Simulation and analysis of a geothermal energy network

A technical and societal perspective on modern energy infrastructure

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Nischal Chaulagain

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Abstract
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As local thermal resources, such as shallow geothermal systems, are integrated and energy flows between connected buildings are started, the role of multiple stakeholders comes into play in these modern district energy systems. Unlike the conventional district networks where energy flows from energy producers to consumers, the role of "prosumers" here becomes of paramount importance. This combined effort for decarbonization of urban heating and cooling is still under a development phase and demands for a comprehensive technical, social, economic and regulatory breakthrough for its wider adoption and application.

This thesis aims to contribute to this body of developing knowledge by first presenting a practical design of a low-temperature geothermal district heating and cooling network that features sectoral coupling of electricity and heat sources with seasonal thermal storage by using geothermal borefields. The thesis comprehensively describes the role of system components and structure in achieving energy sharing between connected buildings and also quantifies possible energy exchange. Furthermore, the decarbonization potential of such systems is presented through a comparative study against conventional and alternative energy sources. Secondly, the social perspective related to the adoption of this improved district heating is discussed with focus on the influence of business models, ownership structures, and legal frameworks on prosumer participation.

Using a digital twin modelling approach, the thesis presents substantial benefits of low-temperature geothermal energy networks with energy sharing between connected properties. The results show an enhancement in the coefficient of performance (COP) of the decentralised heat pumps, thereby reducing active energy consumption by approximately 14 %. When connecting the buildings by energy sharing, thermal load sharing between borefields (energy source) of different properties was observed. Further analysis showed enhancement of the operational life span of borefields owing to the energy exchange. Additionally, the comparative analysis of operational emissions from the presented district network against alternative energy sources proved substantial environmental benefits of these networks.

The thesis also discusses the evolving ownership structure and business models of modern district thermal networks. The thesis discusses that because of its "hassle-free" nature for the end user, "heat-as-a-service" models are perceived to grasp wider public acceptance in future. Furthermore, owing to the longer technical lifespan of district networks, prosumers may be interested to "own" the network to capitalise on the continuous revenue stream that it generates. Additionally, low energy price, and "green value" which the modern energy infrastructure offers were considered as the main drivers for prosumers' participation. Alternatively, the unclear legal definition of "waste heat" in residential buildings was considered as a potential barrier for energy sharing solutions. The thesis suggests that explicit regulatory frameworks to define "heat prosumers" and consideration of waste heat as a financial instrument may potentially enhance prosumer involvement in modern energy infrastructure.

Key Words: 5GDHC, geothermal, Low temperature, energy sharing, sectoral coupling

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Abstract

Responsible for roughly 40 % of global greenhouse gas emissions, energy use for heating and cooling in the built environment constitutes a significant portion of annual total carbon emissions. The effort to decarbonise the heating and cooling sector necessitates efficient production, distribution and end use of energy. In this context, district heating and cooling is considered one of the cost-efficient, reliable and low-emission systems. The benefits are further extended by modern district networks, which facilitate bi-directional energy flows, allow heating and cooling from the same network, promote decentralised energy production and most importantly, allows integration of multiple energy sources, including low-grade thermal sources and energy sharing between buildings.

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This thesis aims to contribute to this body of developing knowledge by first presenting a practical design of a low-temperature geothermal district heating and cooling network that features sectoral coupling of electricity and heat sources with seasonal thermal storage by using geothermal borefields. The thesis comprehensively describes the role of system components including the decentralized heat pumps, and system structure in achieving energy sharing between connected buildings and also quantifies possible energy exchange. Furthermore, the decarbonization potential of such systems is presented through a comparative study against conventional and alternative energy systems. Secondly, the social perspective related to the adoption of this improved district heating is discussed with a focus on the influence of business models, ownership structures, and legal frameworks on prosumer participation.

Using a digital twin modelling approach, the thesis presents substantial benefits of low-temperature geothermal energy networks with energy sharing between connected properties. The results show an enhancement in the coefficient of performance (COP) of the decentralised heat pumps, thereby reducing electrical energy consumption by approximately 14 %. When connecting the buildings by energy sharing, thermal load sharing between borefields (energy source) of different properties was observed. Further analysis showed enhancement of the operational performance of borefields owing to the energy exchange. Additionally, the comparative analysis of operational emissions from the presented district network against alternative energy sources proved substantial environmental benefits of these networks.

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Sammanfattning

Energianvändningen för uppvärmning och kyla i den bebyggda miljön står för cirka 40 % av de globala koldioxidutsläppen. I arbetet med att minska koldioxidutsläppen inom sektorn för uppvärmning- och kyla ingår att skapa en mer effektiv produktion, distribution och slutanvändning av energi. Fjärrvärme och fjärrkyla anses vara ett kostnadseffektivt och pålitligt sätt att möta detta behov. Fördelarna med dessa system utökas ytterligare i moderna fjärrvärmenät, med möjlighet till dubbelriktade energiflöden som möjliggör uppvärmning och kylning från samma nät, främjar decentraliserad energiproduktion och, viktigast av allt, möjliggör integration av flera energikällor, inklusive lågvärdiga värmekällor och energidelning mellan byggnader.

När lokala värmekällor, till exempel energibrunnar, integreras i detta moderna system och energi kan delas mellan sammankopplade byggnader, kommer flera olika intressenter att bli involverade. Till skillnad från konventionella fjärrvärmenät där energin flödar från energiproducenter till konsumenter, blir i nya system rollen som ”prosument” av största vikt. Utvecklingen av framtidens energisystem för uppvärmning och kylning av bebyggelsen, med stora möjligheter för lägre koldioxidutsläpp, befinner sig fortfarande i en utvecklingsfas och kräver ett omfattande tekniskt, socialt, ekonomiskt och regleringsmässigt genombrott för att kunna införas och tillämpas i större utsträckning.

Denna avhandling syftar till att bidra till denna kunskapsbas genom att först presentera en praktisk design av ett lågtempererat delningssystem som kännetecknas av energisystemintegration av el- och värmekällor med säsongsvärmelagring i energibrunnar. Avhandlingen beskriver utförligt systemkomponenternas roll för att uppnå energidelning mellan anslutna byggnader och kvantifierar även möjligt energiutbyte. Vidare presenteras systemens potential för lägre klimatbelastning genom en jämförande studie mellan konventionella och alternativa energisystem. Det sociala perspektivet diskuteras även i denna studie och då i samband med införandet, med fokus på affärsmodeller, ägarstrukturer och de rättsliga ramverkens inverkan på prosumenters deltagande.

Med hjälp av en modell med en digital tvilling, presenterar avhandlingen betydande fördelar med geotermiska lågtempererade energinät, där energidelning sker mellan anslutna fastigheter. Resultaten visar en förbättring av systemprestandan för decentraliserade värmepumpar, med en beräknad minskning av den primära energianvändningen med cirka 14 %. På samma sätt observerades delning av värmebehovet mellan fastigheternas olika borrhål. Ytterligare analyser visade en teoretiskt beräknad förbättring av borrhålens långtidsprestanda tack vare energiutbytet mellan fastigheterna. Dessutom visade en analys avseende driftrelaterade utsläpp på betydande miljöfördelar för det här presenterade systemet med geotermiska lager jämfört med ett traditionellt fjärrvärmesystem.

Avhandlingen diskuterar också ägarstrukturer och affärsmodeller för moderna fjärrvärmenät. Modeller för ”värme som tjänst” upplevs få bredare acceptans hos allmänheten i framtiden på grund av att de är ”bekymmersfria” för slutanvändaren. Dessutom kan prosumenter, på grund av fjärrvärmenätens längre tekniska livslängd, vara intresserade av att ”äga” nätet för att dra nytta av den kontinuerliga intäktsström som det genererar. Dessutom ansågs låga energipriser och det ”gröna värde” som den moderna energiinfrastrukturen erbjuder vara de viktigaste drivkrafterna för prosumenternas deltagande. Samtidigt ansågs den oklara juridiska definitionen av ”spillvärme” i bostadshus ansågs vara ett potentiellt hinder. Avhandlingen föreslår att tydliga regelverk för att definiera ”värmeprosumenter” och betraktandet av spillvärme som ett finansiellt instrument potentiellt kan öka prosumenternas engagemang i modern energiinfrastruktur.

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Abbreviations

4GDH	Fourth Generation District Heating
5GDHC	Fifth Generation District Heating and Cooling
BHE	Borehole Heat Exchanger
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EOS	Embassy of Sharing
EU	European Union
GEN	Geothermal Energy Network
GESS	Geo-Energy Sharing System
GHG	Greenhouse Gas
GWh	Gigawatt Hour
IEA	International Energy Agency
IT	Information Technology
kWh	Kilowatt Hour
LTDN	Low Temperature District Network
MBSE	Model Based Systems Engineering
MWh	Megawatt Hour
RMSE	Root Mean Square Error

RQ	Research Questions
SCOP	System Coefficient of Performance
SEN	Shared Energy Network
SGS	Shallow Geothermal System
TFC	Total Final Consumption
UC	Under Central
ULTDN	Ultra Low Temperature District Network

List of publications

This licentiate thesis is based on the following peer-reviewed publications and is included as appendices.

I. Chaulagain, N., Janson, U., & Javed, S. (2023) "Fifth generation district heating and cooling network coupled with geothermal energy source for a sustainable community: Case study of Embassy of Sharing at Malmö."

   Proceedings of the 20th International Conference on Sustainable Energy Technologies, Nottingham, UK, University of Nottingham

II. Abugabbara, M., Chaulagain, N., Iarkov, I., Janson, U., and Javed, S. (2024)

   "Assessing the potential of energy sharing through a shallow geothermal heating and cooling network,"

   Renewable Energy, volume 231, 120893

III. Chaulagain, N., Everbring, E., Janson, U., Johansson, D. (2025), "Pragmatic design solution to decarbonize building industry through a low temperature district network,"

   Energy and Buildings, volume 344, 115963

IV. Chaulagain, N., Poulsen, S., Janson, U., Everbring, E., Johansson, D.

   "Barriers and Motivations for Prosumer integration in a low temperature district network: A Perspective on ownership, business model and policy frameworks"

   Manuscript submitted

1 Introduction

1.1 Energy- from civilisation to decarbonization

Energy in the form of "controlled fire" has long been regarded as a fundamental and defining catalyst for human evolution (Wayman, 2012). The habitual use of "controlled fire" by our ancestors dates back over 400 000 years, serving purposes such as cooking, social gathering, and keeping warm in colder climates (Bhutada, 2022). This marks the first recorded use of energy for thermal comfort. The fuel for such energy was biomass, typically consisting of wood and dry leaves.

From the dawn of human civilisation to the period of the Industrial Revolution in the 18th century, the sources of energy that aided human evolution have undergone a significant transformation. By the 1900s, coal had largely replaced wood to become the dominant energy fuel (Bhutada, 2022). Over time, new energy sources were discovered, and technological advancements facilitated and ensured the harnessing of a diverse range of energy sources. In the present context, energy sources such as biofuels, natural gas, hydroelectricity, nuclear power, and renewable energy from solar, wind, and other sources make up the energy mix around the globe.

The global debate on energy primarily revolves around two main aspects. The first relates to the source of energy, which in recent decades has seen a strong global push towards renewable and low-carbon options. The second aspect centres around the end use of energy, commonly analysed through Total Final Consumption (TFC) (Millard, 2017). The TFC indicator offers vital insights into how energy is consumed across various sectors such as industry, transport, and households. Along with other indicators, TFC gives a comprehensive view of a country's or the world's energy situation. As defined by the IEA, the TFC is the quantification of final delivered energies that is used as an end "commodity" and doesn't undergo any further transformation into other commodities (International Energy Agency, 2004).

The total final energy consumption for the world and Sweden is presented in Figure 1.1. The two key takeaways from the presented graph are the rising global energy use and the decreasing trend of energy use in Sweden. Statistically, global energy demand rose by almost 2.2 % in 2024, led by the strong surge of electricity demand (World Energy Outlook 2024, 2024). Reportedly, this is attributed to a rise in global cooling demands owing to rising temperatures, electrification of the transport sector, and expansion, digitisation of Information Technology (IT) sectors through a rise in data centres (Global Energy Review 2025, 2025).

Examining where energy is being consumed, it is worth noting that globally, almost 28 % of total energy is consumed for household needs and is responsible for approximately 40 % of annual CO_2 emissions (Wang et al., 2024). Additionally, global space cooling demand is growing astoundingly at the rate of 4 % every year. Projected to incur an additional 40 % of electricity demand by 2030 (World Energy Outlook 2024, 2024), space cooling will constitute a significant share of global GHG emissions with the current energy infrastructure.

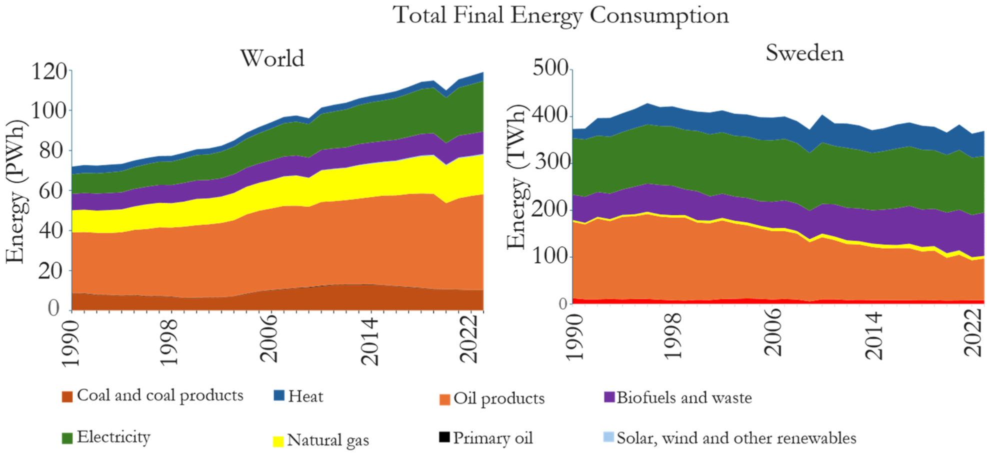

Figure 1.1 Total final energy consumption by source of the world (left) and of Sweden (right). Energy values are presented in Petawatt hours and Terawatt hours, respectively. Data source: (International Energy Agency, 2025)

The energy situation in Europe is resemblant of the energy scenario of the world. In the EU, the heating and cooling sector together make up almost 50 % of the total energy use (Directorate-General for Energy, European Commission, 2023). An alarming matter of concern is that 57 % of this energy comes from fossil fuel-based sources (*Decarbonising Heating and Cooling — a Climate Imperative*, 2023) and is responsible for roughly 40 % of the GHG emissions (Directorate-General for Energy, European Commission, 2023; Vilén et al., 2024). This was one of the driving factors for the introduction of numerous policies at the EU level to enhance energy efficiency and to curb carbon emissions from these sectors.

In the case of Sweden, several factors, including a decrease in space heating energy use due to rising numbers of energy-efficient buildings, a short-term decrease in heating periods owing to rising outdoor temperatures, and improved energy efficiency in the transport sector, are considered some of the contributing factors of the decreasing TFC (*Energy Consumption*, 2025; Swedish Energy Agency, 2022). Additionally, this is also attributed to the European Union's and Sweden's national goals to curb energy use by improving energy efficiency in the residential and transport sectors.

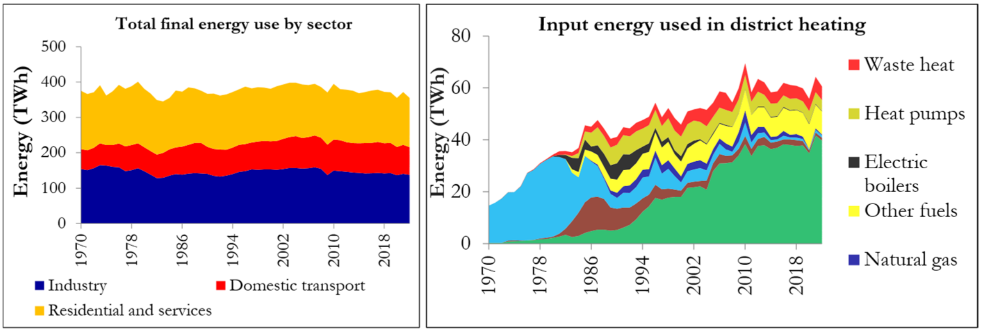

Figure 1.2 Energy use and district heating energy source in Sweden

In the case of Sweden, it is evident from Figure 1.2 that with 140 TWh of energy use, the residential and service sector accounts for almost 40 % of total energy consumption in Sweden, of which approximately 1/3rd is supplied by district heating(Swedish Energy Agency, 2022). This energy is primarily used for space heating and for the production of domestic hot water. Unlike the situation in the European Union, where heating and cooling energy supply and contribute to 40 % of the CO_2 emissions (*Decarbonising Heating and Cooling — a Climate Imperative*, 2023; Directorate-General for Energy, European Commission, 2023), Swedish district heating is relatively cleaner in the context that heat from biomass, renewable electricity, waste heat, and heat pumps constitute a larger share of district heating supply. Besides emissions, another grave concern in Swedish district heating is the distribution loss, which reportedly is around 19 % (Swedish Energy Agency, 2022) of the actual energy consumed by the residential district heating.

Given the status quo where district heating constitutes 1/3rd of the residential energy use with an astounding high level of distribution losses in the Swedish context, it is vital to understand the historical development and transitions in the district heating sector, particularly focusing on the energy source (fuels) and distribution network. Stemming from a coal-based CHP plant with a pipe network supplying 120°C hot water for space heating and DHW, district heating in Sweden began in the 1950s, marking the first generation of DH (Abugabbara et al., 2020; Werner, 2017). Owing to it high working fluid temperatures, the 1st generation featured high distribution losses and posed serious safety concerns. The availability of cheap oil in the 60s caused a fuel transition in DH, where oil replaced coal.

Furthermore, following the oil crisis in the late 70s, the fuel was again shifted to coal. The second-generation DH then used pressurised water as a working fluid with a temperature usually above 100°C. Over time, environmental concerns were growing, which resulted in swift transitions into biomass, waste combustion and installation of industrial-scale heat pumps for hot water production usually around 80°C. A reduction in fluid temperature ensured a reduction in distribution losses. This marked the third generation of DH in Sweden, the EU, and around the world. In the present context, most district heating distribution networks in Sweden and in the EU can be categorised under this 3rd generation of district heating (Werner, 2017). The developments in the DH sector continued with main emphasis on the reduction in fluid temperature, marking the deployment of 4th and 5th generation district networks, which is discussed later in this chapter.

To sum up, stemming from the first use of "forest fire" for thermal comfort to the present context where the 3rd generation of district heating constitutes a significant part of energy distribution, transition in both energy fuel and distribution network is evident. The overall developments point out that the driving force behind the transition is a move towards efficient use of energy and reduction of environmental emissions from the overall energy system. The future energy infrastructure, thus, should evolve towards an efficient energy infrastructure with decarbonised energy sources, distribution and end use. Only then will this discourse contribute to achieving the set goals of national and global emissions and energy efficiency.

1.2 Modern energy infrastructure

In addition to the goals of energy efficiency and decarbonization of the energy sector, assurance of energy security and energy independence are among the major ongoing discussions in the European Union, particularly due to the rising global tensions (Abugabbara et al., 2024). To meet the target of climate neutrality by 2050 as envisioned by the "European Green Deal" policy (Munćan et al., 2024), a restructuring of the conventional energy systems to realise a "modern energy infrastructure" is essential, whose attributes align with efficient production, distribution, and end use of energy.

There are major targets set on energy efficiency in the building sector, both on national and international levels, to decrease the carbon impact and increase energy efficiency (European Union, 2024). Since the overall purpose is to use less energy and to use it more efficiently, an important pathway to reach set targets for the built environment could be to focus on the energy distribution system. The energy demand for a building varies with its usage and tenant-related activities, where heating and cooling are sometimes needed and sometimes result in a surplus. This variation of demands and access could potentially be used for energy sharing between buildings, using existing infrastructure, and thereby enable a very carbon-efficient solution to reach set energy efficiency goals for the built environment.

Energy sharing and energy communities have grown in popularity in the last years but often referring to the sharing of electricity (*Energy Communities*, 2025; F.G. Reis et al., 2021). Another buzzing topic is the "sectoral coupling" in modern energy discussions. The primary goal of sectoral coupling is to shift from a single energy carrier to multiple energy sources so as to benefit from their synergetic interactions. A "system of systems" is realised where multiple energy carriers coexist in an integrated infrastructure (Papadimitriou et al., 2023). This infrastructure is supported through energy conversion and storage of available resources. One such practical scenario could be the integration of Power-to-Heat technologies with shallow geothermal systems (SGS), where heat pumps can be used to deliver instantaneous heating needs and, at the same time, offer storage solutions in a period of excess electricity.

Furthermore, intermittent resources such as solar and wind power coupled with SGS can also be opted for short-term and long-term energy storage, whilst also ensuring that the instantaneous energy demands of the users are met. Together, they form a foundation for a modern energy infrastructure. In addition to utilising the existing local resources, the concept of "sharing" between properties is strengthened by this coupling, where participating real estate shares its otherwise "waste heat" with each other, thereby further promoting decarbonization.

To enable sectoral coupling, a platform is required where the above-mentioned attributes of energy interaction and sharing can be realised. Previous studies have shown that Low Temperature District Networks (LTDN) can play a pivotal role, serving as a platform for the aforementioned "modern energy infrastructure". This, because of its flexibility to integrate multiple infrastructures, including power and heat sources (Falay et al., 2020) and provisioning energy sharing between properties (Abugabbara et al., 2024; Angelidis, 2025).

1.2.1 Low temperature district networks

Multiple terminologies have been used to refer to the evolving 5th generation of DHCs. While some researchers still advocate for the use of term "Fourth Generation District Heating (4GDH)", terminologies such as " Fifth Generation District Heating and Cooling (5GDHC)", "Low Temperature District Network (LTDN)", "Ultra-Low Temperature District Network (ULTDN)", "Geothermal Energy Network (GEN)", "Shared Energy Network (SEN)", and "thermonets" are found being used to refer to this system (Buffa et al., 2020; Lund et al., 2021). A need for uniformity and harmonisation in the nomenclature of such systems was indicated in (Buffa et al., 2019). Though uniformity in nomenclature for the fifth-generation district system does not yet exist, all systems preferentially refer to the DHCs that operate at close to ambient network temperature and are facilitated with heat pumps at the substation level to alter the temperature of working fluid (Lund et al., 2021). In this thesis, the term "low temperature district network" has been used to refer to the studied system.

A schematic representation of a low temperature district heating and cooling network is shown in Figure 1.3. Unlike the conventional linear design of district thermal networks, where heat is produced at a centralised plant and distributed via insulated pipes, LTDN adopts a decentralised and bi-directional design (Boesten et al., 2019; Buffa et al., 2020). With a year-round floating temperature in the grid varying between 5°C to 35°C (Buffa et al., 2019), the overall network dynamics are fundamentally altered in contrast to the traditional networks. A low-grade thermal energy is circulated via the network, and individual end users are responsible for upgrading the quality of heat as per their end requirements. In this stage, the role of heat pumps is of particular importance.

Owing to its low temperature operation, the LTDN architecture allows coupling and integration of diverse low-grade and ambient heat sources, which are thermodynamically incompatible in the context of traditional high temperature systems (*Advantages of 5GDHC Networks (Cold Heat Networks)*, 2025). Low temperature sources such as shallow geothermal energy, solar thermal, lake water, sewage and waste heat from residential and commercial buildings, thus have a great potential for integration to such networks

(*Advantages of 5GDHC Networks (Cold Heat Networks)*, 2025; Boesten et al., 2019). Moreover, the use of decentralised heat pumps and thermal storage facilities for sectoral coupling of electricity and heat sectors ensures flexibility and robustness of modern energy infrastructure.

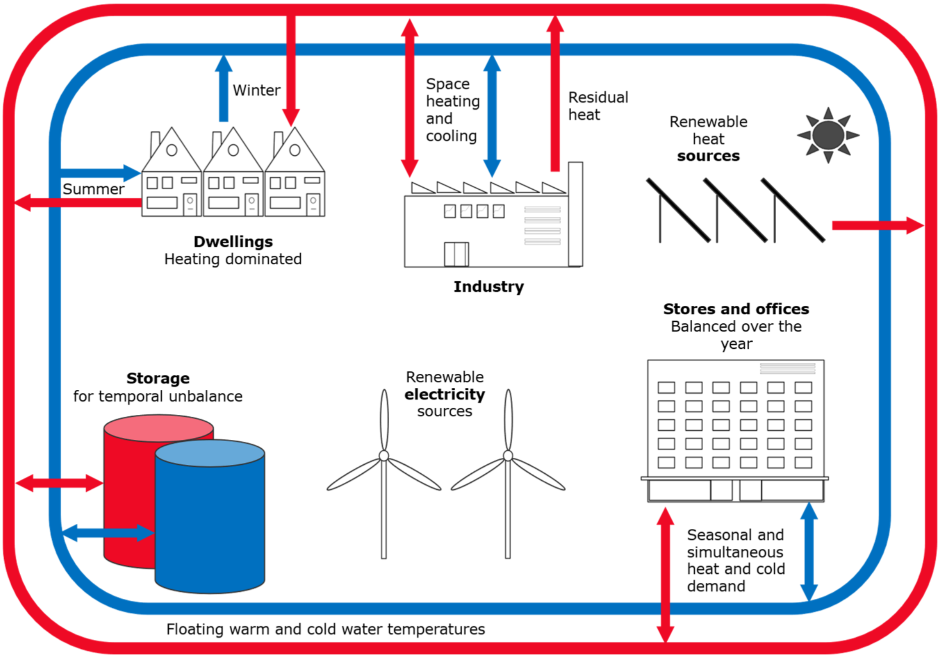

Figure 1.3 A typical architecture of a low-temperature district network (Boesten et al., 2019)

1.3 Research aims and objectives

The needs of this modern world are energy independence, reduction in greenhouse gas emissions, efficient supply, distribution and end use of energy. In that context, the overarching aim of this thesis is to investigate and demonstrate through simulation studies that the low-temperature geothermal networks are a viable platform for modern, decentralised energy infrastructure featuring sector coupling of electricity and heat sectors. The guiding hypothesis for this research is that LTDN functions as a robust system where multiple local energy sources can interact, and moreover, facilitates energy storage and sharing between connected properties thereby promoting energy independence at local level, reduced distribution losses and lowered environmental emissions.

1.3.1 Research Questions

This thesis is guided to answer the following three primary research questions.

RQ 1. How can a low temperature district heating and cooling network be designed for energy exchange between properties?

RQ 2. What is the decarbonization potential of LTDN compared to conventional energy infrastructure?

RQ 3. How can the involvement of various stakeholders, including the prosumers, be motivated and ensured within the evolving ecosystem of modern energy infrastructure?

1.3.2 Objectives

Guided by the above-mentioned research questions, this thesis has three major objectives. The first objective is to demonstrate the technical concept of energy sharing in thermal networks and outline the role of system components by which it can be achieved. The second objective is to demonstrate a physical infrastructure of an LTDN and quantify the energy sharing and its decarbonization potential compared to alternative energy sources through modelling studies. Finally, the third objective is to describe the stakeholder perspective and pathways to motivate their involvement in the adoption and expansion of modern energy infrastructure.

1.4 Overview of Dissertation

This thesis includes seven chapters divided thematically for good readability.

Chapter 1 discusses energy as a vital component of human civilisation and highlights its transitions to the present modern energy infrastructure. It describes the role of modern energy infrastructure in achieving energy efficiency, sufficiency, and decarbonization of energy sources. Furthermore, the overall ground for this research and the underlying research aims and objectives are discussed in this chapter.

Chapter 2 describes the underlying research philosophy and methodology opted for digital twin modelling and simulation of low-temperature networks. The chapter further elaborates on digital twin modelling and interview studies as quantitative and qualitative research methodologies used in this research.

Chapter 3 provides an overview of modelled system components of LTDN. It presents a mathematical representation of system components in Modelica and energy sharing components. Furthermore, a schematic representation depicting the interaction between system components during energy interaction between buildings is discussed.

Chapter 4 describes "Embassy of Sharing" as a case study community. The chapter provides a detailed description of shallow geothermal borefields, thermal load profiles, and a geo-energy sharing system, which is typical for the studied case. Furthermore, design parameters and assumptions made for modelling and simulation are presented.

Chapter 5 presents results obtained from the modelling studies. The chapter describes the technical performance of LTDN, considering three key performance metrics. Furthermore, experts' opinion and perspectives on business models for prosumer-centric district networks, stakeholders' engagement, and pathways for prosumer integrations is discussed in this chapter.

Chapter 6 presents concluding remarks and an overall research summary.

Future research pathways, which include exploration of multiple local and renewable energy sources for LTDN, dynamic energy management with thermal storage considering their intermittent nature at the urban scale, are discussed in *Chapter 7*.

2 Research Methods

This chapter presents the methodology adopted to investigate and analyse the low temperature district network through a modelling and simulation approach within the concept of systems engineering. The methodological framework integrates the "Vee-model" (Sinha et al., 2000; *V-Model - an Overview*, 2025) of systems engineering life cycle with detailed digital twin model-based simulation and analysis of the studied thermal network. The research philosophy, methodological design, and modelling tools, framework used in this research are comprehensively discussed in the following sections.

2.1 Research Philosophy

From a philosophical viewpoint, two major research philosophies are of relevance in this study. The first is positivism, and the second is interpretivism. "Positivism" inclines more towards an objective and measurable understanding of reality. It supports the quantitative analysis of system behaviours relying on empirical data and physical laws. That is, in pursuit of quantitative information such as measured data or simulation outputs to describe reality (Leavy, 2022).

The concept of systems engineering suggests that integration of sub-systems contributes to the understanding of overall system behaviour. The notion of system engineering and positivist research philosophy is well reflected through this research, as we show through modelling studies that heat transfer, fluid flow, energy storage, and energy sharing are not isolated phenomena but are interrelated processes in a larger LTDN and altogether define the behaviour of the studied LTDN.

Additionally, interpretivism research philosophy focuses more on the subjective interpretation of multiple realities. In other words, qualitative inquiry of equally valid knowledge or perspectives (Leavy, 2022; D. U. Sharma, 2024). A pragmatic approach that combines both quantitative and qualitative study of information, a mixed-method approach, has thus been employed in this study to fulfil the requirements of the respective objectives of this research.

2.2 Research Methodology

2.2.1 Quantitative study

The first and second research objectives intend to describe the concept of energy sharing and energy interaction between multiple sources through the study of a practical LTDN. These are answered through analysis of the technical system using parameters such as energy flows, coefficients of performance, and fluid temperature in the LTDN. To study the system, the Model-Based Systems Engineering (MBSE) methodology was opted for in this research.

MBSE is defined as a methodology that relies on "model-centric" representations of a real system to describe its system requirements, behaviour, and performance (IBM, 2023). In this research, digital models have been used to emulate this approach. Digital models can theoretically be a physics-based model or data-driven models that imitates the behaviour of a real system. A digital twin modelling approach, which is an application of MBSE, has been employed, where both physics-based and data-driven digital twins of components of a real system have been developed. The description of those components and underlying physics-based models has been described in later sections.

2.2.1.1 Modelling and Simulation – A tool for MBSE

"Model" is a representation or approximation of a real system or an event in the form of mathematical or physical equations. Experiments performed on the model with a set of defined conditions are referred to as "simulations" (Abugabbara, 2021; Banks & Sokolowski, 2009). As defined by(Banks & Sokolowski, 2009), modelling and simulation is a cost-effective environment to test hypotheses, optimise design and predict system behaviour under various operational conditions. In the MBSE methodology, modelling and simulation serve as an integrated tool for analysis, verification and decision making (Banks & Sokolowski, 2009). It leverages the possibility for empirical experiments in multiple dimensions of system analysis, which otherwise would be too expensive and time-consuming to analyse through a real implementation.

In the context of analysing the behaviour of an LTDN, modelling and simulation tools such as MATLAB, Simulink, ANSYS Fluent, Modelica, TRNSYS and others are widely used as simulation tools to visualise and analyse thermal behaviour and assess the performance at different system levels under steady-state and dynamic conditions.(Abugabbara et al., 2020) have reviewed various research works and commented on the ability of different modelling platforms and their respective applicability to model various aspects of LTDN.

Considering the complex interdependencies of sub-system components, control systems, thermal and hydraulic interactions, Modelica is suggested as a suitable modelling platform (Abugabbara et al., 2020). It is an open source object-oriented, equation-based language which relies on differential algebraic equations to describe the physical system, thermo-hydraulic and control system in this research context (Wetter et al., 2014).

To develop the digital models, the Modelica modelling language platform with Dymola (Brück et al., 2002) as a graphical user interface has been used, following the linear model development cycle inspired by the Vee-model of systems engineering. A procedural flowchart depicting distinct stages of this model development is shown in Figure 2.1.

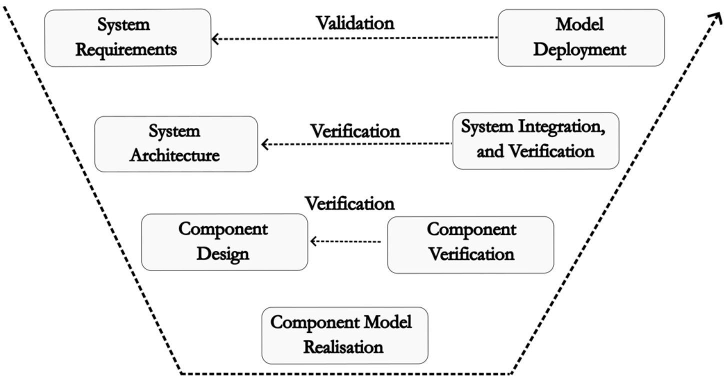

*Figure 2.1 The V-model of system engineering is employed to develop digital models (*V-Model - an Overview*, 2025)*

In the Vee-model shown in Figure 2.1, the process stages flow from left to right. i.e. starting from system requirements and ending with the model deployment. The overall model development cycle can be divided into five distinct phases/stages. The model development begins with the conceptualisation phase, with the identification of system requirements. In this stage, different system components that are required to develop the overall model are identified. Additionally, the modelling environment or platform is identified. In the context of this study, identification of energy sources such as the geothermal borefields, central pipe network layout for distribution, etc., falls under this stage.

The second stage is the preliminary design phase, where the overall system architecture is decided. Different hierarchical abstractions of system components are decided, and subsystem components that make up the overall system are planned in this stage. The third stage is the critical design phase, where actual digital twins of sub-system components are designed in Modelica. This can include, for example, the models for circulation pumps and heat pumps, pipe networks, control systems and others.

The fourth stage is the integration and test phase, where sub-system components designed in the previous stage are validated against test data from verified sources, and component models are approved for further integration in system design. Validated component models are then assembled at pre-defined hierarchical abstraction to build an overall substation model. The overall sub-station model is validated against test data or against a physically explainable operational trend based on expert experience. Finally, the approved model is deployed for further parametric investigations or research.

2.2.2 Qualitative Study

The third objective of this research was to identify the stakeholders' perspective and ways to motivate their inclusion in modern energy infrastructure in the role of prosumers. Guided by interpretivism research philosophy, literature review and expert interviews were performed to identify the stakeholders' perspective.

A Mixed-Method research approach with dominantly qualitative analysis was opted for this study. The adopted mixed-method design incorporates a quantitative and qualitative approach to analyse the information and develop a deeper and thorough understanding of the research questions (Dawadi et al., 2021). In this study, a thorough analysis of information from published literature is triangulated with findings from interview studies or vice versa to develop a comprehensive understanding and for validation of research information, which is in line with the methodology described by (Dawadi et al., 2021; McLeod, 2024).

Based on the research method mentioned above, information relating to business model developments, ownership structures, and legal instruments from published research materials were gathered. Additionally, a semi-structured interview approach was employed to gather expert opinions and perspectives on this research issue. The findings from the literature review were compared with the expert opinions and experiences. This methodological approach is termed "Convergent parallel Mixed-Method Design" and has been described in detail in (Dawadi et al., 2021; McLeod, 2024).

In the case of expert interviews, a preliminary questionnaire with 14 questions divided thematically into ownership, responsibility, and risk sharing, customer value proposition incentives, case studies and experiences, prospects and outlook were sent out a week before the actual interview. A 90-minute Microsoft Teams meeting was conducted individually with the participants. Consent from the interviewee was taken to record and transcribe the meeting for study and documentation purposes. Experts from diverse professional backgrounds were interviewed to grasp the diverse experiences and perspectives on the study sector. The scope, however, was limited due to the availability of interviewees. In total, 7 interviews were conducted. The professional background of the interviewee included experts from academia, real estate developers, business developers, consultants and policy makers.

2.3 Overview

To sum up, different research methods have been opted for to meet the specific objectives of this research. Furthermore, this thesis is a compilation of sub-research tasks, which are presented in the appended four papers. The readers are advised that, though multiple research methodologies have been opted to describe each section in the appended papers, only the research methodology linked to the main aim of the paper is highlighted in the Table 1. An overview of the different methods adopted in each appended paper is presented in Table 1.

Table 1 Overview of research methods adopted in the appended papers

Appended Paper	Methodology	Data collection methods	Data sources	Main aim/Research question
Paper I	Qualitative Analysis	Literature review	Project reports Engineering and process drawing	RQ 1
Paper II	Quantitative analysis	Digital Twin Modelling	Case studies Simulation results	RQ 1 RQ 2
Paper III	Quantitative analysis	Digital twin modelling	Case studies Simulation results	RQ 1 RQ 2
Paper IV	Mixed approach with a dominant qualitative	Literature review Expert Interview	Scholarly articles Interview notes, transcripts	RQ 3

3 Energy sharing component modelling

In this chapter, the design and modelling of major system components, including the heat pump and geothermal sharing control system, which are vital to achieve energy sharing, are described. The described components and system design are typical for the low-temperature network of the studied community "Embassy of Sharing", which is comprehensively discussed in Chapter 4. Readers are also advised that the terminology used to represent the system components such as the heat pump, heat exchangers, control valve, distribution pipe and others are typical to this studied system. The characteristic feature of this low-temperature network includes decentralised heat pumps and a shallow geothermal borefield for individual substations. A two-pipe central network connects all substations to serve as a Geo-Energy Sharing System. (GESS). The system architecture designed to achieve energy sharing between buildings is comprehensively discussed in this chapter.

3.1 Heat pump

The digital twin of heat pumps included in the system is modelled using a multivariate equation fit method. Heat pump performance data for a set of source and condenser temperatures provided by the heat pump manufacturer were employed to obtain the multivariable equations. The variables used in the model are the outgoing temperatures on the condenser and the evaporator side. The model uses a set of heat load coefficients (α), and electrical power coefficients (β) to determine the available heat at the condenser side and electrical power used by the compressors. The model equation defining the performance is presented in Eq. (1) and Eq. (2).

$$\dot{Q}_{ava} = \alpha_1 + \alpha_2 T_{loa,out} + \alpha_3 T_{Sou,out} \qquad \text{Eq. (1)}$$

$$P = \beta_1 + \beta_2 T_{loa,out} + \beta_3 T_{Sou,out} \quad \text{Eq. (2)}$$

$$COP = \frac{\dot{Q}_{ava}}{P} \quad \text{Eq. (3)}$$

$$\dot{Q}_{eva} = \dot{Q}_{ava} - P \quad \text{Eq. (4)}$$

In Eq. (1) and Eq. (2):

$\dot{Q}_{ava}$ is the available heat at the condenser side,

$T_{loa,out}$ is the load side entering water temperature,

$T_{Sou,out}$ is the source side entering fluid temperature,

P represents the electrical power used by the heat pump.

Following the conservation of energy principle, the energy balance, as shown in Eq. (4), is used to calculate the heat extracted on the evaporator ($\dot{Q}_{eva}$). Finally, the heat pump performance is determined in the form of the Coefficient of Performance (COP) metric using Eq. (3).

3.1.1 Heat pump model validation

A setup for heat pump performance validation was developed where fluid temperature from the borefield (source) and supply temperature from the condenser was emulated through a tabulated data. Available heat output at the heat pump condenser and respective compressor power values obtained were plotted against the manufacturer's data and are presented in Figure 3.1. The presented model equations predict available heat and compressor power with a coefficient of determination (R^2) value of 0.98 against the manufacturer's data.

Furthermore, the average Root Mean Squared Error (RMSE) was calculated for available heat, and compressor power for each set of outgoing temperatures. The RMSE value describes the average magnitude of error between simulated and measured values, where a higher RMSE signifies significant error and a lower RMSE signifies a more accurate and a good fit model (D. K. Sharma et al., 2022).

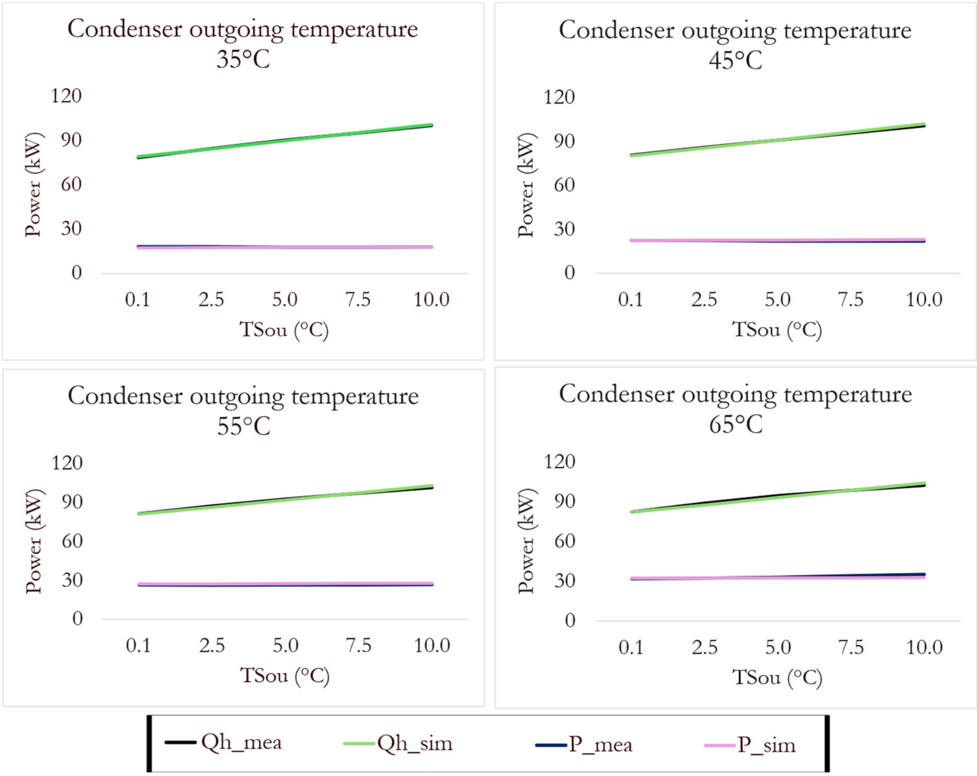

Figure 3.1 Graph depicting the correlation of measured and simulated heat output, and the electrical power consumption of the heat pump

The RMSE values for the presented four outgoing temperatures from the condenser is around 0.78 for ($\dot{Q}_{ava}$), and 0.85 for compressor power (P). The highest RMSE value was 1.33, observed for compressor power for an outgoing temperature of 65°C.

Additionally, the Coefficient of Variance of Root Mean Square Error (CVRMSE) was calculated to identify the variation of errors between different condensing temperatures. The lowest CVRMSE of 0.83 % was obtained for ($\dot{Q}_{ava}$) at 35°C and the highest was 4.48 % for (P) at 65°C, outgoing condenser temperature. For all, other condensing temperatures, the CVRMSE were below 1.4 % for ($\dot{Q}_{ava}$) and 4.2 % for (P). As the presented error metrics falls within the acceptance range, below 15 % for CVRMSE, and above 0.75 for R^2, suggested by ASHRAE guideline 14 (Ruiz et al., 2017), this mathematical model of heat pump was accepted for further modelling and evaluation of the system.

3.2 Shallow geothermal energy as a balancing unit

In the context of thermal energy extraction, various technological systems have been developed that can harvest energy from the environment (air, water or soil). Ground source heat pumps are one such technology, which relies on a working fluid (mix of refrigerant and/or water) to dissipate/extract energy to/from the ground (soil). In contrast to outdoor air, whose temperature fluctuates quite rapidly in response to instantaneous weather conditions, the ground is relatively resilient because of its high thermal capacity and state of thermal equilibrium with the long-term atmospheric conditions and solar radiation (Figueira et al., 2024).

The geothermal energy stored in the ground up to the first 200 m is usually around 2 °C (Figueira et al., 2024) above the annual average local air temperatures, which enables it to act as a large heat reservoir/storage in the capacity of a heat source and heat sink for any energy system. One such system that facilitates this energy exchange to and from the ground is a Shallow Geothermal System (SGS).

Numerous configurations of SGS can be found applied in various settings around the globe. These configurations are mainly differentiated based on pipe layout on the ground and loops of circulation fluid (El Haj Assad et al., 2022). In the context of this research, a collection of numerous closed-loop vertical Borehole Heat Exchangers (BHE), interchangeably termed as a borefield over this thesis, is the SGS for the studied energy community. Owing to its potential for thermal storage, SGS offers a unique position as an energy balancing unit for the LTDN in case of energy surplus or energy deficit in the central distribution network.

Modelling of borefields in Modelica is conducted using a pre-defined "Geothermal Borefields" component from the Modelica Buildings Library (Wetter et al., 2014). These borefield components allow to model any number of BHEs by specifying their arrangement in a Cartesian coordinate system. The physical energy interaction with the ground is segregated into two parts. First is the energy exchange between the working fluid and the borehole walls. Second is the energy transfer between the borehole walls, filling materials and the ground. A schematic Modelica implementation of this coupling between the borehole component and the ground energy exchange component is shown in Figure 3.2. The borehole thermal capacitance and resistance are used to identify the energy exchange with the fluid. This is achieved through the thermal resistance and capacitance model developed by Bauer et al. (Bauer et al., 2011). The second part, which is the energy exchange with the ground, is determined by the load aggregation method using the borefields' temperature response, commonly known as the g-functions (Abugabbara et al., 2024). A comprehensive description of the borefield model and its mathematical implementation in Modelica can be found in Paper II (Abugabbara et al., 2024).

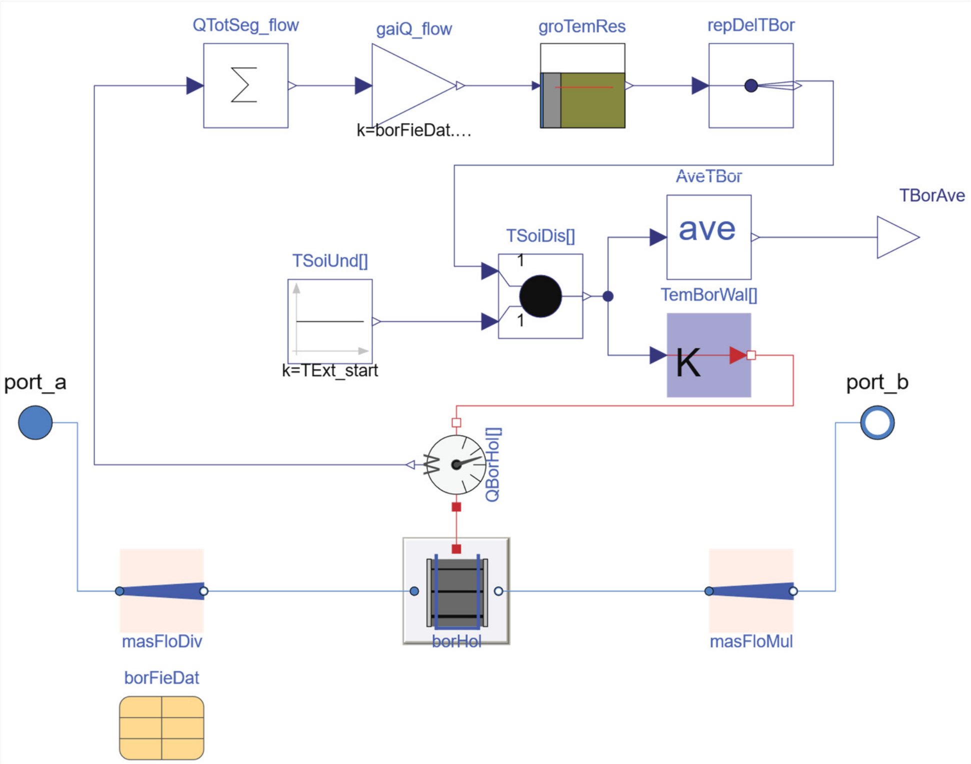

Figure 3.2 Modelica implementation of geothermal borefield component. Adopted from Modelica Buildings Library (Wetter et al., 2014)

3.3 Geothermal energy storage and sharing

It was previously discussed that borefields can act as a large thermal reservoir. However, when coupled to a larger thermal system or substation, only an optimal system design and control mechanism for fluid exchange through the borefield to store or to share energy will ensure enhancement of the overall substation/system performance.

Thermal demands or load profiles of the substation are the deciding variable that defines the possibility for energy storage. A substation connected to a building with a heating demand has the possibility to either extract heat from its energy source (borefield) or from the GESS system. From a thermodynamics perspective, a higher fluid temperature is beneficial to meet the heating demand. This entails that a "higher fluid temperature" decides the choice between borefield or GESS as an energy source for the substation. In heating operation mode, the byproduct is a "colder fluid temperature" return from the heat pump.

Conversely, as in the heating mode, a "colder fluid temperature" is beneficial for the substation when the connected building has a cooling demand. The byproduct during the cooling operation is a "higher fluid return temperature". During this operational mode, there is a possibility to extract heat from the building, and from the condenser side of heat pumps (active cooling). A substation with a cooling demand thus has the possibility to store heat in its borefield or share it with other connected substations.

Comparing the two operational modes, it is worth noting that, only in a scenario where opposing thermal demands exist between the substations, the possibility for thermal energy sharing is maximised. Alternatively, only the necessity of cooling demand in one of the substations ensures the possibility for and maximises energy storage and/or energy sharing.

A snippet of a Modelica model for a substation from the case study community "Embassy of Sharing" for different flow configurations during cooling mode operation is shown in the following sections to describe how energy storage and energy sharing are achieved through a geothermal borefield. As the main objective here is to describe the flow configuration during energy storage and energy sharing modes, only a cooling distribution circuit connected to one heat pump is shown in the Figure 3.3 to Figure 3.6.

3.3.1 Standalone operation

In some cases, it is in the best interest to operate substations as a separate entity. This could be in cases such as the same nature of thermal needs in all substations, or a disruption in the central distribution network or cases where a more favourable temperature is available in its own borefield than on the GESS. In the following sections, both free cooling and active cooling system designs used in the "Embassy of Sharing" is described.

3.3.1.1 Free cooling through borefield

In case of cooling demand in the substation, the borefield can act as a primary energy source for cooling as long as the possibility for free cooling exists. The free cooling operation in this system is made possible by the heat exchanger named "VVX 41", which extracts heat from the building's cooling return. The flow scheme during free cooling is represented in Figure 3.3.

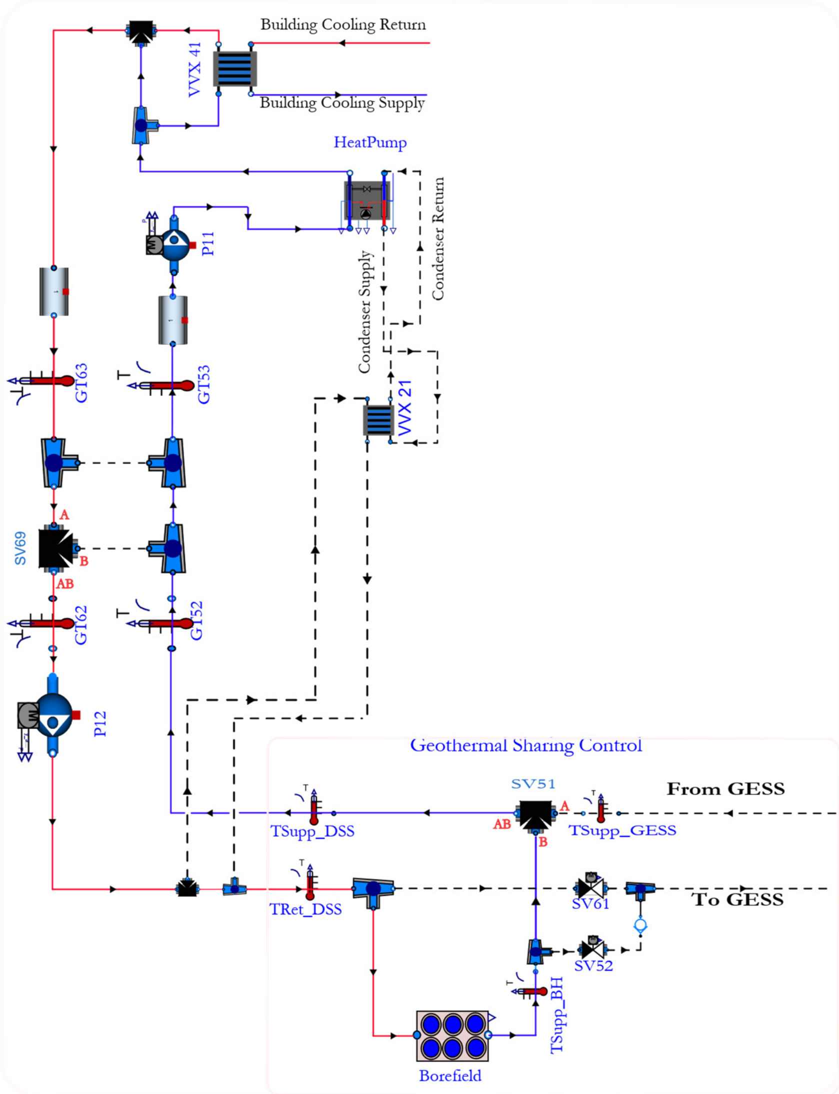

Figure 3.3 Flow configuration during free cooling on a standalone-operated substation (Note: Solid lines represent the active flow path, and dotted lines indicate no flow on the circuit)

In this mode, heat pumps are turned off and circulation pumps P11 and P12 move the same amount of fluid through the circuit to deposit the extracted heat from the building into the borefield.

3.3.1.2 Active cooling and energy storage on borefield

When the possibility of free cooling ceases to exist, active cooling through the heat pumps is activated to produce the necessary cooling effect. As a result, heat is produced on the condenser side of heat pumps as a byproduct.

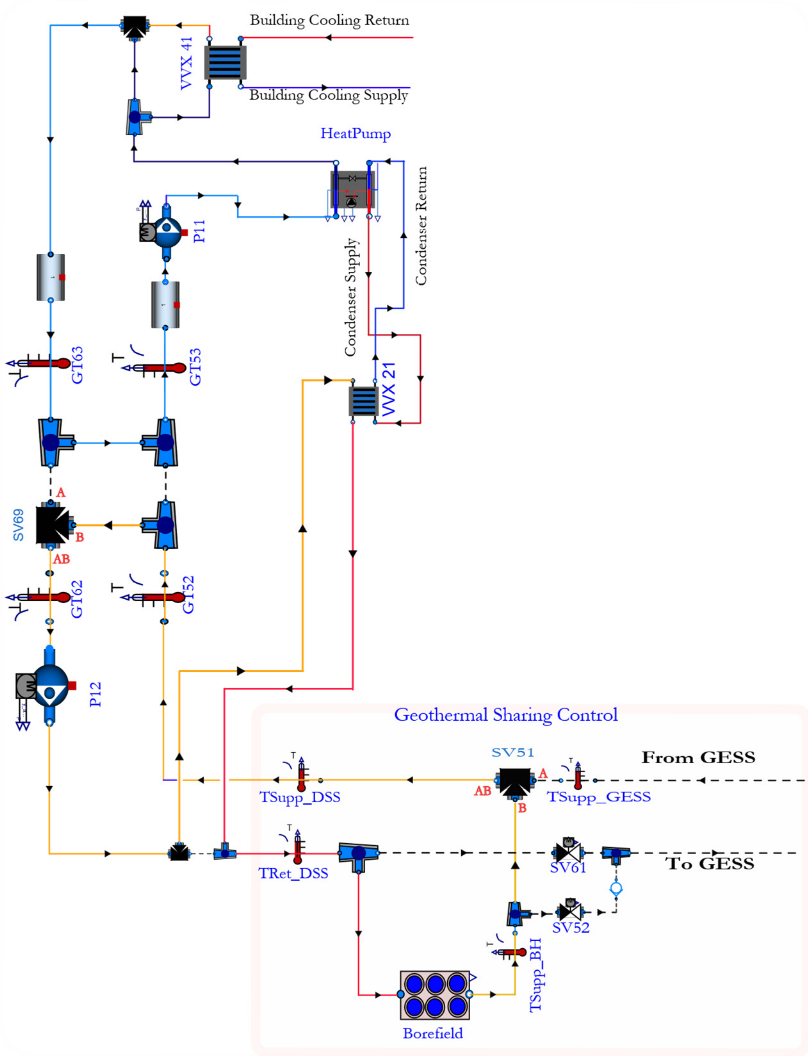

Figure 3.4 Flow configuration during active cooling on a standalone-operated substation

In this mode of operation, the three-way valve directs the return flow towards the heat exchanger "VVX 21" through which the condenser heat from the heat pump is extracted and injected in the borefield. As this injected heat, raises the fluid temperature in the borefield, the evaporator side of the heat pump is hydraulically separated from the borefield circuit to ensure a colder fluid circulation on the evaporator side. This hydraulic separation is achieved by regulating the three-way valve SV69. The hydraulic separation ensures heat storage in the borefield without compromising the performance of the heat pump. For better readability, a flow configuration for this mode of operation is presented in Figure 3.4.

3.3.2 Networked operation through GESS

3.3.2.1 Free cooling through GESS

If such a scenario exists where fluid temperature in the GESS is lower than that from the borefield, it is thermodynamically beneficial to prioritise GESS for substation cooling. As long as the fluid temperature at GESS, measured by "TSupp_GESS" is lower than the building cooling return, free cooling through GESS is activated. Figure 3.5 shows fluid flow path during this operating scenario.

The three-way valve SV51 in this scenario is regulated to keep the "TSupp_DSS" temperature as low as possible. In this scenario, if SV51 is fully open (A to AB), all flow goes toward GESS and mixes with the flow from other substations. This mixing, being dependent on the flow from other substations, can create an unfavourable temperature for cooling. Therefore, to avoid mixing of the entire flow in the GESS, SV51 regulates slowly to maintain the lowest possible temperature at "TSupp_DSS". The cooling return from heat exchanger VVX 41 is directed through the borefield and back to the GESS to store any heat as possible.

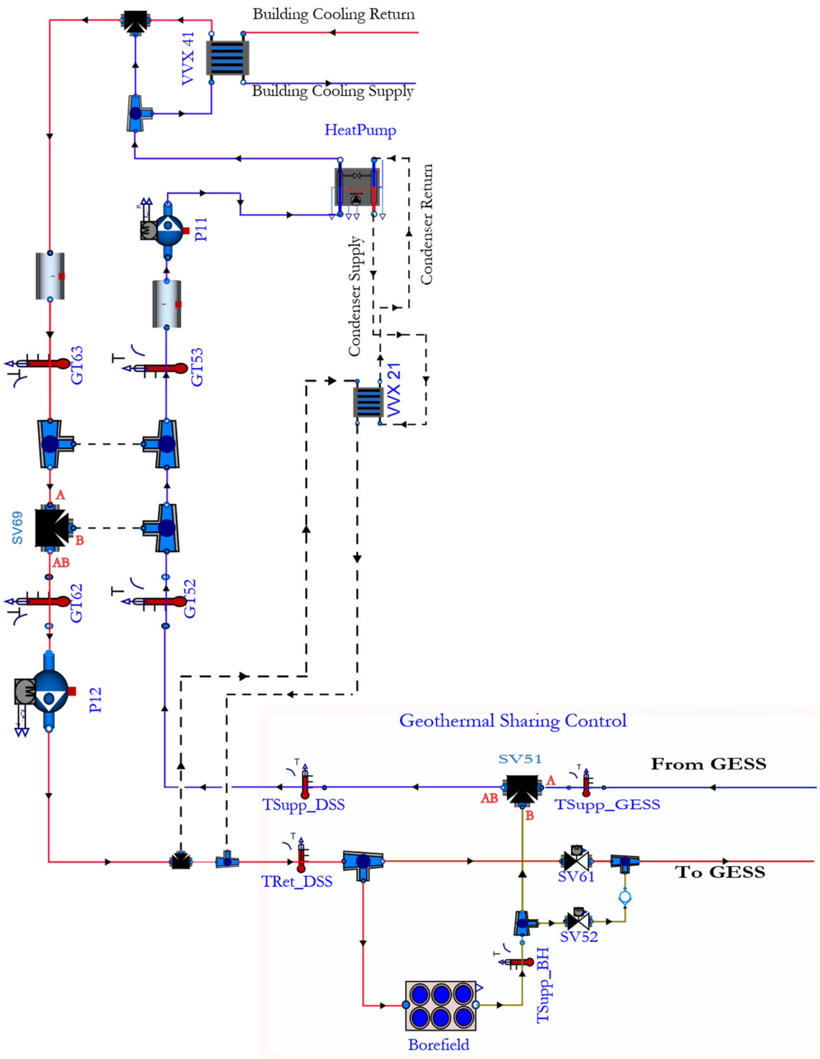

Figure 3.5 Flow configuration during free cooling through GESS

3.3.2.2 Active cooling and Excess Heat sharing to GESS

Energy sharing at its peak is usually observed when one of the substations is in active cooling operation mode and another substation has a heating demand. As described in section 3.3.1.2, during active cooling, excess heat from heat pump condenser, which is of higher quality, can be extracted and exchanged directly to the GESS network. The fluid temperature in the GESS rises because of which substation with a heating demand can be benefited.

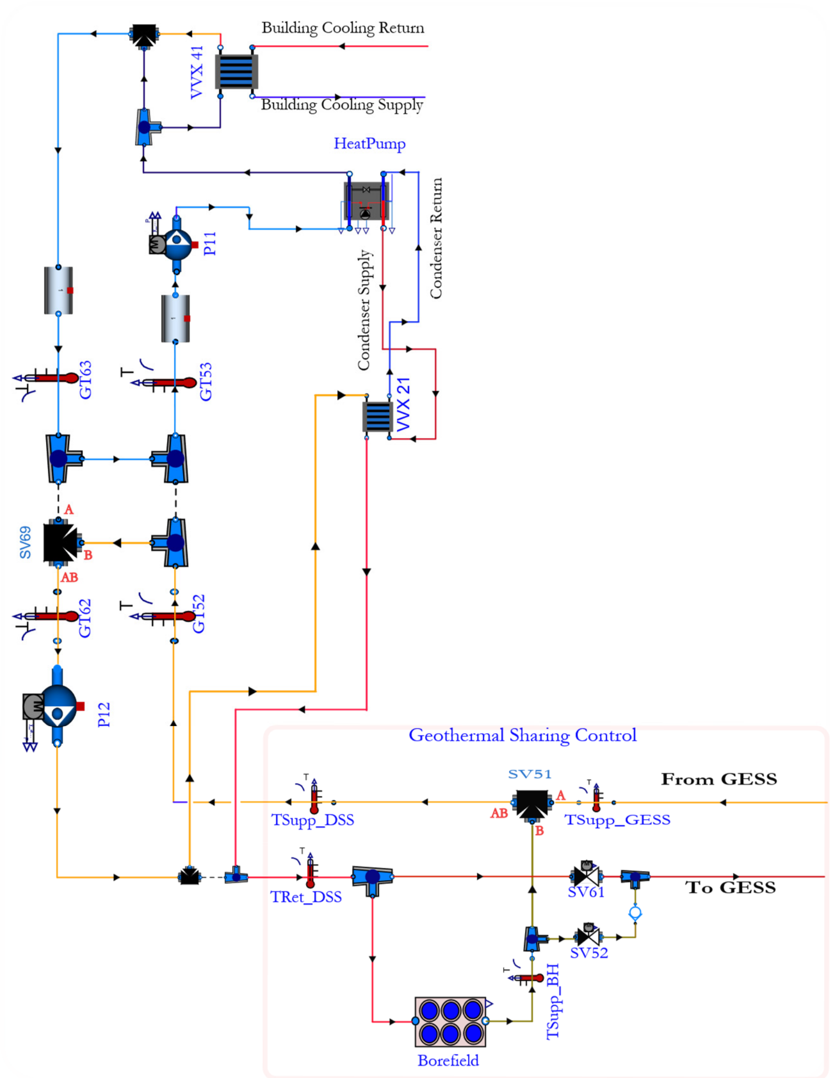

Figure 3.6 Flow configuration showing active cooling of substation and energy sharing to the GESS

To ensure that high-quality heat is exchanged to the GESS without compromising the COP of the heat pump at the substation having a cooling demand, SV51 is regulated to supply a higher fluid to the GESS and a lower fluid temperature to the building with cooling demand. For a substation with cooling demand, it is preferable to supply the lowest possible temperature and ensure the highest possible return temperature to GESS. Similarly, for a substation with a heating demand, the highest possible supply temperature and the lowest possible return temperature to GESS is preferred.

The role of control valves SV52 and SV61 is of particular importance in this scenario. SV52 and SV61 determine whether the flow should pass through the borehole storage before reaching GESS or not, depending on the temperatures "TRet_DSS" and "Tsupp_BH".

In the configuration represented in Figure 3.6, to ensure flow of high-temperature fluid to GESS, control valve SV61 is kept fully open, and SV52 is closed. Simultaneously, SV51 supplies a mixed fluid from the borefield and GESS to the substation with cooling demand. The control algorithm for SV51 ensures that the supplied fluid temperature, measured with "TSupp_DSS" is as low as possible. This configuration ensures a suitable temperature for all sharing sub-stations.

4 Embassy of Sharing: Case Study

In this chapter, a physical low-temperature district heating and cooling network designed for the “Embassy of Sharing” community based in Hyllie, Malmö is presented. Notable features of the LTDN are discussed, and the digital twin model of the substation used for modelling and simulation studies is presented. Subsequently, thermal demand profiles of the studied buildings and the overall modelling assumptions considered in the Modelica model for various system components are discussed.

4.1 Building typologies and functions

The Embassy of Sharing community is an ongoing development project at Malmö, Sweden, and consists of eight buildings served by six individual thermal substations. The EOS community, with a heated floor area of 61 901 m^2, houses spaces for residence, offices, recreation, and commercial purposes. Owing to the diverse use-types of buildings, EOS has thermal energy needs for both heating and cooling, which amounts to an estimated 2.2 GWh and 0.4 GWh of energy, respectively, for heating and cooling annually.

A schematic representation of the Embassy of Sharing (EOS) community is shown in Figure 4.1. Each substation is named UC (Swedish - Undercentral) followed by a numeric alphabet to denote an individual entity. UC 1 and UC 6 serve two separate buildings, while the rest are tied to a single building. The functional typology of buildings, their estimated peak thermal demand, and the number of planned BHEs per sub-station for the community are shown in Table 2.

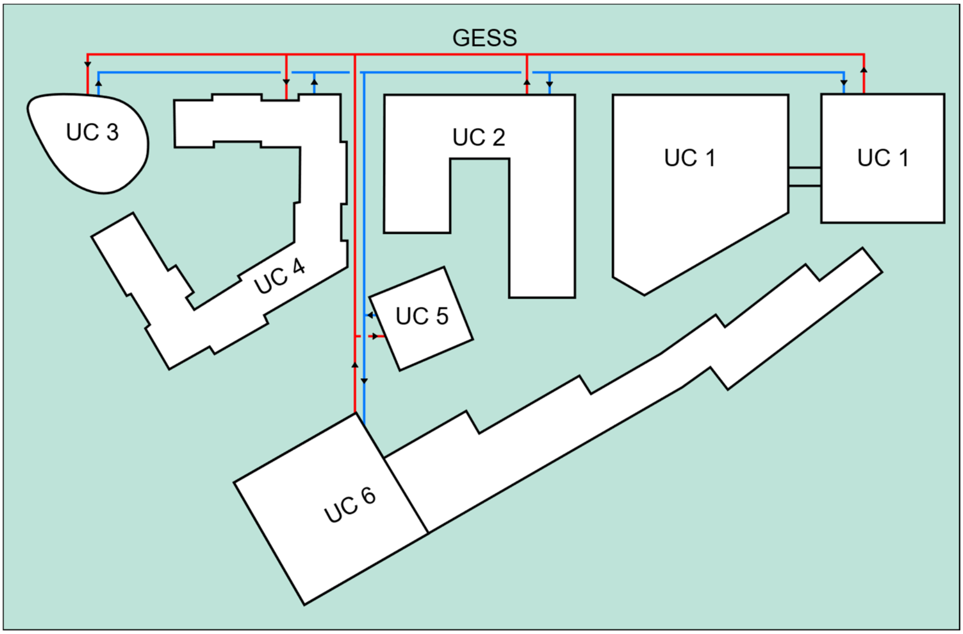

Figure 4.1 Schematic layout depicting the plan view of the Embassy of Sharing community (Note: The solid blue and red lines represent the geo-energy sharing system (GESS), a pipe network that connects all substations)

Table 2 Description of the substation's thermal demand and specification of borehole heat exchangers

Sub-Central (UC)	Functionality	Peak energy demands (kW)		Borehole heat exchangers	
		Heating	Cooling	Numbers	Total Depth (meters)
UC 1	Office, Library	500	600	30	9 000
UC 2	Hotels, Apartments	385	291	18	5 400
UC 3	Residential	235	NA	12	3 600
UC 4	Residential	285	NA	15	4 500
UC 5	Residential	187	NA	10	3 000
UC 6	Production centres, shops	210	311	18	5 400

To meet the thermal needs of the buildings, the community is equipped with a low temperature district heating and cooling network. As one of the energy sources, the network is integrated with a total of 102 vertical shallow geothermal borehole heat exchangers (BHEs) running approximately 31 000 meters of total depth. Additionally, heat pumps are equipped at each building level to alter the fluid temperature to meet the building's individual thermal demands.

In this study, two substations, UC 1 and UC 3, are considered for modelling studies. UC 1 connects two office buildings and has a heated floor area of 15 766 m^2. Similarly, UC 3 is connected to a residential building with a heated floor area of 7 242 m^2. Notably, the UC 1 has both heating and cooling demands during different periods of the year according to its usage. Alternatively, UC 3, the residential building, only has space heating and DHW demand throughout the year.

4.2 Demand profiles

A bar graph plot presented on Figure 4.2 represents the year-round monthly energy demand profile of two connected substations: UC1 (office) and UC3 (residential apartment). The cooling energy demand is represented with negative values to indicate the energy being removed from the building. UC 1, which is an office building, has a peak heating load of approximately 200 kW, while in summer it has a peak cooling load of 580 kW. The accumulated yearly energy demand of substation 1 is approximately 457 MWh, of which 137 MWh is the energy used for space cooling, and 320 MWh is used for space heating and domestic hot water production. It is worth noting that, though substation experiences higher peak loads for space cooling, it only represents about 30 % of the total energy demand.

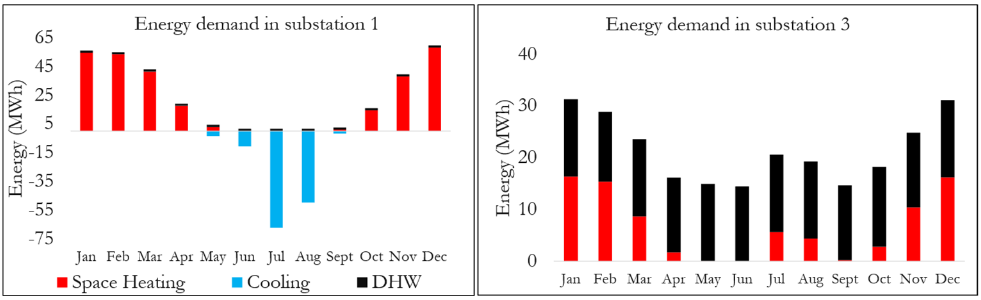

Figure 4.2 Monthly thermal energy demand profile for studied substations

Similarly, it is evident from the presented bar graph that UC 3, which comprises apartments, does not have a cooling need during the summer period. The accumulated yearly heating energy demand is approximately 250 MWh, of which 176 MWh is used for domestic hot water production, comprising slightly above 2/3 of the total energy use of the substation. It is noted that the standardized value of DHW requirement advised by the Swedish building code, of 2 kWh/ m^2 per year in office building and 20 kWh/ m^2 per year for residential building (Svensson, 2016) has been used to estimate the energy use for DHW production; These thermal demand profiles were provided by the developer (Granitor AB) of EOS community, the energy modelling for which is beyond the scope of this thesis.

4.3 Geo Energy Sharing System (GESS)

A two-pipe system facilitates connection between substations and is termed the Geo Energy Sharing System (GESS). The central distribution network consists of two pipes, which serve as both supply and return nodes for substations. To analyse the functional attributes of this system including energy sharing through the connection between two substations, namely UC 1 and UC 3, a Modelica model was built up which is shown in Figure 4.3. As shown in Figure 4.3, two distribution pipes are connected via check valves at both ends, ensuring a unidirectional flow of the working fluid. The return node of UC 3 is connected immediately before the supply node for UC 1. Similarly, the supply node of UC 3 is connected immediately after the return node of UC 1.

The arrangement of the substation connection to the GESS is of particular importance here. The above-presented connection ensures the most favourable inlet temperature for both substations during sharing. As an example, the high-temperature return fluid to GESS from UC 1 during its active cooling operation is immediately used by UC 3 to meet its heating demand. Similarly, the cold return from UC 3 because of its heating demand is used by UC 1, ensuring favourable fluid inlet conditions for both substations.

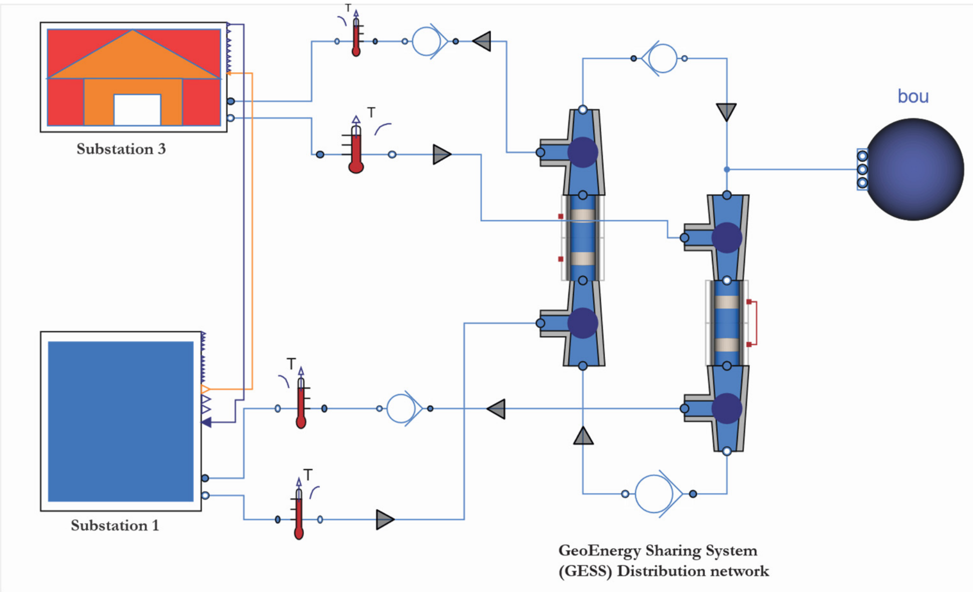

Figure 4.3 Modelica representation of two substations (UC 1 and UC 3) connected through GESS

4.4 Design parameters and simulation cases

The analysis of a technical performance of a geothermal energy network is conducted by analysing its key performance characteristics. Hence, relevant key performance indicators were chosen during the design phase of modelling and simulation. The chosen key performance indicators were the coefficient of performance of the overall system (SCOP), net thermal energy extracted and injected from/to the borefield, average fluid temperature from the borefield, average fluid temperature in the distribution network (GESS), and operational emissions of the system.

The model parameters and post-processing output variables were set up accordingly to gather data on above mentioned indicators. The design parameters used for the two different modelling approaches are shown in Table 3 and are described in detail in the appended papers, Paper II and Paper III. Paper II describes the thermos-hydraulic and control models for different system components used for analysis. One of the major modelling differences in the two appended papers is the modelling approach opted for in the modelling of the heat pump unit.

In paper II, the heat pump, which is one of the major components for energy transfer in the substation, was modelled using a Carnot efficiency model. Two heat pumps were modelled to represent the heating effect of seven actual heat pumps installed. The model assumed that the heat pump delivered instantaneous building heating demand at a fixed outgoing temperature of 45°C for space heating and 57°C for DHW demand. In simpler terms, a heat pump produces the same heating effect as prescribed by demand profiles at stated temperatures. The coefficient of performance was scaled based on the prescribed Carnot efficiency, instantaneous heat output and compressor power.

In paper III, the heat pump was modelled using a data-driven multi-variable equation, in other words, a data-driven digital twin based on manufacturer-stated heat output and electrical consumption. Further, all seven installed heat pumps were modelled and individually controlled based on the required temperature in the space heating and domestic hot water circuit. The setpoint for DHW was fixed to 55°C. In the case of space heating, a temperature-compensated curve was used to prescribe the space heating setpoint. A Proportional-Integral (PI) control algorithm controlled the number of heat pumps operating at any point to deliver the required temperature in the distribution circuit. A detailed description of the control algorithm for heat pumps based on DHW and space heating is presented in Paper III.

Table 3 Design parameters used for the two modelling approaches

Description	**Setpoint/Representative values**		
	Paper II	**Paper III**	**Unit**
Design supply temperature for space heating	45	Based on a demand-based temperature compensated curve varying between 20 to 45	°C
Design supply temperature for space cooling	16	Demand-based temperature varying between 14 to 18	°C
Design supply temperature for domestic hot water	57	55	°C
Evaporator temperature difference (outlet – inlet)	−4	-3	K
Condenser temperature difference (outlet – inlet)	10	8	K
Pressure drops over the condenser and evaporator	30 000	Based on the heat pump manufacturer (21000/16000)	Pa
Carnot efficiency (scaled based on the actual installed heat pump)	65	Ratio of actual heat output over compressor power	%
Pump hydraulic and motor efficiencies	70	Based on the manufacturer's stated performance curve for power and volume flow rate	%
Number of boreholes in substation 1/substation 2	12/30	12/30	–
Borehole depth in substation 1/substation 2	285/300	285/300	m
Borehole burial depth (active groundwater level)	5	5	m
Borehole radius	0.07	0.07	m
U-tube pipe outer diameter	45	45	mm
Pressure losses over the borehole	250	250	Pa/m
Borehole thermal resistance*	0.1	0.1	(m·K/W)
Ground thermal conductivity*	2	2	W/(m·K)
Undisturbed ground temperature*	10.3	10.3	°C
Load aggregation time resolution	3600	3600	s
Number of cells per aggregation level	5	5	–
Distribution network (GESS)			
Pipe total length	184	184	m
Pipe hydraulic diameter	180	180	mm
Pipe surface roughness	0.025	0.025	mm
Pipe thermal conductivity	0.17	0.17	W/(m·K)
Burial depth	1.02	1.02	m
Pipe spacing (Outer dimension)	0.5	0.5	m

Three different simulation scenarios were created to understand the energy interaction between substations. Standalone simulations of each substation were carried out as the first scenario. These simulations were run for 25 25-year period to observe the accumulated SCOP over the years and average fluid temperatures from the borefield. These simulations presented an understanding of the energy balance of the borefield and the gradual loss of SCOP over the years.

The second and third sets of simulations were conducted to analyse energy interaction between two substations. The two substations were connected through GESS, where the geothermal sharing control system is presented in the section 3.3.2, was responsible for ensuring energy exchange between substations. Since cooling demand at substation 1 (UC 1) was the driving factor for energy exchange, two scenarios for cooling supply temperature were simulated. The first scenario was a low temperature cooling condition where the design cooling supply temperature was based on a demand-based temperature curve varying between 10°C to 14°C. In the second case, a high temperature cooling setup was simulated with a design cooling supply regulated between 14°C to 18°C. These two scenarios essentially helped analyse the free cooling possibilities through GESS and the enhancement in SCOP of overall LTDN. A detailed description of different simulation scenarios is presented in the appended papers.

5 Results and Discussion

In this chapter, the key results and observations from simulation and interview studies are presented. First, the results from modelling and simulation studies are presented relying on key performance indicators, namely System Coefficient of Performance (SCOP), net energy balance of the borefield and fluid temperature in the borefield, and distribution network to analyse and describe the technical performance of the studied system. Secondly, a set of comprehensive observations from literature and interview studies conducted to identify the prosumers' perspectives on modern energy infrastructure based on a low-temperature district network is discussed.

5.1 Modelling and Simulation

The thesis investigated both standalone and networked operation of substations. Since each substation has the potential to operate independently of the other, system performance and energy balance over the borefield for standalone operation were investigated and compared with that of networked operation for possible exchange of energy, and eventual enhancements on system performance because of the synergetic effect of two substations.

This section is adapted from the appended Paper II and Paper III.

5.1.1 System performance

It has been previously discussed that in this study, the LTDN consists of two substations, where UC 1 is connected to two office buildings and UC 3 is connected to one residential building. Additionally, UC 1 consists of 7 decentralised heat pumps, whereas UC 3 consists of 2 decentralised heat pumps. Over the operation period, individual heat pumps will have their instantaneous COP because of the varying fluid inlet and outlet conditions.

As the main objective is to compare performance at system levels rather than at component levels, the accumulated system coefficient of performance

(SCOP), which is the ratio of total delivered heating effect and electrical power consumed by heat pumps at any point, is used as a performance metric and is presented in Figure 5.1. In the figure, the accumulated SCOP over a year for standalone and networked operation of a substation is presented, where standalone refers to an independently run substation and networked represents two substations connected via the GESS system. A glance at the presented figure shows that, when two substations are connected to operate as a network, the overall SCOP of both substations increases.

There are two key takeaways from the presented graph. First, though resulting in an annual electrical energy saving of 0.1 MWh, the SCOP of 3.4, in networked operation for substation 3 (residential building), is not considerably higher than that for its standalone operation. This is attributed to its operation for dominantly DHW production. At higher outgoing fluid temperatures (55°C and above) on the condenser, the COP of the heat pump drops considerably and is approximately 3.3. This correlates with the manufacturer's data for heat pump performance presented in Figure 3.1 and shows a high accuracy of the mathematical model.

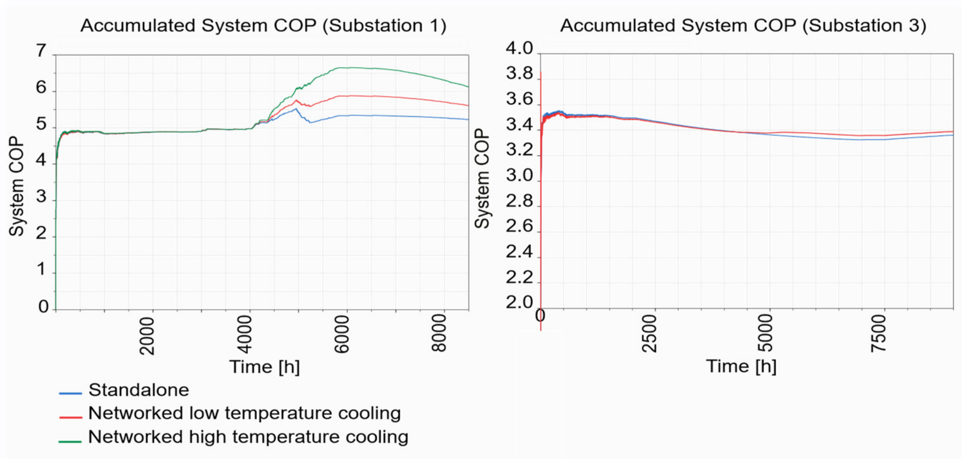

Figure 5.1 Overall system performance considering SCOP as key performance indicator (Left: SCOP for residential building; Right: SCOP for office building)

The second key takeaway is an increase in free cooling on Substation 1 during networked operation. SCOP for three different scenarios is presented in Figure 5.1. The design considerations for networked low temperature cooling and networked high temperature cooling have been described in section 4.4, where different cooling setpoints are used to denote the two scenarios. With a high temperature cooling setpoint (14°C to 18°C) the working fluid from GESS offers higher potential for free cooling of UC 1, leading to a higher SCOP. In a networked operation mode, a year-round accumulated SCOP of 6.2 can be obtained on UC 1, which is approximately 1 unit higher than the SCOP of the standalone mode. The increase in SCOP is directly proportional to a lowered electrical consumption of the heat pumps. This results in a reduction of 12 MWh of electrical energy required to operate the heat pumps. Compared to the energy use during standalone operation (85 MWh), this correlates to a 14 % reduction in electrical energy consumption and has been comprehensively discussed in *paper III*.

5.1.2 Borefield energy balance

In this study, borefields are one of the major components of the geothermal energy network as they not only serve as an energy source and sink but also as an energy balancing and storage unit. As shown in the demand profiles in Figure 4.2, the net year-round heating energy requirement of both substations are higher than the cooling energy demand. In such a scenario, when substations are run as a standalone entity, net heat extraction from the borefield is higher than the heat injection. This operational scenario thus leads to depletion of the borefields' thermal core and, in turn, reduces their life span. The thermal depletion of the borefield can be observed through the decreasing fluid temperature trend from the borefield, shown with blue curves in Figure 5.2.

The temperature profiles in Figure 5.2 describe how fluid temperatures from the borefield evolve over a 25-year period. The most interesting highlight of these temperature profiles is the reasonably high average fluid temperature reaching as high as 30°C on UC 1, which is the main basis for energy sharing between the two substations. The benefits of this synergy can be visualised through the SCOP profiles presented in Figure 5.1. The minimum and maximum brine temperature from the borefield over 25-year period is of particular importance as it has a major impact on the performance of heat pumps.

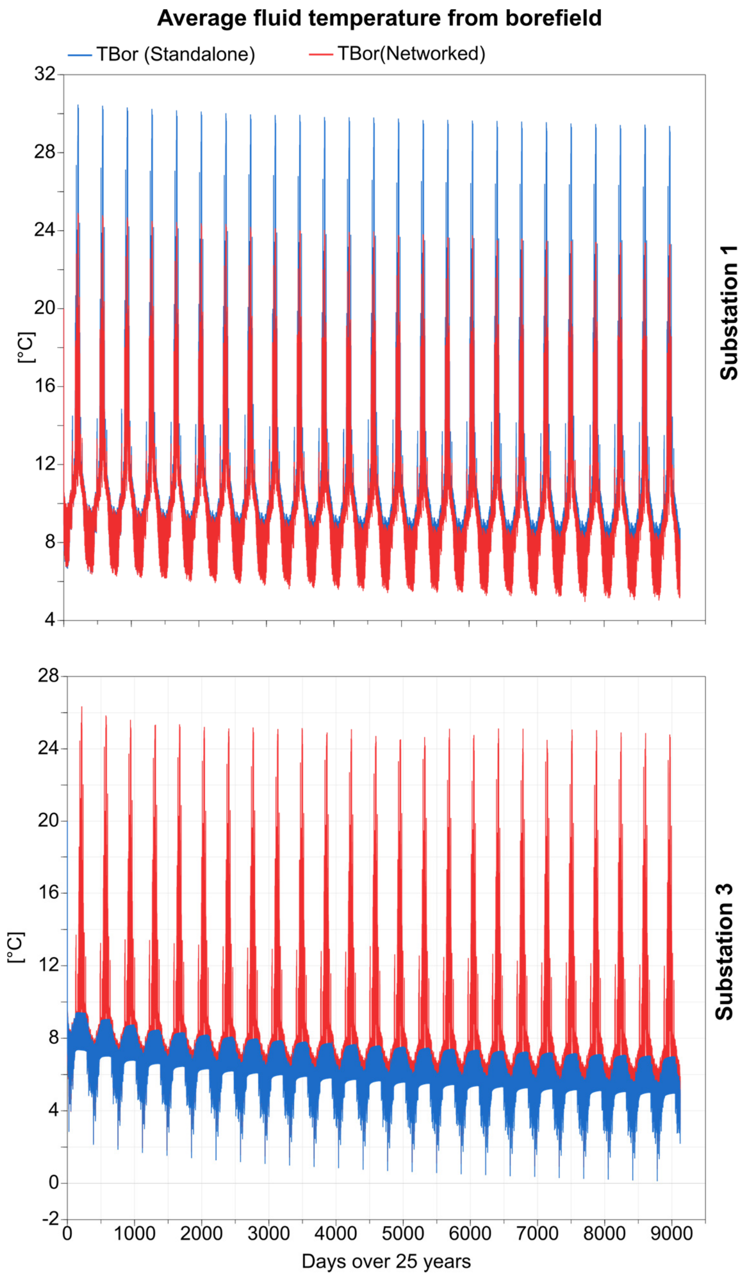

Figure 5.2 Average fluid temperature profile for substation 1 and substation 3 over 25 years (Chaulagain et al., 2025)

In case of a networked operation, it was observed that brine temperature is largely affected due to energy sharing with UC1 and reaches as high as 26°C in year 1 and a maximum of approximately 24°C by the 25th year. The high average brine temperature in UC 1 is the result of replenishment of the borefield with excess condenser heat output from the heat pumps during active cooling operation.

Figure 5.3 (A) and (B) depicts the hourly thermal load (kW) values and net energy extraction (MWh) from the borefield in UC 1 and UC 3, respectively. The positive thermal load refers to the heat extraction rate, and the negative thermal load refers to the heat injection rate into the borefield. The parameter "net energy extracted" refers to the difference between the energy extracted and injected into the borefield. Since both substations have dominant heating demands, the net energy extracted is a positive value.

As seen in Figure 5.3 (A), when the UC 1 is running in a standalone mode, heat is injected at the rate of almost 800 kW into the borefield, resulting in high brine temperature as presented in Figure 5.2. As a result of this high heat injection, it was observed that around mid-August (ca. 6000 hours in Figure 5.3) the net energy extracted from the borefield tends towards zero, indicating net zero energy extraction from the borefield or energy balance, in other words. The practical implication of this is observed with an operational longevity for the borefield.

It is evident from Figure 5.3 (B) that heat is injected into the borefield of UC 3 during summer because of networked energy sharing between two substations. This is the excess heat from the office building shared due to the synergetic coupling. One most interesting observation to consider is that the net energy extracted from the borefield for UC 3 when operating as a standalone entity was around 180 MWh, while the same is 135 MWh as a networked substation. This is a reduction of 45 MWh net energy extraction, which is met by the additional 50 MWh energy burden on the borefield of UC 1 as discussed earlier. This quantifies the load and energy sharing between two substations through their borefields. The net benefit with sharing can further be quantified with the amount of reduction in the energy demand to run the heat pumps and replenishment of the borefield core of each substation.

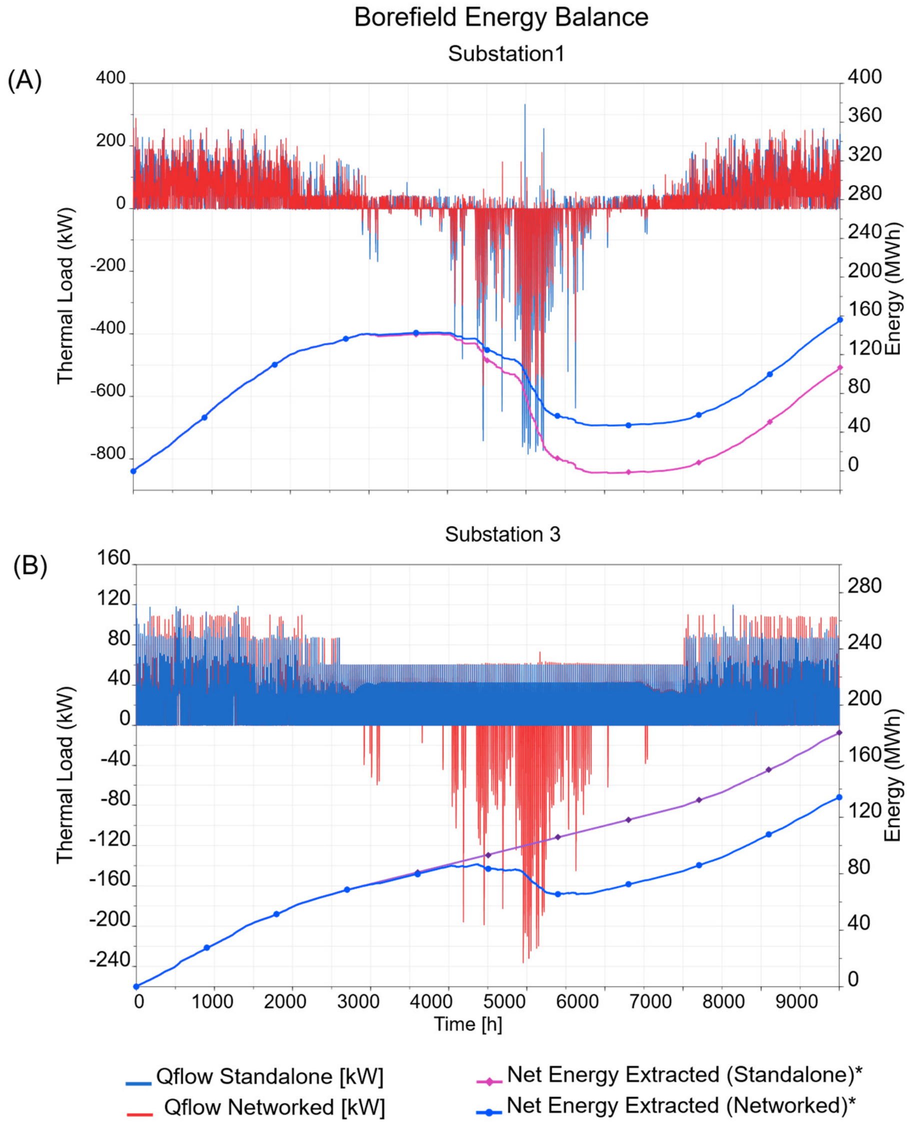

Figure 5.3 Hourly load and energy balance for borefield of Substation 1 (A) and Substation 3 (B) (Chaulagain et al., 2025)

5.1.3 Operational environmental impact

Identification of the decarbonisation potential of the low-temperature geothermal energy network was one of the guiding research questions. Thus, a what-if scenario was hypothesised and the studied LTDN was compared against potential district heating and cooling solutions/services readily available at the community's vicinity. For heating, the district heating of Malmö was considered an alternative source. For cooling, an air source heat pump with a COP of 4 was considered as an alternative source. The chosen metric for comparison was global warming potential, considering operational emissions for different energy sources. The emissions factors used in this comparison for electricity are 0.037 kgCO2 equivalent per kWh, 0.056 kgCO2 equivalent per kWh for district heating average in Sweden (*Swedish National Board of Housing, Building and Planning (2024)*, 2024), and 0.137 kgCO2 equivalent per kWh for district heating in Malmö region (*Energiföretagen Sverige*, 2025).

The operational emissions associated with the LTDN at EOS are drastically lower than the potential alternatives, as presented in Figure 5.4. Specifically, the LTDN's emissions (5.85 tonnes of CO2 eq.) represent only 7 % of the emissions compared to the existing district heating of Malmö (84.05 tonnes of CO2 eq.) This indicates a significant decarbonization potential and motivation for transitioning to modern LTDN technology for the heating and cooling sector.

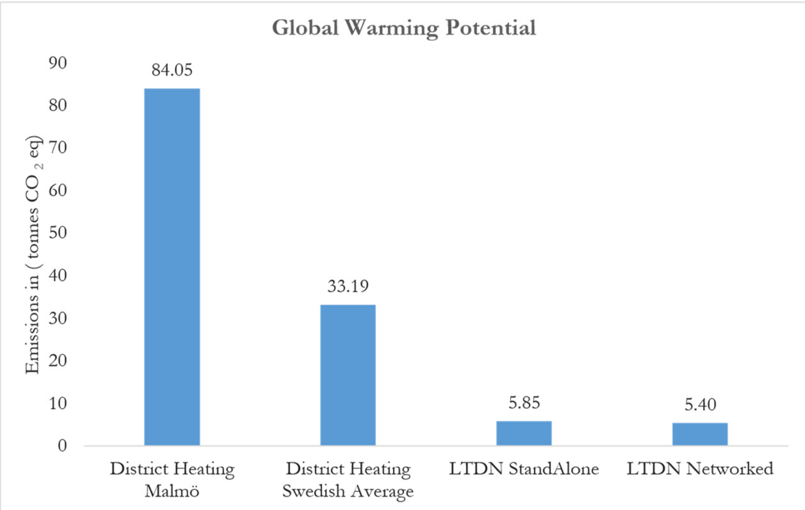

Figure 5.4 Evaluation of operational emissions for proposed LTDN and potential alternative heating solutions for EOS (Chaulagain et al., 2025)

Additionally, the benefit of the energy coupling or sharing system is also observed in the form of further reduction in emissions. It was found that connecting substations to operate as a network would provide an additional 10 % reduction in emissions compared to standalone operation. It is however important to note that these findings are based on annual operational emissions and can only be complemented through a complete life cycle assessment considering all life cycle stages of LTDN.

5.2 Interview Studies

This section is adapted from appended Paper IV.

It was indicated in Chapter 2 that an interview study was conducted to identify the perspectives of professionals on changing dynamics of energy infrastructure and how users can be motivated to participate as prosumers in such modern energy networks. Besides the technical possibilities and viability of a modern energy network, its wider acceptance and motivation for transition rely on various societal aspects of its application. Through literature reviews and interview studies, it was found that the business models, ownership structures and policy frameworks adopted for the modern energy networks, affects the involvement of stakeholders.

It was found that, aspects of business models, ownership structures and underlying legal, regulatory frameworks are not isolated but deeply interconnected and their intricate interplay collectively impacts the integration of prosumers, stakeholders. The following sections presents the expert opinions and perspectives that contribute for stakeholders' engagement and active participation.

5.2.1 Business models, ownership and policy frameworks

In the context of modern energy systems based on geothermal energy networks, a possibility for two-way flow of heat exists. Heat energy can flow from distribution networks to individual households and back. A technical design solution for the same was also discussed in the preceding chapter. "Consumers" of heat, as in the traditional approach, can also be the "producers" of heat and thus are termed as "prosumers" in modern energy infrastructure. The concept of "prosumers" is established within the power market through the EU Clean Energy Package. However, in the Swedish context, one regulatory/policy gap identified was the lack of an explicit definition of "heat prosumer". This creates a legal uncertainty, whether they should be considered as "energy consumers" or "energy producers", making it further difficult to establish clear rights and responsibilities between the stakeholders involved.

The other important aspect is the distribution of risks and responsibilities of the energy network. In practice, risks and responsibilities are automatically associated based on the ownership deeds of the parties involved. Since geothermal energy networks are decentralised energy networks which are formed in smaller groups and may be connected to realise a larger network, the ownership structure of such smaller local networks plays a vital role in decision-making, financing and prosumer participation.

The above attributes of financing, decision-making are essentially answered by "Who owns the network?" Most of the interviewees expressed that a co-ownership model among the prosumers is beneficial for such local networks. The risks and responsibilities of the grid, including its operation and maintenance, are split among the users or handled by a board of community members. Though securing capital and technical expertise to develop and operate the system could be potentially challenging compared to established utilities/energy companies, local self-consumption is promoted as prosumers are the owners, and network operation for shared benefits can be maximised with this approach.

Some interviewees brought out the term "joint ownership" instead of co-ownership to describe a model which reaps the benefits of a co-ownership model together with the access to low-interest public financing, loan guarantees, and technical expertise enjoyed by established energy companies. A case of Denmark was presented to describe this scenario. The interviewee stated that:

"District heating companies are non-profit and publicly owned (by consumers or municipalities), with access to low-interest public financing and loan guarantees. They may have a monopoly, but cannot make a profit, while the value chain behind them (developers) can. This model is unique to Denmark." He also noted that "district heating companies formally cannot own the units inside the building as they are on private property, though some still do for unknown reasons. In the deep geothermal project in Aarhus, the geothermal company Innargi offers "energy-as-a-service" where they take the drilling risk and the construction costs, and the district heating company or consumer-owned utility simply purchases energy, having no ownership of the geothermal infrastructure. This approach de-risks investment for consumer-owned utilities and could, in principle, be extended to other heat sources than geothermal."

Business model is another intricate dimension of this trilogy. In basic terminology, a business model essentially describes the relationship between how resources are utilised to create value for the customers to generate revenue for the business. A Peer-to-Peer (P2P) heat trading model was described as a possible alternative, as this has been extensively developed in the power sector, and experts believe that it readily applied to the heat sector. A non-monetary P2P model was described by the developers of Embassy of Sharing. This model is typical for Embassy of Sharing and is currently in the investigation phase. As stated by one of the interviewees:

"Imagine a neighbourhood where one building with excess thermal heat can directly sell it to another building needing heat. The technology, LTDN at Embassy of Sharing, exists now, but the business model for transaction and billing is complex. If the volume of P2P heat exchange is not that huge, rather than establishing infrastructure and manpower for such complex and financially small transactions, maybe it's beneficial to give it for free. Taking heat from those who have surplus to give to those who are in deficit."

This approach resembles more like the story of "Robin-Hood", "taking from the rich and giving to the poor". This non-monetary heat sharing model is thus being presented as a "Robin-Hood Model" in energy sharing.

In the conventional district heating and cooling business, "heat" is a commodity where users pay for units of used heating and cooling energy. Energy companies produce heat /coolth centrally and distribute via central pipe networks to the households, where they are charged for the consumed energy. Each household owns the equipment (radiators) inside their house and is responsible for its maintenance. The ground for this model lies in a one-way flow of heat where utilities push their business commodity (heat) to customers.

A slight variation to the conventional business model is "Energy-as-a-service", interchangeably termed as "Heat-as-a-service", which is one of the growing business models in modern geothermal district networks. Compared to the conventional model, every component, including network pipes, radiators, heat pumps, circulation pumps and other auxiliary components of LTDN, is owned, managed, and operated by the energy company. Prosumers are not required to contribute hefty capital investment for the installation of heat pumps, radiators and other units. This simplifies things for the prosumers, together with risk mitigation and convenience.

For a willing set of prosumers, there may also be an opportunity to own the infrastructure with a "heat-as-a-service" model. One possible motivation could be the technical life and financial depreciation of the system. Usually, the technical life of distribution networks, which are a set of Polyethylene (PE) pipes (above 100 years), is largely greater than their economic depreciation period (roughly 30 years to 40 years). Thus, there is a potential opportunity for a continuous revenue stream from such investments, which prosumers can capitalise on.

5.2.2 Barriers and motivations for prosumer involvement

The primary driver for prosumer involvement in a modern low temperature district heating and cooling network was found to be "cost", i.e. people want to reduce their heating and cooling bills. So, they are naturally motivated to any energy solutions that can contribute to reducing the energy bills. In that context, the cost savings potential of LTDN through energy sharing was considered a motivation for prosumer involvement. Furthermore, the added value of cooling, lowered carbon footprint, and energy independence were considered as potential motivators.

The technical complexity and perceived higher upfront cost to install heat pumps, solar thermal systems, borefield, etc., for general households was considered as a potential barrier for participation. A simple plug-and-play solution where the households do not have to worry about the technicalities of the system, and with clear financial benefits, is what most households opt for. To reiterate, money and convenience are what people ultimately base their decision on when it comes to transitioning to a new energy system.

The lack of explicit legal, regulatory frameworks to govern prosumer-integrated district heating and cooling networks and a lack of consistent financial incentives for setup and operation were considered a major setback for modern energy infrastructure.

5.3 Concluding discussion

The guiding hypothesis of this thesis was that the transition towards energy independence, reduction in GHG emissions and development of a modern energy infrastructure necessitates a fundamental re-evaluation and restructuring of how energy is generated, distributed and consumed.

Revisiting the first and the second research questions, which aimed to answer the technicalities of energy exchange between properties and the decarbonization potential of such networks, the case study showed that, with adoption of local shallow geothermal borefields, and decentralized heat pumps at building levels, a sectoral coupling of electricity and heat sector can be established where a pipe network connecting different buildings facilitate energy exchange with each other.

The results evidently showed that a low-temperature geothermal energy network can serve as a platform for modern energy infrastructure where multiple energy sources can interact. Operating with a lower distribution loss compared to a conventional district network, and the synergetic effect of energy sharing resulting in lowered active energy use, this infrastructure has the potential to significantly contribute to the decarbonization of space heating and cooling.

The integration of low-grade thermal sources, such as the shallow geothermal borefields and waste heat to/from buildings, presented in this research show promising potential for network flexibility and will potentially define the future energy infrastructure. This has also been presented and advocated by professionals and academics (Gadd et al., n.d.; Lygnerud et al., 2023; Werner, 2017). Application of these networks potentially enhances the robustness and reliability of energy infrastructure at the local level. A "system-of-systems" can be formed by combining those local networks to realise a larger energy infrastructure, which, coupled with the power sector, potentially strengthen flexibility and boost energy sufficiency at regional and national levels.

Additionally, though a clear benefit of heat pumps' use in this modern network is presented in this thesis, one overarching discussion could be on the mere shifting of the emission source in future energy networks. Heat pumps, being one of the key components of this infrastructure, its use entails that the emissions source is shifted from conventional biomass, waste incineration, and fossil-based combined heat and power plants to the local and national electricity mix. That is, the cleaner the electricity mix, the more decarbonised the modern energy infrastructure.

6 Conclusion

This thesis aimed to demonstrate a low-temperature geothermal network as a platform for modern energy infrastructure where sectoral coupling of energy sources and energy sharing is envisaged. To achieve this aim, this research explored the two dimensions of a low-temperature geothermal energy network. The first facet was to present a technical design of a low-temperature geothermal energy network guided to identify its system performance, energy sharing potential and decarbonization potential. A model-based systems engineering methodology was opted to develop a digital twin of the network using the Modelica modelling language. The developed digital twin was used to analyse the technical performance of the system using three key performance indicators.

The study showed a geothermal energy sharing control system which ensured a suitable fluid source temperature for connected substations with opposing thermal demands. The networked operation of two substations with energy sharing of heating and cooling was found to enhance the overall SCOP of the systems in both substations. The year-round accumulated SCOP was found to increase from 5.2 to 6.2 for an office building substation with cooling demands and from 3.3 to 3.4 for a residential building substation with dominant space heating and domestic hot water demand. In terms of energy use, the increased SCOP, because of energy sharing, contributed to reducing the electrical energy used to operate the heat pumps in the substation by approximately 14 %.

Simultaneously, energy sharing through borefields contributed to the recharging of the residential buildings' borefields. The study showed that annually, 45 MWh of energy can potentially be deposited into the residential buildings' borefield because of thermal exchange between two buildings. Residential buildings in general have higher net heat extraction from the borefield, mostly due to higher heating demand for space heating and DHW production, leading to its' rapid depletion. Recharging of the borefield through a connected substation, as in this context, contributes to its extended service life.

Another key takeaway was the decarbonisation potential of the studied system. Through impact evaluation considering operation energy use, it was identified that in comparison to readily available traditional district heating and cooling solutions at the study location, emissions from the presented LTDN were only 7 %. These findings emphasise the potential for substantial environmental benefits with the adoption of such systems and the decarbonization of urban heating and cooling infrastructure.

The second facet of this study investigated the societal aspects of LTDN, focusing more on how ownership structures, business models and policy frameworks affected or motivated wider public participation in the role of prosumers for this modern energy infrastructure. The study indicated that the number of prosumers is expected to rise in the future, with co-operative ownership models anticipated to gain popularity in future energy systems. In addition to peer-to-peer heat trading models, as widely adopted in the power sector, heat-as-a-service business models were considered as potential approaches to enhance public involvement and acceptance.

Additionally, the primary motivators were identified as network ownership, reduced energy costs, and environmental benefits or "green value" associated with modern energy infrastructure, such as the presented low-temperature geothermal energy network. Alternatively, the study also found that, absence of a clear legal definition of "waste heat" and its recognition as a financial asset in the case of residential buildings was considered a major barrier for participation of "heat prosumers". Furthermore, a lack of an explicit regulatory framework defining the "heat prosumers" was perceived as a barrier, as it may lead to prosumers being regulated as energy suppliers, which potentially amplifies legal restrictions and administrative obligations.

6.1 Research limitations

This thesis employed digital twin modelling of a low-temperature district network to analyse its system performance and investigate the possibilities for energy coupling and energy sharing between properties. However, several limitations related to modelling of the network were encountered during the research.

First, a multi-variate regression model of the heat pump was developed using the manufacturer's data with fluid source temperature ranging between 0°C to 10°C. As discussed earlier, while this model performs with high accuracy within this operating range, heat pump performance may not be represented accurately outside this temperature range.

The energy sharing between two substation was originally intended to be validated with real-time measurements from substations. However, owing to the delays is construction of those substations, this validation was not conducted and thus will be addressed in future research.

While the study demonstrated immediate benefits of coupling electricity and heat sector through the heat pumps such as increased system efficiency, and seasonal thermal storage, the author recognizes that only a detailed economic and environmental impact analysis of the overall network configuration will provide a comprehensive picture of its viability. Conducting such an analysis was beyond the scope of this thesis.

Finally, Modelica models of system components including control valves, circulation pumps, borefield and pipe section, available in the "Modelica Building Library" were used in this study. The reliability and accuracy of these component models have been verified by their developers and therefore fall outside the scope of this research for independent re-validation.

7 Future Research

This research has investigated the technical design solution to couple the heat and power sectors through the use of heat pumps on a geothermal energy network. Based on this groundwork/ foundation, future research shall investigate deeper into sector coupling of multiple energy sources, including photovoltaic, solar thermal, waste heat from industries, residential, and other potential renewable energy sources. The intermittent nature of energy from renewable sources needs to be efficiently harvested. Thus, future research shall be guided to develop an efficient, automated energy planning control mechanism that prioritises energy sources based on their availability and intermittent nature.

Considering an energy community at a local level, the research shall explore available energy resources for a given place and time and prioritise these resources based on their intermittent nature, either to meet instantaneous user demand or allocate for thermal storage. Cities of today contain both energy producers and consumers, which can be coupled through a robust sectoral coupling mechanism as presented in this study. The future research will apply this knowledge to see how the algorithm can be used to enable energy resilience on a local basis, using existing infrastructure.

As identified from the interview studies, energy cost, environmental benefits and energy independence are some of the major motivators for prosumers' participation. Thus, future research on sectoral coupling mechanisms will be guided to prioritise energy sources based on their availability, contribution to emissions, and cost for the immediate user. As such, the cost-effective and low-emission energy source is prioritised to meet the instantaneous demand, and the other sources are allocated for short-term and long-term storage. This is expected to address energy management issues with active prosumers' involvement in modern energy infrastructure. Additionally, local production, sharing and prioritising energy sources for immediate and future use will enhance energy affordability, energy security and energy efficiency.

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