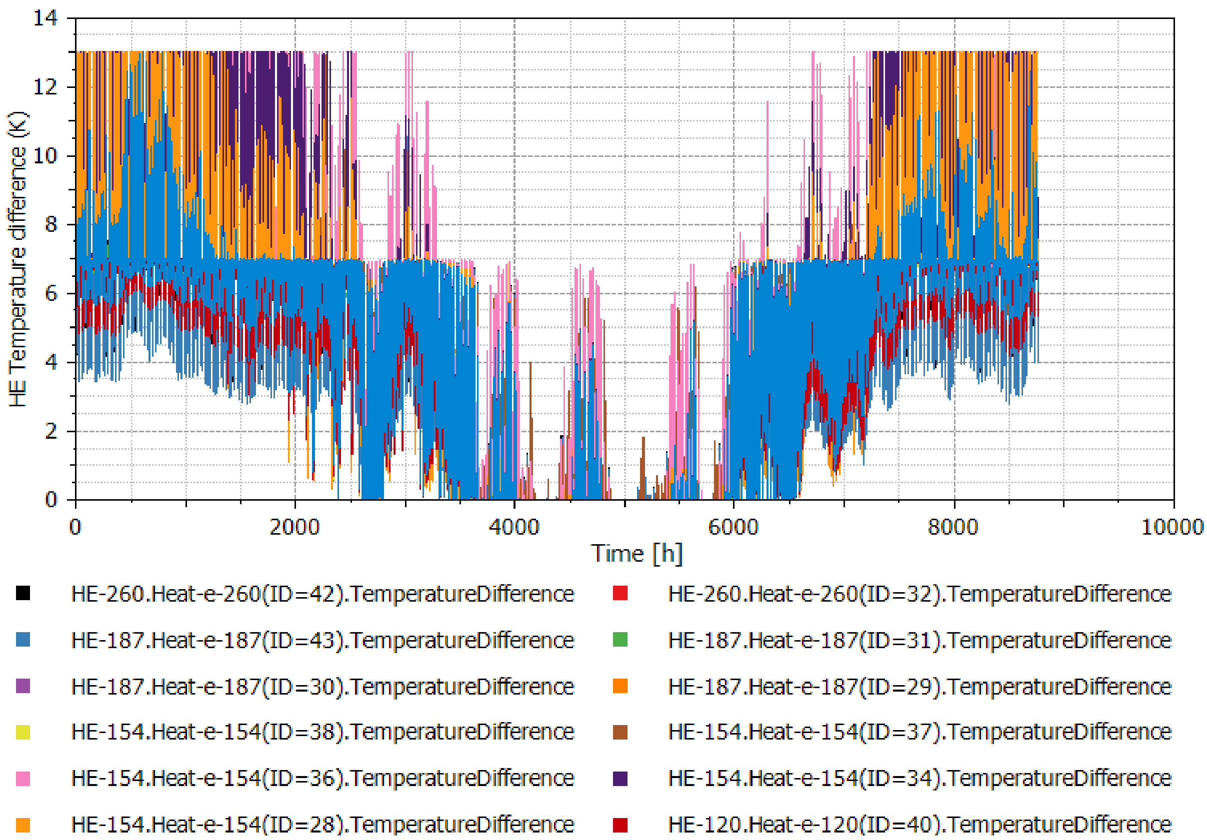


Figure B.5: Temperature difference for various HE