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District heating and cooling systems transition

Evaluation of current challenges and future possibilities

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221 00 Lund
+46 46-222 00 00

District heating and cooling systems transition

Evaluation of current challenges and future possibilities

MARWAN ABUGABBARA

FACULTY OF ENGINEERING | LUND UNIVERSITY



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Evaluation of current challenges and future possibilities

Marwan Abugabbara



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DOCTORAL THESIS

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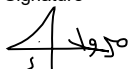
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District heating and cooling systems transition

Evaluation of current challenges and future possibilities

Marwan Abugabbara



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In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarises the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

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Lund University, Faculty of Engineering
Department of Building and Environmental Technology
Division of Building Services
SE-221 00 Lund
Sweden

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MADE IN SWEDEN 

*To my mother,
Maisa Farrag
(1954 – 2013)*

*To my father,
Ya'koub Abujbara
(1946 – 1999)*

“Be grateful to Me and to your parents;
to Me is the final destination.”

[The Noble Quran, 31:14]

﴿أَنْ أَشْكُرَ لِي وَلِوَالِدَيْكَ إِلَى الْمَصِيرِ﴾

[لُقْمَانَ : ١٤]

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Reaching this milestone would not have been possible without the struggle my parents had to go through to prepare me for the long road ahead. My father experienced the ethnic cleansing of Palestine that started in 1948 when he was uprooted from his home, pushed into the sea, and sent to life in exile. Alone, my mother carried out the difficult task of raising four small Palestinian refugees with restricted movement and limited access to healthcare and education. She succeeded in her task thanks to her unshakable faith and her Egyptian natural talent for preservation. Together, my parents embodied struggle in their life, remained steadfast, and became more loving parents. They have an immeasurable influence on my life as all my work shows parts of them.

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Marwan Abugabbara
Lund, Rabi' al-Awwal 1445
September 2023

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Abstract

District heating and cooling systems offer a cost-effective and secure supply of heating and cooling to connected buildings. They are widely recognised as a key solution to decarbonise the building sector due to their high potential of integrating renewable energy sources. The systems traditionally involved generating heating and cooling centrally with distribution through separate pipes before delivery to end-customers. Nowadays, advanced concepts of district heating and cooling feature, for example, integration of low-enthalpy renewable energy sources such as shallow geothermal, simultaneous supply of heating and cooling through the same piping network, and combining district and heat pump technologies. Despite their high potential in achieving carbon neutrality, such advanced concepts have major technical challenges, and their practical implications need to be thoroughly evaluated.

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the implications of district heating and cooling systems transition from technical, social, and political aspects.

The thesis adds to the existing body of knowledge on district heating and cooling in several dimensions. The application of the developed model on the analysed systems reveals several benefits for new technologies of district heating and cooling including but not limited to, electrification of thermal networks using decentralised heat pumps, sharing energy flows between connected buildings, and reducing network heat losses in combined heating and cooling systems. Moreover, the model application shows that the newly developed analytical method yields a fast, yet accurate, modelling approach to evaluate the hydraulic states in bidirectional networks with any number of connected prosumers.

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Popular science summary

District heating and cooling systems provide heating and cooling to buildings through a piping network. In traditional district heating applications, a warm fluid is pumped from a heat production plant into the network to reach all connected buildings. A similar process happens for district cooling applications but for cold fluid production and distribution. One advantage of these systems is that all buildings in the connected network can have a safe and secure energy supply. Moreover, due to economies of scales and scope, the efficiency of the energy system increases and therefore the CO₂ emissions decrease.

One major issue with district systems is the problem of heat losses through the piping network. As the distance between the plant and the last connected building becomes longer, the more losses there are. At the same time, the plant must always produce fluid temperatures that satisfy the requirements of all connected buildings. This is why research on district systems aims to develop technologies that work with low fluid temperatures in the network.

Reducing the network temperature has several other advantages. It opens opportunities to use renewable energy sources that were not possible before. For example, using the solar energy or the heat stored in the ground, or simply the air around us to heat up or cool down our buildings have all

become possible. However, achieving this transition within the system is not easy due to several challenges.

One challenge is linked to the fluid temperature we get from the renewable sources which is not always suitable for direct heating and cooling. A possible solution is to install heat pumps in each building. Heat pumps have a similar working principle as water pumps. Instead of lifting water from one level to another, heat pumps left the fluid temperature in the pipe from one temperature level to another. Combining district systems and heat pumps can achieve more energy-efficient systems, reduce carbon emissions even further, and ensure comfort in buildings. However, the complexity of the system and its capital and maintenance costs may increase.

Another challenge is related to the difficulty of predicting how these new technologies would work in reality. Computer models can help us to do research on such systems and investigate their expected behaviour before they are built. We can use these models to run several computer experiments to answer different questions about the system design and expected performance, and even to tell us how much the system would approximately cost throughout its life cycle.

This thesis will try to address these challenges by presenting a simulation model for new technologies of district heating and cooling. The developed models are presented as graphical icons that illustrate the actual physical components of the system. All equations that describe the behaviour of the components are contained inside these icons. Once models for small components are built, models for large district systems can be composed by connecting the different components. This is the method that has been used to develop computer models using the Modelica language which is suitable for modelling large and complex systems like district heating and cooling.

After presenting the developed model for simulating advanced concepts of district heating and cooling, the thesis presents its application to three real-world systems. The research shows that new technologies of district systems with features like low network temperature, simultaneous supply of heating and cooling, and integrated heat pumps have the potential to increase energy efficiency and reduce carbon emissions. More research is still needed to establish industry standards and policy frameworks to facilitate the transition to greener district heating and cooling.

Nomenclature

Terminology

District heating and cooling systems, district heating and cooling networks, and district heating and cooling grids: terms that are used interchangeably throughout the thesis. It is considered sufficient to use only *district heating and cooling* as an all-encompassing term.

Bidirectional low temperature networks: thermal piping networks that can supply simultaneous heating and cooling and where the fluid, or the energy carried by the system, can reverse its direction.

Piping network, piping grid, and piping loop: terms that are used interchangeably throughout the thesis to indicate the heating and cooling distribution system.

Substation, building substation, decentralised substation: a technical room that serves as the link between the district network supply side and the building demand side. The room consists of technical installations such as heat pumps, chillers, heat exchangers, circulation pumps, valves, and domestic distribution pipes. One substation can serve a single or multiple buildings at the same time.

Prosumers: a term which is a portmanteau of the two words heat producers and consumers.

Abbreviations

4GDHC	Fourth-Generation District Heating and Cooling Systems
5GDHC	Fifth-Generation District Heating and Cooling Systems
ASHP	Air-Source Heat Pump
BLTNs	Bidirectional Low Temperature Networks
BHEs	Borehole Heat Exchangers
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
LCC	Life Cycle Costing
SPF	Seasonal Performance Factor

Latin letters

c_f	Pipe friction factor	[-]
c_{f2}	Modified pipe friction factor	[-]
c_p	Specific heat capacity	[J/(kg·K)]
D	Pipe hydraulic diameter	[m]
e	Absolute pipe roughness	[m]
ϵ	Pipe relative roughness	[-]
$f_p(x)$	Dimensionless flow-pressure function	[-]
F	Factor for pipe fitting losses	[-]
k	Fluid resistance factor	[-]
k_0	Constant used in the analytical method	[N]
k_1	Constant used in the analytical method	[-]
k_2	Constant used in the analytical method	[kg/(m·s)]
L	Length	[m]
\dot{m}	Mass flow rate in a pipe segment	[kg/s]
\dot{M}	Prosumer mass flow rate	[kg/s]
P	Power	[W]
\dot{Q}	Heat flow rate	[W]
r	Radius	[m]
R	Thermal resistance	[(m·K)/W]
Re	Reynolds number	[-]
t	Time	[s]
T	Temperature	[K]
u	Fluid velocity	[m/s]
\dot{V}	Volume flow rate	[m ³ /s]

x	Normalised Reynolds number	[-]
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Greek letters

Δp	Pressure drop	[Pa]
ΔT	Temperature difference	[K]
η	Efficiency	[%]
λ	Thermal conductivity	[W/(m·K)]
μ	Fluid dynamic viscosity	[kg/(m·s)]
ν	Number of pipe segments or prosumers	[-]
ρ	Fluid density	[kg/m ³]

Subscripts

bf	Borefield
c	Cooling/cold
comp	Compressor
cond	Condenser
dss	Decentralised substation
evap	Evaporator
f	Fluid
h	Heating
hp	Heat Pump
nom	Nominal
ps	Prosumer
ret	Return
sup	Supply
tr	Transition to turbulent flow regime
tub	Tube
ug	Undisturbed ground
w	Warm

List of publications

This thesis is based on the following peer-reviewed publications which form the appendices and are referred to in the text by their Roman numerals:

- I. Abugabbara, M., Javed, S., Bagge, H., & Johansson, D. (2020). Bibliographic analysis of the recent advancements in modeling and co-simulating the fifth-generation district heating and cooling systems. *Energy and Buildings*, 224, 110260.
- II. Abugabbara, M., Lindhe, J., Javed, S., Bagge, H., & Johansson, D. (2021). Modelica-based simulations of decentralised substations to support decarbonisation of district heating and cooling. *Energy Reports*, 7, 465–472.
- III. Abugabbara, M., Javed, S., & Johansson, D. (2022). A simulation model for the design and analysis of district systems with simultaneous heating and cooling demands. *Energy*, 261, 125245.
- IV. Abugabbara, M., Gehlin, S., Lindhe, J., Axell, M., Holm, D., Johansson, H., ... Javed, S. (2023). How to develop fifth-generation district heating and cooling in Sweden? Application review and best practices proposed by middle agents. *Energy Reports*, 9, 4971–4983.

- V. Claesson, J., Lindhe, J., Abugabbara, M., Johansson, D., & Javed, S. (2023). A new analytical method for modeling network hydraulics in district systems with bidirectional mass and energy flows. Manuscript submitted to *Science and Technology for the Built Environment*.
- VI. Abugabbara, M., Lindhe, J., Javed, S., Johansson, D., & Claesson, J. (2023). Comparative study and validation of a new analytical method for hydraulic modelling of bidirectional low temperature networks. Manuscript submitted to *Energy*.
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The author's contributions:

Paper I: Conceptualisation, Literature review, Methodology, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing.

Paper II: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing.

Paper III: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing.

Paper IV: Conceptualisation, Literature review, Methodology, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review and editing.

Paper V: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Visualisation, Writing – original draft, Writing – review and editing.

Paper VI: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Visualisation, Writing – original draft, Writing – review and editing.

Paper VII: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing.

The additional related publications listed below are not included in this thesis:

- I. Abugabbara, M., & Lindhe, J. (2021). A Novel Method for Designing Fifth-Generation District Heating and Cooling Systems. *In the 10th International Cold Climate Conference, 20-21 April, Tallinn, Estonia.*
- II. Abugabbara, M. (2021). Modelling and Simulation of the Fifth-Generation District Heating and Cooling. *Licentiate Dissertation, Lund University.*
- III. Abugabbara, M., Alberdi-Pagola, M., Javed, S., & Erbs Poulsen, S. (2022). Integration of ground-source heat pumps in combined district heating and cooling networks: A holistic modeling framework. *In European Geothermal Congress, 17-21 October, Berlin, Germany.*
- IV. Bournas, I., Abugabbara, M., Balcerzak, A., Dubois, M.-C., & Javed, S. (2016). Energy renovation of an office building using a holistic design approach. *Journal of Building Engineering, 7*, 194–206.

Chapter 1

Introduction

1.1 Past, present, and the future

District heating and cooling (DHC) are widely recognised as a key solution for decarbonising buildings due to their high potential of integrating renewable energy sources (Lund et al., 2010; Lund et al., 2018). They also offer high security of heating and cooling supply to connected buildings with low investment and maintenance costs for end-customers (Frederiksen and Werner, 2013). The European Union deployed in July 2021 the legislative package *Fit for 55* which provides regulatory instruments to reduce EU's carbon emissions by 55 % compared to 1990's level (European Commission, 2021). The package recognises the key role of DHC in decarbonisation and presents drivers for the growth of the DHC market including, e.g., the planning for local heating and cooling in cities with more than 45,000 inhabitants, the mandatory waste heat recovery for data centres above 1 MW, and the sector integration with electricity and thermal storage (Euroheat & Power, 2023). DHC have gained such recognition due to the continuous development which has been characterised through five generations that are discussed below from three time perspectives reflecting the past, the present,

and the future (Buffa et al., 2019; Lindhe et al., 2022; Lund et al., 2014; Pellegrini and Bianchini, 2018; Revesz et al., 2020; Wirtz et al., 2020a).

In the context of the past, the first district heating (DH) system was built in Lockport in the United States in 1870 to distribute steam for industrial applications and was categorised as the first generation of district technologies (Werner, 2017b). To reduce distribution losses and the risk of explosions, the second generation featured the use of pressurised high temperature water over 100 °C instead of steam. In the 1980s, it became a standard practice for buildings to be heated using water radiators that typically operate at water temperatures around 80 °C. This led to the introduction of the third generation which is dominantly found in today's applications and is distinguished by its prefabricated components.

A similar development stages of district cooling (DC) was identified by Østergaard et al. (2022). The first generation DC was introduced in the 19th century in the United States to supply cooling to the food industry through refrigerants. The second generation DC was established when comfort cooling was supplied to commercial and public buildings using compression or absorption chillers with water as a distribution fluid. The third generation was realised in the 1990s by utilising multiple decentralised sources for cooling production. The previous three generations of DHC mainly use waste heat, biofuels, and fossil fuels with high carbon emissions and limit the integration of renewable energy sources.

In the context of the present, the majority of existing DHC systems are third-generation systems. District systems currently connect 350 million buildings globally and supply more than 65 million people in Europe (Corscadden et al., 2021; IEA, 2022). Although DH supplies only 8 and 12 % of the global and European heat demands of all buildings, there is an increase in the market penetration which has lately reached a 3 % annual increase (Euroheat & Power, 2023). The market share for DH in Sweden is about 60 % of all delivered heat to all buildings and the country plans to make DH fully decarbonised by 2030 by producing heat from bioenergy with carbon capture and storage and waste incineration technologies (Euroheat & Power, 2022; Werner, 2017a). In Denmark, a national framework was outlined to make DH operate with 100 % renewable energy sources (Lund et al., 2010).

District cooling, on the other hand, delivers much smaller amounts that are globally estimated to nearly 83 TWh (Werner, 2017b), of which one-third is delivered in the Middle East. Sweden has the largest DC system in Europe with an installed capacity in 2020 of 270 MW and total delivery of

335 GWh and a pipe length of 250 km (Jangsten, 2020). It is expected that the share of DC in the European market will also increase due to the foreseeable increase in cooling demands in buildings because of warm summer events and to improve comfort (Hitchin et al., 2013).

To meet the needs of the future by improving energy efficiency and reducing the emissions of greenhouse gases, a fourth generation district heating and cooling (4GDHC) was developed in 2014 (Lund et al., 2018; Lund et al., 2014; Østergaard et al., 2022). The fourth generation is widely recognised by its five abilities: 1) to supply low-temperature heating and domestic hot water to energy-efficient buildings, 2) to distribute heating with low network losses, 3) to integrate renewable energy sources, 4) to increase sector coupling between electricity, gas, and thermal networks, and 5) to provide financial and motivation structures for realising future sustainable energy systems. In 2019, a fifth generation district heating and cooling (5GDHC) was developed and a growing use of the term is found in the literature (Bellardi et al., 2023; Buffa et al., 2019; Calise et al., 2022; Gillich et al., 2022; Gjoka et al., 2023). The fifth generation embodies three additional and distinctive features: 1) supplying simultaneous heating and cooling to connected prosumers, 2) combining district and heat pump technologies locally at the building level, and 3) utilising low-enthalpy renewable energy sources such as shallow geothermal for direct supply of cooling and heating.

To date there has been little agreement on the use of standard definitions of future technologies of DHC systems and the issue has been discussed by Sulzer et al. (2021) and Lund et al. (2021). Despite the current lack of accepted definitions for advanced DHC concepts, the different used terms point in one way or another to a common sustainable energy transition. The Dictionary of Energy (Cleveland and Morris, 2015) defines energy transition as: *“a change in the primary form of energy consumption of a given society; e.g., the historic transition from wood to coal and then to oil and gas in industrial Europe.”* A similar change between the five generations of DHC can be established based on the network temperature levels and the type of fuel inputs to describe DHC systems transition.

To support DHC systems transition, modelling and simulation can be employed as a useful tool which can also help accelerate the implementation of advanced DHC systems. Due to the large scale of an actual DHC system, performing experiments using real-world systems would be too expensive and time consuming. Therefore, simulations can be designed to address

specific questions about the system design and the expected system performance under certain operating conditions before the system is built. Accordingly, modelling and simulation can further assist product development, cost reduction, and aggregation of system knowledge between experts and users.

Traditional modelling approaches of DHC systems involve commercial tools such as EBSILON®Professionals (Iqony Solutions GmbH, 2023) and Fluidit™ (Fluidit Oy, 2023) that are designed to target specific customer groups. Having an integrated open-source modelling tool capable of performing different experiments, i.e., simulations would pave the way towards better understanding and increased knowledge about advanced DHC technologies. The development of such a tool to identify current challenges and future possibilities for successful DHC systems transition sets the primary objective of this research.

1.2 Research objectives

The main objective of this research is the development of a simulation model for advanced district heating and cooling systems featuring low network temperature, simultaneous supply of heating and cooling, decentralised heat pumps at the building level, and bidirectional mass and energy flows. The aim is to develop a multi-domain model to include thermal, hydraulic, and control aspects of the system in one integrated environment to provide fast, yet accurate, simulations.

An additional objective of the research is to contribute to the already growing body of research on advanced district heating and cooling systems by analysing existing systems and sharing the learned lessons.

Furthermore, this research provides a roadmap for DHC systems transition in general and in Sweden in particular. This goal is achieved by exploring existing and future challenges from a holistic point of view taking into account technical, social, and political aspects.

1.3 Research approach and general methods

Figure 1.1 shows a broad overview of the research design including the research approach, the general used methods, and the connection between

the different methods and the appended papers. The research has been carried out following the hypothetic-deductive approach commonly referred to as the scientific method. It is systematically divided into four steps covering problem identification, solution formulation, solution testing, and solution adjustment. The methodological procedure of the scientific method contains the elements of the positivism philosophical stance which is influenced by the rise of experimental science and holds that “*every rationally justifiable assertion can be scientifically verified or is capable of logical or mathematical proof*” (Walliman, 2001).

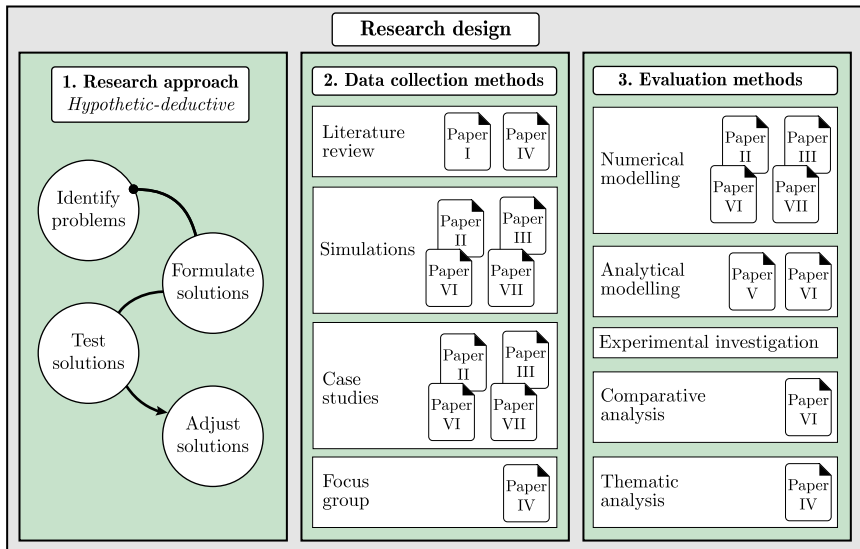


Figure 1.1 Overview of the research design.

The problems in this thesis are mainly related to the current high network temperature in most existing DHC systems which increases the use of input fuels, limits the coupling between the heat and power sectors, and decreases the system resilience to changes in heating and cooling demands. To address these problems, advanced technical solutions of DHC systems have been formulated featuring low network temperature, simultaneous supply of heating and cooling, and combining district and heat pump technologies. These solutions have been theoretically and practically tested by employing the presented evaluation methods. Finally, the solutions have been improved by aggregating the learned lessons and proposing best practices for the successful implementation of the advanced technical solutions.

The second part of the research design involved data collection, which started with a systematic literature review to situate the research in an existing body of work and to identify the state-of-the-art for modelling and simulating advanced concepts of DHC systems. A link between the literature was established using bibliographic maps and based on different bibliometrics to find the most suitable modelling paradigm to analyse the studied systems. An additional review was conducted to survey the current DHC situation in Sweden concerning the market situation, existing business models and pricing mechanisms, types of system ownership, and the combination of DHC and heat pump technologies. The literature review identified Modelica as a suitable modelling language for modelling advanced DHC concepts. The development of a multi-domain model with Modelica was then carried out to perform simulations using data retrieved from several case studies. Furthermore, a qualitative data collection method was adopted by analysing the opinions of a focus group representing architects, engineers, district heating companies, property owners, and builders who participated in best practice and roadmapping workshops.

The evaluation methods mainly consisted of numerical modelling using the multi-domain Modelica model that includes the thermal, hydraulic, and control domains. Moreover, a new analytical method for modelling network hydraulics in district systems with bidirectional mass and energy flows was developed to provide an easy and fast evaluation of the hydraulic states in closed loops with any number of connected prosumers. Experimental and comparative studies have been performed to validate the new analytical method using a lab test bench and against established numerical methods. Finally, the collected qualitative data was analysed based on the themes discussed by the focus group to identify the current and future technical, social, and political challenges of DHC systems transition.

1.4 Thesis outline

This thesis is divided into six themed chapters linking theory and practice. The theoretical part is covered in Chapters 2 and 3, while Chapters 4 and 5 focus on practice. A short description of each chapter is provided below.

Chapter 1 establishes the research context by briefly reviewing the development of district heating and cooling. The chapter also includes a brief

literature review of the approaches used for the modelling and simulation of district heating and cooling systems.

Chapter 2 demonstrates the development of a multi-domain model for the simulation of advanced district heating and cooling concepts. The chapter provides a background about the Modelica language with a short review of its applications in modelling DHC in general and 5GDHC in particular. The chapter is based on Papers I, II, III, and VII.

Chapter 3 presents a new analytical method for modelling network hydraulics in advanced district systems with bidirectional mass and energy flows. The chapter describes the motivation and the mathematical formulation of the new method. A simple procedure consisting of eight steps is provided in the chapter to evaluate the hydraulic states in bidirectional low temperature networks with any number of connected prosumers. The chapter extends Papers V and VI.

Chapter 4 applies the developed model to three case studies to evaluate the system performance of both existing and under construction systems. The chapter provides detailed analyses of different concepts and outlines several practical recommendations based on the gained lessons from each case study. The validation of the new analytical method for modelling network hydraulics in BLTNs is discussed in the chapter in considerable detail.

Chapter 5 puts forward transition pathways for successful implementation of new technologies of district heating and cooling systems based on experts' opinions. Implications concerning technical, social, and political aspects are listed. The chapter extends Paper IV.

Chapter 6 concludes the thesis with a research summary and overall findings. It also lists the limitations of the thesis and possible directions for future research on related topics.

Chapter 2

Multi-domain modelling and simulation

2.1 Background

This section is based on Paper I.

This section begins by laying out the definition of some important terms that will be used throughout the remaining parts of the thesis. For complex and large physical systems such as district heating and cooling, the term ‘multi-domain modelling’ implies the representation of the different system components while taking into account several application domains such as thermal, hydraulic, and control in the same model. According to Hafner and Popper (2017), the term ‘model’ broadly refers to the mathematical representation of system entities or processes. On the other hand, the term ‘simulation’ is used to refer to an experiment performed on the model and is designed to answer specific questions about the model’s behaviour under certain conditions. The term ‘physical modelling’ is distinguished as it is used to describe mathematical models that are virtual prototypes of physical components to mimic the system. Countless advantages can be attained

through modelling and simulation, such as the increased understanding of complex physical systems, the reduction of time and cost for building the system through design optimisation, and the suppression of unwanted second-order effects, just to name a few.

The behaviour of a physical component like a heat pump is described by differential algebraic equations where time derivatives are used. In addition, physical components require digital controls that are described by discrete equations with time-, state- and step-events to ensure safe and reliable operation. Therefore, the resulting model to describe a heat pump produces a hybrid system of continuous time, discrete time, and discrete events. For that reason, the need for a multi-domain modelling paradigm capable of modelling complex physical systems with a large number of components such as district heating and cooling becomes increasingly important.

An international project was launched in 2012 by the International Energy Agency Energy in Buildings and Communities Programme (IEA-EBC) Annex 60 to develop free open non-proprietary, new generation computational tools for building and community energy systems based on the Modelica, Functional Mock-up Interface (FMI), and Building Information Modelling (BIM) standards (Wetter et al., 2013). The Modelica language is an equation-based object-oriented multi-domain modelling language and is one of the most well-known tools for analysing complex large physical systems. Component models developed in Modelica can be inherited and/or reused to build large system models using a graphical Lego-like modelling approach inside one integrated environment.

The Modelica language was developed in 1996 through an international effort benefiting from acausal modelling and object-oriented constructs (Mattsson and Elmqvist, 1997). Acausal modelling implies the absence of explicit input and output relationship between the system components, while object-orientation allows inheriting and/or editing already existing models for rapid prototyping. Since its inception, Modelica has been warmly received by the world community in modelling and simulation and has been utilised in many sectors such as automotive, aerospace, electric, and energy (Fritzson, 2004).

Several Modelica libraries are openly accessible to model building and district energy systems. The *AixLib* developed by RWTH Aachen contains a wide range of heating, ventilation, and air-conditioning components (Maier et al., 2023; Müller et al., 2016). It also provides models for generating building demand profiles based on either low or high order building models.

The *Buildings* library from Lawrence Berkeley National Laboratories supports model-based research on building and community energy systems by offering robust and validated models (Wetter et al., 2014). The library also includes tools for pre- and post-processing, regression tests, co-simulation, and real-time data exchange with building automation systems. The *IDEAS* library developed by KU Leuven allows simultaneous transient district energy simulations both at the building and the feeder levels (Baetens et al., 2015). Additionally, the *BuildingSystems* library developed by UdK Berlin can be used to simulate single- or multi-zone buildings or city districts (Nytisch-Geusen et al., 2013). Different components from different libraries can be reused to assemble large complex system models since all component models comply with the specifications of the Modelica language.

From the user's point of view, Modelica models are described by graphical icons which encapsulate the model equations. The icons have standardised interfaces which are called ports that exchange the model variables with other models through connection lines. Depending on the model domain, the model ports exchange two kinds of variables, namely *potential* and *flow* variables. Potential variables describe the change of the system behaviour based on their values and have the same value within the same connection line, such as temperature and pressure in the thermal and fluid domains, respectively. Flow variables on the other hand represent the time derivative of a conserved quantity and are represented by the heat flow rate in the thermal domain and by the mass flow rate in the fluid domain.

A growing body of research has utilised Modelica to model DHC systems in general and advanced DHC technologies in particular. An early example is found in the work of Lauster et al. (2014) which aimed for the quick generation of building demand profiles for a district scale using the low order thermal network models. Schweiger et al. (2017) presented a Modelica framework for dynamic thermo-hydraulic modelling and optimisation of DHC systems and highlighted several benefits including continuous time optimisation, model reusability, and applicability on several domains. Lately, Hinkelman et al. (2022) modelled a detailed district cooling system using existing component models from the *Buildings* library to represent the central plant, the distribution network, the connected buildings, and the control systems. Gautier et al. (2022) demonstrated coupling a geothermal borefield with a DHC system that operates near the ground temperature to provide resilient cooling to US commercial buildings. Maccarini et al. (2023) analysed the influence of varying temperatures in building systems on the size

and performance of 5GDHC networks and concluded that each Kelvin degree reduction in the building systems can lead to 1.5 % savings in electric energy.

Based on the previous studies, it can be concluded that Modelica is highly suitable for modelling advanced concepts of DHC systems and was therefore chosen as the modelling environment for its reliability and validity. The following sections demonstrate the development of a Modelica model for simulating advanced DHC concepts with features including but not limited to, simultaneous supply of heating and cooling, decentralised supply temperature modulation at the building level, and uninsulated distribution pipes. The model has been developed using newly developed components and existing components from the open-source Modelica libraries.

2.2 Model description

This section is based on Paper II, Paper III, and Paper VII.

Any district heating and cooling system can be generally compartmentalised into three main subsystems that can be modelled in isolation. Figure 2.1 shows Modelica icons for the three subsystems which include: 1) the building delivery system, 2) the distribution network, and 3) the energy source and/or sink together with the established connection lines between the subsystems. The blue circles at the start and end of each connection line denote the fluid ports that exchange the model variables represented by the fluid pressure and the mass flow rate. A positive fluid direction is indicated by a flow from the blue-filled circle to the white-filled circle. In the opposite direction, the flow is reversed and has a negative sign.

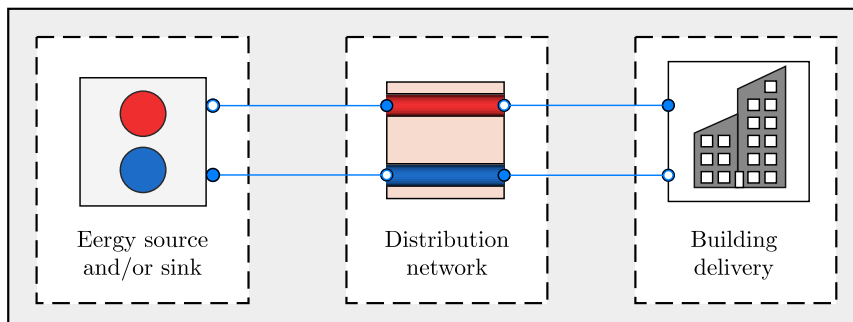


Figure 2.1 A global perspective of the developed model showing its three main subsystems.

For each subsystem, several components and design alternatives can be adopted. For instance, the building delivery system may incorporate heat pumps, mechanical chillers, and heat exchangers used for free cooling and, in some cases for free heating as well. Similarly, the distribution network can have different topologies with one- two- or even three-pipe systems based on design requirements (Arabkoohsar and Alsagri, 2020; Bünning et al., 2018; Lindhe et al., 2022; Sommer et al., 2020). Finally, the energy source and/or sink is used for heat extraction and/or injection from/into the network and may include, e.g., central plants, seasonal storage, or renewable energy sources such as solar thermal and/or geothermal. The description of these three subsystems according to the applications considered in this study is provided in the following subsections together with their control strategies.

2.2.1 Building delivery systems

A building delivery system incorporates the connection to the building distribution system such as radiators and chilled beams as well as the connection to the distribution network as shown in Figure 2.1. The different included components can be seen in the substation model diagram presented in Figure 2.2. At the top of the figure, the component with the number label 1 contains the building heating and cooling demands. Demand profiles can be obtained by one of the three following common approaches. The first is related to measured data from existing buildings that are collected to mainly analyse an already built system. The second approach involves obtaining simulated demand profiles using a whole-building energy simulation program like EnergyPlus (Crawley et al., 2001), TRNSYS (Klein et al., 1976), or IDA-ICE (EQUA, 2023). A downside of this approach is that an integrated simulation environment including building and district systems may no longer exist due to the need for data exchange between different tools using for example synchronous co-simulation. A third approach offers the possibility to model buildings in Modelica with either high or low levels of physical details. Our recommendation is to avoid modelling buildings in Modelica with a high level of physical details for two main reasons. First, buildings involve many components that result in thousands of differential equations where the code becomes large and the Modelica solver may be extremely slow in solving the unknowns (Nicolai and Paepcke, 2017). Second, buildings with high thermal inertia can tolerate the daily variations in the supply from DHC while maintaining good indoor comfort (Kensby et al., 2015). Therefore, modelling buildings in Modelica without much detail

using the so-called Reduced Order Models (ROM) available in the *AixLib* library is more favourable to simplify the model without losing accuracy. This approach relies on data enrichment and statistical databases to parameterise the building to describe the building envelope, occupancy profiles, and schedules for the heating, ventilation, and air-conditioning systems (Remmen et al., 2017). The type of model application and the type of experiments performed on the model decide which approach is most suitable. For the applications presented in Chapter 4, the first two approaches have been utilised.

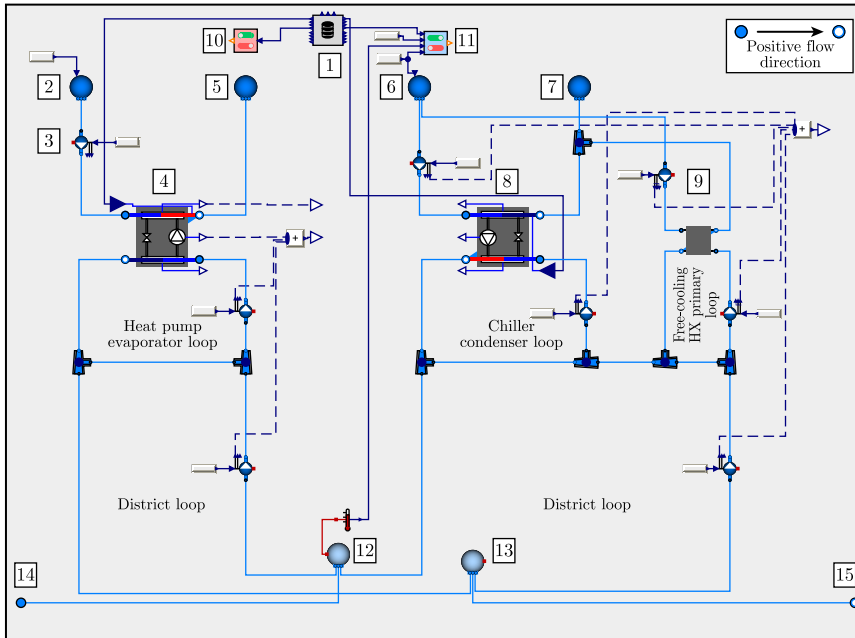


Figure 2.2 Diagram of a substation model with installed heat pump, mechanical chiller, and free-cooling heat exchanger.

Components 2 and 5 in Figure 2.2 represent the return and supply from and to the building heating system, respectively. For simplicity reasons, these components have been modelled as infinite sources and sinks with prescribed temperatures without the need to model the building's heating system. The circulation pump at point 3 draws water to the inlet of the condenser in the amount of:

$$\dot{m}_{\text{hp,cond}} = \frac{\dot{Q}_h}{\Delta T_{\text{hp,cond}} \cdot c_{p,\text{water}}} \quad (2.1)$$

where $\Delta T_{\text{hp,cond}}$ is the temperature difference between the inlet and outlet of the heat pump condenser, and $c_{p,\text{water}}$ is the specific heat capacity of water. The pumping power of the circulation pump is defined as:

$$P_{\text{pump}} = \frac{\dot{V} \cdot \Delta p}{\eta_{\text{hyd}} \cdot \eta_{\text{mot}}} \quad (2.2)$$

where \dot{V} is the volume flow rate, Δp is the pump pressure rise, η_{hyd} and η_{mot} are the pump hydraulic and motor efficiencies, respectively.

The heat pump shown at point 4 is modelled with a coefficient of performance (COP) adjusted based on a prescribed Carnot efficiency as:

$$COP_{\text{hp}} = \eta_{\text{Carnot}} \cdot \frac{T_{\text{hp,cond}}}{T_{\text{hp,cond}} - T_{\text{hp,evap}}} = \frac{\dot{Q}_h}{P_{\text{comp}}} \quad (2.3)$$

where η_{Carnot} is the Carnot efficiency and is equal to 30 % based on the recommendation of Zarin Pass et al. (2018), $T_{\text{hp,cond}}$ is the prescribed heat pump condenser leaving temperature, $T_{\text{hp,evap}}$ is the heat pump evaporator temperature, \dot{Q}_h is the heating demand, and P_{comp} is the compressor's input electric power.

Cooling is delivered similarly with components 6 and 7 representing the return and supply to and from the building cooling system. Both the mechanical chiller and the free-cooling heat exchanger shown in points 8 and 9 provide cooling. The mechanical chiller is also modelled with a prescribed Carnot efficiency, whereas the free-cooling heat exchanger is modelled with a capacity defined as:

$$\dot{Q}_{\text{hx}} = \varepsilon \cdot \dot{m}_{\text{hx}} \cdot c_{p,\text{water}} \cdot (T_{\text{pri,in}} - T_{\text{sec,in}}) \quad (2.4)$$

where ε is the heat exchanger effectiveness, $T_{\text{pri,in}}$ and $T_{\text{sec,in}}$ are respectively the inlet temperatures to the primary and secondary sides of the heat exchanger.

The control of heating and cooling equipment is described in components 10 and 11, respectively. In a heating mode, only the heat pump operates and it is therefore controlled using a simple on/off controller based on the heating demand. On the opposite side, cooling can be provided by more than one equipment. The conditions which determine the operation of the chiller and the free-cooling heat exchanger to provide cooling are described in the cooling mode controller shown in Figure 2.3. This kind of controller is based on the finite state machine (FSM) algorithm which is particularly useful in

modelling discrete events and reactive systems (Goyal, 2021). The state graph located at the top of Figure 2.3 shows that the cooling equipment are decomposed into four different states where each equipment is only allowed to be in one state at a time. The transition between the states is determined by a set of prescribed conditions that are shown in the state graph. The Modelica Standard Library comes with a state graph package that enables convenient visual description of the states and the transition logics using simple graphical components. The initial state, indicated by the OFF state, is illustrated by the double square as shown in Figure 2.3. Cooling can be

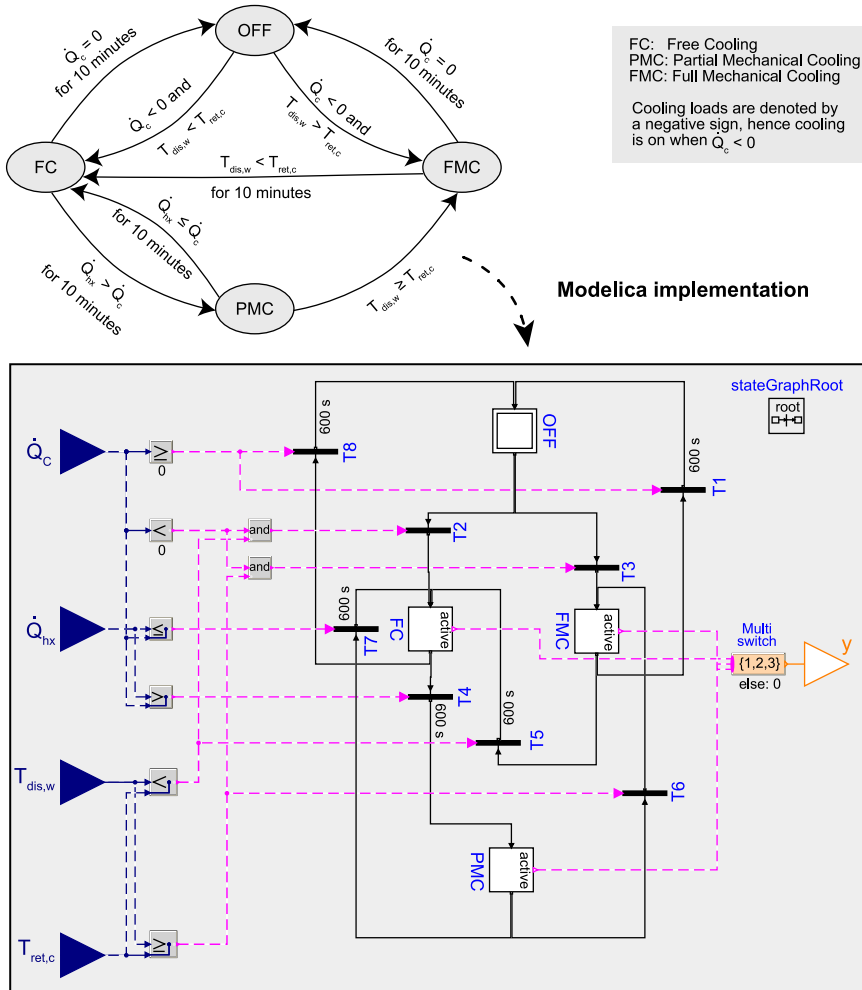


Figure 2.3 State graph for the cooling mode controller and the equivalent Modelica implementation.

provided by either one of the following three modes: 1) through the free-cooling heat exchanger only (Free Cooling mode), 2) through the mechanical chiller only (Full Mechanical Cooling mode), or 3) through the simultaneous operation of the heat exchanger and the chiller (Partial Mechanical Cooling mode). Transition T2 from the OFF to the FC is triggered when the temperature in the district warm pipe is lower than the return temperature of the building cooling loop. The state PMC is activated when cooling demands exceed the capacity of the free-cooling heat exchanger and when the mechanical chiller compensates for the remaining demands, as shown in transition T4. The state FMC is only activated when the temperature in the district network is not suitable for direct cooling. To avoid short cycling between the different states, a delay time of 600 seconds forces the equipment to remain active in a particular mode before transition.

For each component in the substation model shown in Figure 2.2, pressure drops are calculated based on the nominal fluid resistance k_{nom} retrieved from input nominal parameters that constitute the first point in the flow-pressure drop relationship curve. The relationship is defined as:

$$\dot{m} = k_{\text{nom}} \cdot \sqrt{|\Delta p|} \cdot \text{sign}(\Delta p); \quad k_{\text{nom}} = \frac{\dot{m}_{\text{nom}}}{\Delta p_{\text{nom}}} \quad (2.5)$$

It should be noted that local energy sharing within the substation in the case of simultaneous heating and cooling takes place in the mixing volumes shown at points 12 and 13 in Figure 2.2. The extracted and/or injected energy from/into the distribution network is realised through the two fluid ports with numbers 14 and 15 denoting the connection to the district warm and cold pipes, respectively.

2.2.2 Distribution network

In advanced concepts of DHC systems with low network operating temperature, distribution pipes are typically uninsulated and act as a horizontal heat exchanger with the ground. Figure 2.4 shows the developed model for uninsulated double buried pipes involving its two parts for steady-state heat losses and pressure drops due to pipe wall friction. The pipes are discretised into a number of segments with equal length along the flow path. For each segment, steady-state heat losses are calculated according to standard SS-EN 13941-1 (Svenska institutet för standarder, 2021) based on the multipole method originally developed by Wallentén (1991).

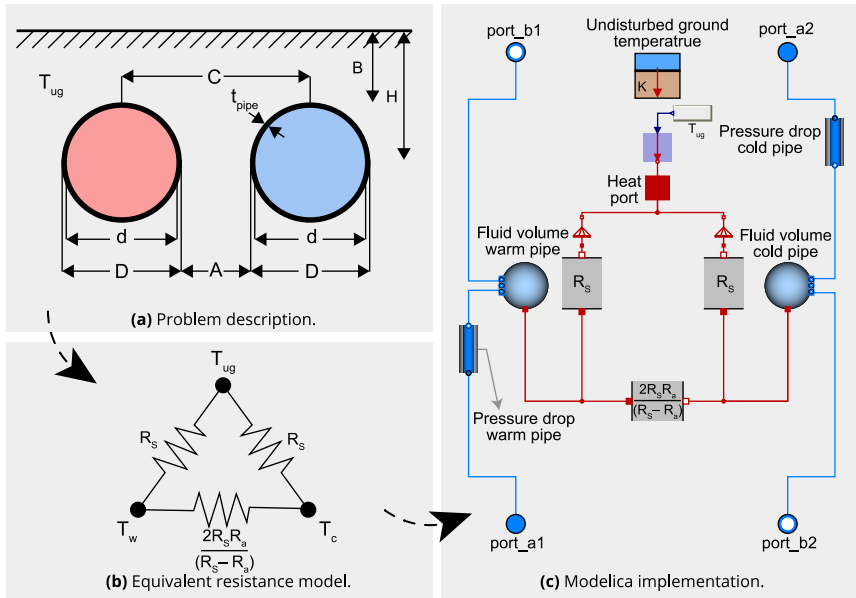


Figure 2.4 Description of steady-state heat losses in an uninsulated double buried pipe.

Heat losses are calculated based on a superposition of symmetrical and anti-symmetrical problems. The former takes into account the interaction between the pipes and the surrounding and not with each other, while the latter considers the interaction between the pipes and not with the surrounding. The equivalent resistance model adopted from van der Heijde et al. (2017) graphically represents the different thermal resistances included in the problem description similar to the representation of the thermal behaviour in borehole heat exchangers (Claesson and Hellström, 2011) and thermal energy storage systems (Hellström, 1991). The mathematical derivation of the thermal resistances and the losses to the ground are described below.

The zero-order multipole formulae for the symmetrical resistance R_s and the anti-symmetrical resistance R_a is defined as:

$$R_s = \frac{1}{2 \cdot \pi \cdot \lambda_{\text{soil}}} \cdot \left[\ln \left(\frac{4 \cdot H_0}{D_{\text{out}}} \right) + \beta + \ln \left(\sqrt{1 + \left(\frac{2 \cdot H_0}{C} \right)^2} \right) \right] \quad (2.6)$$

$$R_a = \frac{1}{2 \cdot \pi \cdot \lambda_{\text{soil}}} \cdot \left[\ln \left(\frac{4 \cdot H_0}{D_{\text{out}}} \right) + \beta - \ln \left(\sqrt{1 + \left(\frac{2 \cdot H_0}{C} \right)^2} \right) \right]$$

where λ_s is the soil thermal conductivity, D_{out} is the pipe outer diameter, H_0 is a corrected depth that considers the ground surface resistance as $H_0 = H + R_0 \cdot \lambda_s$, and β is a dimensionless resistance parameter equivalent to:

$$\beta = \frac{\lambda_{\text{soil}}}{\lambda_{\text{pipe}}} \cdot \ln \left(\frac{D_{\text{out}}}{D} \right) \quad (2.7)$$

The boundary undisturbed ground temperature T_{ug} at the pipe burial depth is expressed according to ASHRAE (2013) as:

$$T_{\text{ug}} = T_{\text{ms}} + A_{\text{sur}} \cdot e^{-B \sqrt{\frac{\pi}{\alpha \cdot \tau}}} \sin \left(\frac{2 \cdot \pi (t - t_{\text{lag}})}{\tau} - B \sqrt{\frac{\pi}{\alpha \cdot \tau}} \right) \quad (2.8)$$

with T_{ms} being the annual mean surface temperature, A_{sur} is the annual surface temperature amplitude, B is the depth, α is the soil diffusivity, τ is the annual period length, t is the time step, and t_{lag} is the phase lag of the soil temperature.

Finally, heat losses in the warm and cold pipes are calculated as:

$$\dot{Q}_{\text{loss,w}} = \left[\frac{1}{R_s} \cdot (T_w - T_{\text{ug}}) + \frac{R_s - R_a}{2 \cdot R_s \cdot R_a} \cdot (T_w - T_c) \right] \quad (2.9)$$

$$\dot{Q}_{\text{loss,c}} = \left[\frac{1}{R_s} \cdot (T_c - T_{\text{ug}}) + \frac{R_s - R_a}{2 \cdot R_s \cdot R_a} \cdot (T_c - T_w) \right]$$

The second part of the distribution network model deals with modelling pressure drops due to pipe wall friction. The relationship between the flow and pressure drops is defined in Equation (2.5). The nominal pressure drop in each pipe segment is defined as:

$$\Delta p_{\text{nom}} = F \cdot k \cdot c_{f2}(\text{Re}, \epsilon) \cdot \dot{m}_{\text{nom}} \quad (2.10)$$

where F is a factor that includes fitting losses, k is a fluid resistance factor, c_{f2} is a modified friction factor that depends on Reynolds number Re and the pipe relative roughness ϵ . The factor k is defined as:

$$k = \frac{L \cdot \mu^2}{2 \cdot D^3 \cdot \rho} \quad (2.11)$$

where L is the pipe segment length, μ is the fluid dynamic viscosity, D is the pipe hydraulic diameter, and ρ is the fluid density.

The modification c_{f2} is based on the friction factor c_f derived from the Moody diagram. The modification is intended for robust computer calculations to avoid the problem of division by zero which occurs at zero mass flow rates which leads to zero Reynolds number. As a remedy to this problem, the friction factor c_f is redefined as:

$$c_{f2} = c_f \cdot Re^2 \quad (2.12)$$

where Reynolds number is expressed as:

$$Re = \frac{4 \cdot |\dot{m}|}{\pi \cdot D \cdot \mu} \quad (2.13)$$

The value of Reynolds number determines the flow regime. If Re_1 and Re_2 denote respectively the Reynolds number leaving the laminar region and entering the turbulent region, the computation of the modified friction factor c_{f2} in the laminar region when $Re \leq Re_1$ is based on the Hagen Poiseuille equation (Reay et al., 2014) and is expressed as:

$$c_{f2} = c_f \cdot Re^2 = 64 \cdot Re \quad (2.14)$$

The lower boundary of the transition region Re_1 is defined according to Idelchik (1986) as:

$$Re_1 = 745 \cdot \exp \begin{cases} 1 & \epsilon < 0.0065 \\ \frac{0.0065}{\epsilon} & \end{cases} \quad (2.15)$$

The upper boundary of the transition region is reached when $Re_2 = 2000$ (Shashi Menon, 2015). Inside the transition region, approximations are made to determine the modification friction factor using cubic Hermite spline interpolation to obtain a continuous function.

Lastly, in the turbulent region when $Re \geq Re_2$, the modified friction factor is derived based on the Swamee-Jain equation (1976):

$$\gamma_2 = 0.25 \left[\frac{Re}{\log\left(\frac{e}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)} \right]^2 \quad (2.16)$$

where e is the pipe absolute roughness.

A comparative study of the hydraulic behaviour of this model against other methods is presented in Section 4.4.2 and explained in detail in appended Paper VI.

The temperature control of the fluid in the distribution network can be based on several strategies including, e.g., maintaining the warm and cold fluids at prescribed constant temperatures, maximising the utility of direct cooling by controlling only the temperature of the fluid in the cold pipe, and floating the fluid temperature between minimum and maximum levels. For the applications included in this thesis, the free-floating strategy has been mainly utilised. The objective of this kind of control strategy is to keep the network temperature floating between prescribed minimum and maximum levels. Typical temperature levels for advanced DHC systems for the applications considered in this study are between 5 and 40 °C. The energy source and/or sink is responsible for maintaining the prescribed temperature levels in the network. In certain applications, a central reversible heat pump connected to the energy source and/or sink is used to modulate the network temperature. Such applications are explained in further detail in Section 4.1.

2.2.3 Energy source and/or sink

As mentioned earlier, an energy source and/or sink may incorporate different components according to the preferred design choice. In this section, the focus is put on shallow geothermal energy due to its pivotal role in DHC systems transition by supplying emission-free heating and cooling (García-Céspedes et al., 2023; Tester et al., 2021). Other types of energy sources/sinks incorporating, e.g., air-source heat pumps, cooling towers and an accumulator tank are described in section 4.1 and appended Paper III. The Modelica model for a geothermal bore field had its earliest implementation by Picard and Helsen (2014) and was later extended by Laferrière et al. (2020). The model combines borehole and ground models as illustrated in Figure 2.5 and is capable of simulating any arbitrary configuration of

connections. The description in this section is provided for single U-tube heat exchangers as shown in Figure 2.5. The borehole is vertically discretised into segments of equal length to account for the vertical variations in the fluid temperature. Each segment has an identical borehole wall temperature without taking into account the conductive heat transfer between the segments. The thermal resistances inside each segment are determined using the thermal resistance and capacity model developed by Bauer et al. (2011). This model is valid for boreholes filled with grout, which is a common practice in many parts of the world including the system analysed in Section 4.2. However, the practice is different in Sweden where boreholes are naturally filled with groundwater and where natural convection heat transfer is strongly linked to the bore hole thermal resistance (Spitler et al., 2016). For the first kind of boreholes filled with grout where heat transfer is conductive, a condensed description of the thermal resistances is provided below.

The first thermal resistance in Bauer's et al. model is between the fluid and the filling material is defined as:

$$R_{ig} = \frac{1}{Nu \cdot \pi \cdot \lambda_f} + \frac{\ln\left(\frac{r_{tub}}{r_{tub,in}}\right)}{2 \cdot \pi \cdot \lambda_p} + z + R_g \quad (2.17)$$

where Nu is Nusselt number, λ_f and λ_p are respectively the fluid and pipe thermal conductivity, r_{tub} and $r_{tub,in}$ are respectively the tube outer and inner radius, z is a parameter for locating the centre mass of the filling material, and R_g is the thermal resistance between the outer pipe wall to the borehole wall.

The parameter z is expressed as:

$$z = \frac{\ln\left(\frac{\sqrt{r_b^2 + 2 \cdot r_{tub}^2}}{2 \cdot r_{tub}}\right)}{\ln\left(\frac{r_b}{2 \cdot r_{tub}}\right)} \quad (2.18)$$

where r_b is the borehole radius. The thermal resistance between the outer pipe wall to the borehole wall R_g is defined as:

$$R_g = 2 \cdot R_b - \frac{1}{Nu \cdot \pi \cdot \lambda_f} - \frac{\ln\left(\frac{r_{tub}}{r_{tub,in}}\right)}{2 \cdot \pi \cdot \lambda_p} \quad (2.19)$$

where R_b denotes the thermal resistance between the fluid and ground and is calculated based on the multipole method described by Claesson and Hellström (2011).

The thermal resistance between the two zones of the filling material R_{gg} is defined as:

$$R_{gg} = \frac{2 \cdot R_{gb} (R_{ar} - 2 \cdot z \cdot R_g)}{2 \cdot R_{gb} - R_{ar} + 2 \cdot z \cdot R_g} \quad (2.20)$$

where R_{gb} is the thermal resistance between the filling material and the borehole wall and calculated as:

$$R_{gb} = (1 - z) R_g \quad (2.21)$$

The thermal resistance between the outer wall of the two pipes R_{ar} is determined based on the delta-circuit resistance model by Eskilson and Claesson (1988) as:

$$R_{ar} = R_a - 2 \left(\frac{1}{Nu \cdot \pi \cdot \lambda_f} + \frac{\ln \left(\frac{r_{tub}}{r_{tub,in}} \right)}{2 \cdot \pi \cdot \lambda_p} \right) \quad (2.22)$$

It is worth noting that the thermal resistance R_a refers to the total resistance at zero heat flux around the borehole boundary and is determined according to Claesson and Hellström (2011).

The final calculation step in the thermal resistance and capacity model is related to finding the capacities of the filling material and the fluid as shown in Equation (2.23).

$$C_g = \rho_g \cdot c_{p,g} \cdot \pi (r_b^2 - 2 \cdot r_{tub}^2) \quad (2.23)$$

$$C_f = \rho_f \cdot c_{p,f} \cdot 2 \cdot \pi \cdot r_{tub,in}^2$$

The second part of the borefield model shown on the right side of Figure 2.5 aims to describe the heat transfer in the ground. Because heat extraction and/or injection from/into the ground mainly depends on the total district network demands, the time resolution in which these are prescribed plays an important role in the model's computational performance. Using hourly resolutions of building demands is common, while high resolutions of up to

15 minutes are becoming more and more important to analyse peak demands for system sizing. To reduce the simulation time, the ground model uses the load aggregation method developed by Claesson and Javed (2012). The reader is reminded that Modelica runs in the continuous-time domain, which in turn calls for some adjustments to the load aggregation method. These adjustments have been presented by Laferrière et al. (2020) to allow simulations with variable time steps to describe the borefield temperature response. The borefield temperature response, commonly known as the *g-function*, essentially gives the relation between the changes in the borehole wall temperature at a certain point in time and the heat extraction/injection rates at all preceding times. Historically, the concept of the *g-function* was originally developed by Eskilson (1987). Ever since, the concept has been implemented in several tools for modelling ground heat transfer. The first attempt to evaluate the *g-function* in Modelica was made by Cimmino and Bernier (2014) and was later refined by Cimmino (2018).

Each borefield configuration has a unique temperature response, i.e., a unique *g-function*, which is evaluated as a combination of the finite line source (FLS) solution, the cylindrical heat source (CHS) solution, and the infinite line source (ILS) solution. Li et al. (2014) proposed a correction of the *g-function* to account for the cylindrical geometry as:

$$g(t) = g_{\text{FLS}} + (g_{\text{CHS}} - g_{\text{ILS}}) \quad (2.24)$$

The heat transfer in the ground is modelled analytically according to Equation (2.25) as a convolution integral between the heat flux at the borehole wall and the borefield's temperature response.

$$\Delta T_b(t) = \int_0^t \dot{Q}(\tau) \cdot \frac{dT_{\text{step}}(t - \tau)}{d\tau} d\tau \quad (2.25)$$

where ΔT_b is the temperature difference at the borehole wall, \dot{Q} is the heat flux at the borehole wall, and dT_{step} is the ground temperature response.

Taken together, the two parts that constitute the borefield model are evaluated each time a unique borefield is simulated. During the translation of the Modelica model into flat equations, the *g-function* is evaluated for the unique borefield configuration and is stored locally in the computer to reduce the simulation time if the same borefield configuration is to be modelled again.

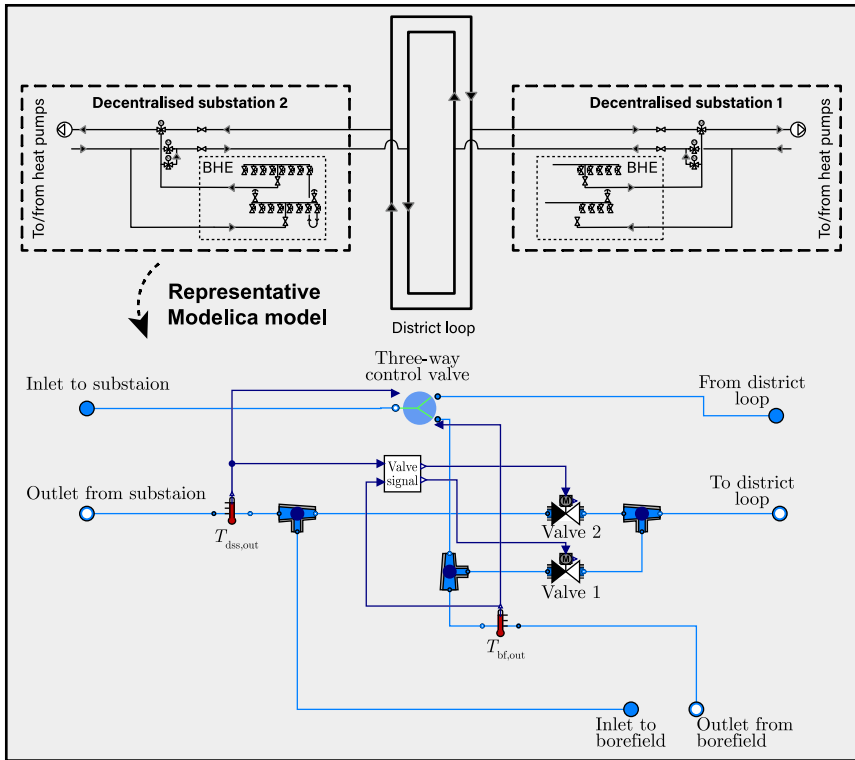


Figure 2.6 Schematics of a district network with the energy sharing concept (top) and the Modelica implementation for the energy sharing controller (bottom).

In energy communities that enable energy sharing between several borefields, a novel control strategy has been developed. The illustration of the control logic on the flow schematics is shown in Figure 2.6 according to the case presented in Section 4.3. In such an energy sharing concept between separate borefields, each decentralised substation has its own geothermal borefield that provides direct cooling through heat exchangers and heating through heat pumps. Instead of seeing each substation with its borefield as an individual system, an energy community can be realised by connecting all borefields in a neighbourhood through a piping network to exchange energy with each other. The distribution network shares the available energy with any of the connected substations. The temperature levels in each borefield and the demand type in each substation determine whether or not energy sharing is possible. Consider the Modelica flow diagram shown at the

bottom of Figure 2.6. Heating is injected from the building into the network when Valve 2 is open when the following condition holds:

$$T_{\text{dss,out}} > T_{\text{bf,out}} \quad (2.26)$$

where $T_{\text{dss,out}}$ is the temperature of the outgoing fluid from the decentralised substation and $T_{\text{bf,out}}$ is the temperature of the outgoing fluid from the bore field. Valves 1 and 2 have opposing operations, when one is open, the other is closed. This allows either direct heating injecting from the building or through the borefield.

The three-way control valve determines which of the fluids is more favourable to be supplied to the building based on the building demand type and the fluids' temperature levels. In a heating mode, the three-way valve prioritises a higher fluid temperature from either the borefield or from the district loop in order to increase the performance of the heat pumps. In contrast, the three-way valve allows the fluid with the lowest temperature level to be supplied to the building when a cooling demand exists.

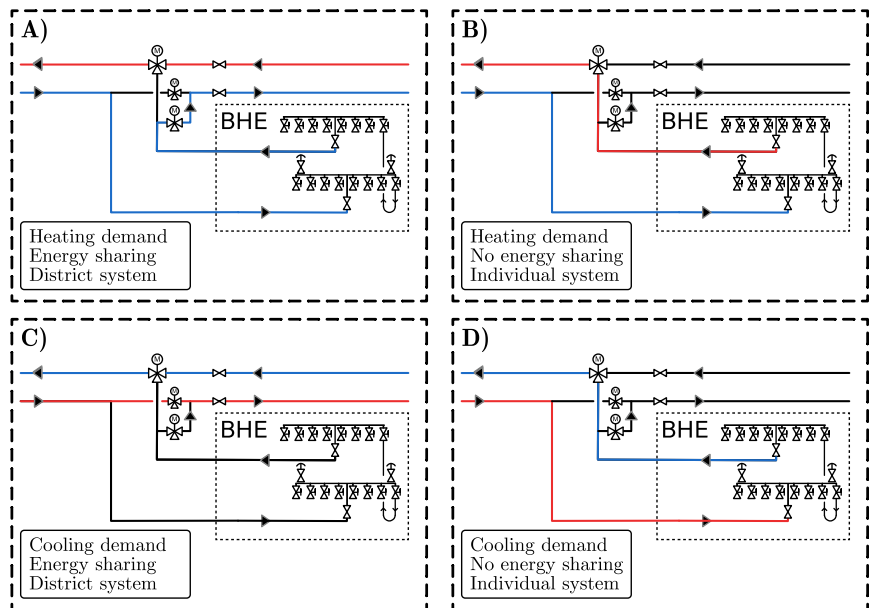


Figure 2.7 Schematic diagrams of different fluid flows based on building demand type and possible energy sharing.

Different operational scenarios may occur where a single substation can be either an individual system or a part of a district system. Figure 2.7 shows

four of such possible scenarios as indicated by the fluid flows. The scenario depicted in Figure 2.7(A) describes the situation when heat is extracted from the network and delivered to the building and at the same time the cold fluid leaving the borefield is injected into the network. This scenario takes place in summer when the substation has demands for domestic hot water production and when other connected buildings have cooling demands that can be provided by the injected cold fluid into the network. If the network fluid temperature is lower than the fluid temperature leaving the borefield, energy sharing is no longer possible and the substation operates as an individual system, as shown in Figure 2.7(B). This scenario is expected to happen in winter when heating demands dominate. However, if cooling is required in winter for specific buildings like datacentres and hospitals, energy sharing through the district system becomes possible as shown in Figure 2.7(C). The last scenario shown in Figure 2.7(D) presents the summer case when cooling demands dominate making the individual system with supply from the borefield more efficient for cooling supply compared to the district system with relatively higher temperatures.

2.3 Model validation

To increase confidence in the output from the developed model, different validation methods have been utilised depending on the type of reference data sets. In cases where obtaining measured data from existing systems was possible, a framework for probabilistic model validation was developed based on Paper III. Otherwise, when the model was compared against reference values obtained from other modelling tools, mismatches were calculated directly, and the model was assessed using validation metrics based on Paper VI. These two approaches are briefly explained in this section.

The first validation method compares measured quantities from thermal energy meters to similar modelled values which both have uncertainties that could impact the validation results. Therefore, probabilistic validation becomes particularly useful to constitute a relationship between error and probability that is useful for statistical inference every time a new set of measured data is used. Such a relationship is established using the cumulative distribution function (CDF) which gives the probability of the absolute model error being less than a benchmark level. Figure 2.8 shows the developed framework for performing model probabilistic validation using thermal energy meter data consisting of mass flow rates, inlet and outlet

temperatures, and the corresponding heat flow rates. In Step 1, unrepresentative data are neglected and not considered in the validation data set. The benchmark level is determined in Step 2 based on the calculated

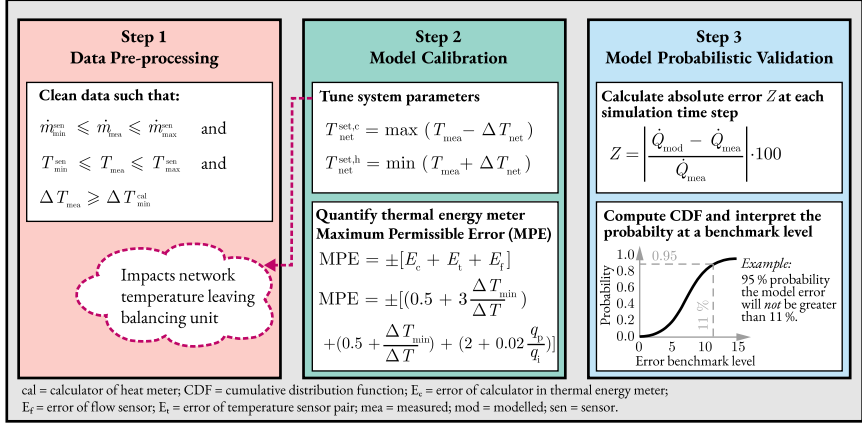


Figure 2.8 Steps for performing model probabilistic validation with data from thermal energy meters.

thermal energy meter's maximum permissible error. Finally, the CDF is computed and the probability of the model error is found. This validation method has been applied in Case study I presented in Section 4.1.

In the second validation method, validation metrics such as the coefficient of determination R^2 , the normalised mean bias error (NMBSE), and the coefficient of variation of the root mean square error (CV(RMSE)) have been determined according to Equation (2.27) to analyse specific characteristics about the developed model.

$$R^2 = \hat{p}^2, \quad \hat{p} = \frac{\sum_{i=1}^n (y_{ref} - \bar{y}_{ref})(y_{mod} - \bar{y}_{mod})}{\sqrt{\sum_{i=1}^n (y_{ref} - \bar{y}_{ref})^2 \sum_{i=1}^n (y_{mod} - \bar{y}_{mod})^2}}$$

$$NMBE = \frac{1}{\text{Mean}(y_{ref})} \cdot \frac{\sum_{i=1}^n y_{ref} - y_{mod}}{(n-1)} \times 100 \quad (2.27)$$

$$CV(RMSE) = \frac{1}{\text{Mean}(y_{ref})} \cdot \sqrt{\frac{\sum_{i=1}^n (y_{ref} - y_{mod})^2}{(n-1)}} \times 100$$

The coefficient of determination essentially gives the square of the Pearson correlation and shows how much of the variance in the reference data set can

be explained by the developed model. On the other hand, the NMBE points to whether the developed model is under- or overshooting its predictions. Finally, the CV(RMSE) indicates the model's ability to capture the overall shape and pattern of the reference data set as the metric is not subject to cancellation errors. These three metrics have been used in the comparative validation presented in Section 4.4.2.

2.4 Summary

A multi-domain simulation model for advanced district heating and cooling concepts was developed using the Modelica language featuring simultaneous supply of heating and cooling, decentralised temperature modulation using distributed heat pumps and mechanical chillers, and uninsulated distribution pipes with operating temperature near the ground. The system model was divided into three main subsystems including the building delivery system, the distribution network, and the energy source and/or sink. Given the several advantages that Modelica offers including, e.g., the rapid virtual prototyping and the reusability of existing models, each subsystem model can be easily modified to accommodate different design alternatives while essentially retaining the system architecture. The developed model certainly adds into gaining deeper insights into the expected performance of advanced concepts of DHC systems. Its application on several case studies is presented separately in Chapter 4.

Chapter 3

Improved hydraulic modelling of bidirectional networks

3.1 Motivation

New concepts of district heating and cooling face several technical challenges due to changes in the method of producing and distributing heating and cooling. Traditionally, heating or cooling is produced in a central plant and is subsequently distributed through a piping network to the end-customers. Flow circulation is achieved with the help of a central pumping station that restricts the heat-carrying fluid to flow only in one direction from the central plant towards the end-customers. In recent DHC technologies featuring low network temperatures to levels near the ambient in addition to the decentralisation of heating and cooling production, connecting multiple heat prosumers to the same network has become possible. In these networks, the fluid or the energy carried by the system can flow in any direction.

Several network topologies are found in the literature that adopt the prosumer concept, with a two-pipe network consisting of a warm and a cold side being the most common (Bünning et al., 2018; Lickleder et al., 2021; Wirtz et al., 2020b; Zarin Pass et al., 2018). Connected prosumers to a two-pipe network extract the fluid from either the warm or the cold pipe at varying amounts and directions depending on the demand type. Consequently, a distinct pressure cone is created at each connection point. The heat-carrying fluid can therefore flow in any direction and the energy carried by the system can flow either out of or into the system. These systems are referred to as Bidirectional Low Temperature Networks (BLTNs).

Hydraulic systems typically have fast dynamic response that are difficult to control due to nonlinear characteristics such as deadband, friction, and hysteresis (LeQuoc et al., 1992). Nonlinear hydraulic connections may become more apparent in BLTNs since the network has an inherent closed loop topology. Moreover, and due to the modular network structure, a meshed network consisting of several closed loops can be formed after connecting new prosumers to an existing BLTN (von Rhein et al., 2019). Such a change in the mechanism of connecting new buildings can create pressure cycles at the connection points leading to a nonlinear hydraulic system which in turn impacts the electric pumping power. This change in operation is fundamentally different compared to traditional open DHC networks whose topology is described by a tree that produces a linear hydraulic system (Cantoni et al., 2007; De Persis and Kallesoe, 2011).

To shed more light on the hydraulic aspects in BLTNs and traditional unidirectional DHC networks, Figure 3.1 contrasts the pressure gradient curves in both types. Traditional networks typically have a single pressure cone along the pipe length whose highest pressure drop is compensated by the central pump. On the contrary, circulation pumps in BLTNs that are installed at each prosumer level create their own pressure cone and, hence, the pressure gradient curve can take any arbitrary shape depending on the prosumers' demands. Another distinctive feature of BLTNs is the closed loop network topology where the pipeline starts and ends at the tank connection.

Standard practices for modelling district network hydraulics involve solving the flow system using numerical methods. In such approach, the system elements, e.g., pipes, are first defined as a set of mathematical equations. The entire flow system typically produces a highly nonlinear set of equations with implicit nature, which are solved using algorithms such as the

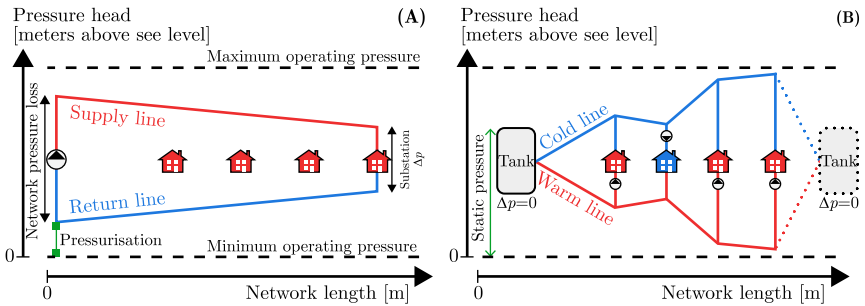


Figure 3.1 Qualitative representation of the pressure gradient curve in a unidirectional district heating network (A) and a bidirectional low temperature network (B).

Newton-Raphson method. An initial approximate solution is found by employing iterative techniques aiming to balance the pressure by adjusting the mass flows. Convergence to an accurate solution is finally achieved by utilising matrix techniques alongside iterative algorithms.

Numerical methods are prone to errors related to, e.g., discretisation of time steps, iteration, values near the zero region, and convergence. When implemented in a tool for modelling network hydraulics, numerical methods may cause the simulation to terminate if numerical errors emerge. The tool in such cases provides an error message which is usually uninformative and requires considerable time and effort to fix. Therefore, analytical methods are more favourable given their explicit nature, ease of implementation, and quick modelling time.

A new fast analytical method for modelling hydraulics in BLTNs is presented in this chapter to contribute to a better understanding of the complex hydraulic interactions between connected prosumers. Additionally, the new analytical method can be easily implemented in any software to ensure safe and accurate design and analysis of new or existing BLTNs. In the following sections, the problem is described together with the mathematical derivation and a summary of the full solution. The validation of the new method against a controlled test setup and other numerical methods is discussed extensively in Section 4.4.

3.2 A new analytical method

This section is based on Paper V.

This section presents the new analytical method for modelling hydraulics in BLTNs with any number of connected prosumers. The section first introduces the sign convention and notations used in the method. Next, the mathematical derivation of mass balances and node pressures is explained using an example of a simple BLTN. Afterwards, two important functions that comprise the main part of the analytical solution are introduced, and their characteristics are analysed.

3.2.1 Sign convention and notations

Figure 3.2 shows a descriptive BLTN with three connected prosumers and a tank together with the used sign convention and notations. The network consists of a warm pipe shown in red and a cold pipe shown in blue. Each prosumer extracts or injects a mass flow \dot{M}_ν depending on the heating and cooling demand with ν equals to $\nu = 1, 2, 3$. The prosumer mass flows may be positive or negative or zero as indicated by the arrows shown in the figure. A positive direction implies that the heat-carrying fluid, which is water in this application, flows from the prosumer into the warm red pipe. The direction is reversed for negative mass flows. The piping loop is connected at the start and end to a stratified tank.

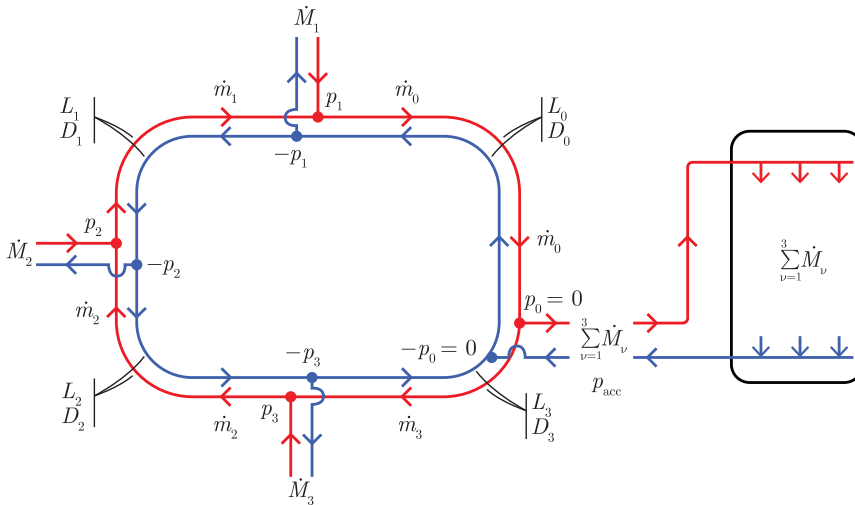


Figure 3.2 A descriptive BLTN and notations for three connected prosumers and an accumulator tank.

The number of pipe segments and nodes is equal to $\nu + 1$ enumerated counterclockwise starting from $\nu = 0$ at the tank to $\nu = 3$ at the last

connected prosumer. The first pipe segment $\nu = 0$ connects the tank node 0 to the first prosumer at node $\nu = 1$. Each pipe segment has the length L_ν and hydraulic diameter D_ν . The flow in the warm pipe of segment ν is \dot{m}_ν and has a clockwise positive flow direction. The flow is exactly antisymmetric between the warm and cold pipes except when the water viscosity varies due to the change in water temperature. The analysis in this chapter is provided for the warm side with a constant viscosity. The impact of varying viscosities is examined in detail in Paper V.

3.2.2 Mass balance and node pressure

For each node in the warm pipe shown in Figure 3.2, the mass balance is fulfilled such that:

$$\begin{aligned}
 \dot{m}_\nu + \dot{M}_\nu &= \dot{m}_{\nu-1}, \quad \nu = 1, 2, 3; \\
 \dot{m}_1 &= \dot{m}_0 - \dot{M}_1, \\
 \dot{m}_2 &= \dot{m}_1 - \dot{M}_2 = \dot{m}_0 - \dot{M}_1 - \dot{M}_2, \\
 \dot{m}_3 &= \dot{m}_2 - \dot{M}_3 = \dot{m}_0 - \dot{M}_1 - \dot{M}_2 - \dot{M}_3; \\
 \dot{m}_0 - \dot{m}_3 &= \dot{M}_1 + \dot{M}_2 + \dot{M}_3
 \end{aligned} \tag{3.1}$$

In the above equation, \dot{m}_0 represents the unknown mass flow at the first pipe segment $\nu = 0$. The network mass balance is fulfilled for any value of \dot{m}_0 which is obtained by the bifurcation function described in Section 3.2.4.

The excess pressure p_0 above the accumulator at node $\nu = 0$ is zero. The water pressure at the accumulator p_{acc} is the sum of the atmospheric pressure p_{atm} and an overpressure $p_{\text{o.p.}}$. Let p_ν denote the pressure above the accumulator at node ν :

$$p_{\text{acc}} = p_{\text{atm}} + p_{\text{o.p.}}, \quad p_{\text{total, warm side, } \nu} = p_{\text{acc}} + p_\nu; \quad p_0 = 0 \tag{3.2}$$

Given $p_0 = 0$ implies that the pressure p_1 at node $\nu = 1$ is proportional to the pressure drop in the first pipe segment $\nu = 0$.

3.2.3 Flow-pressure function

The pressure drop in circular pipes is generally expressed by the Darcy-Weisbach equation as:

$$\Delta p = c_f \cdot \frac{L}{D} \cdot \frac{\rho \cdot u^2}{2} \tag{3.3}$$

where c_f is the pipe friction factor, L is the pipe length, D is the hydraulic diameter, ρ is the fluid density, and u is the bulk fluid velocity.

The pipe friction factor c_f can be obtained from the Moody diagram based on the flow regime. A transition value of Reynolds number at around $Re_{tr} = 2000$ determines the flow regime. In the laminar region which occurs when $Re < Re_{tr}$, the friction factor is expressed by the Hagen–Poiseuille equation as:

$$c_f = \frac{64}{Re} \quad (3.4)$$

The pressure drop in the laminar region then becomes:

$$\Delta p = \frac{64}{Re} \cdot \frac{L}{D} \cdot \frac{\rho \cdot u^2}{2} = \frac{32\mu^2}{\rho} \cdot \frac{L}{D^3} \cdot Re, \quad Re = \frac{\rho D u}{\mu} \quad (3.5)$$

Blasius equation (Massey, 2006) is commonly used to describe the friction factor in smooth circular pipes in the turbulent region when $Re > Re_{tr}$. To account for the case of flow reversal with negative fluid velocity, the term u^2 is replaced with $u |u|$ and Equation (3.3) becomes:

$$|Re| > Re_{tr} : \quad \Delta p = c_f \cdot \frac{L}{D} \cdot \frac{\rho u |u|}{2}, \quad c_f = \frac{0.316}{|Re|^{0.25}} \quad (3.6)$$

Three constants are now introduced together with their corresponding units:

$$\begin{aligned} k_0 &= \frac{32\mu^2}{\rho} \cdot Re_{tr} \quad (\text{N}), & k_1 &= \frac{0.079}{16} \cdot Re_{tr}^{0.75} \quad (-), \\ k_2 &= \frac{\pi\mu Re_{tr}}{4} \quad (\text{kg}/(\text{m} \cdot \text{s})) \end{aligned} \quad (3.7)$$

A normalised Reynolds number x is expressed based on the mass flow \dot{m} and constant k_2 as:

$$x = \frac{Re}{Re_{tr}}, \quad Re = \frac{\rho D u}{\mu}, \quad \dot{m} = \frac{\pi\rho D^2 \cdot u}{4}, \quad x = \frac{\dot{m}}{k_2 \cdot D} \quad (3.8)$$

The normalised Reynolds number x indicates the flow regime. The flow is laminar for $-1 < x < 1$ and is turbulent for $x > 1$ and $x < -1$.

A combined flow-pressure function based on Equations (3.3) to (3.8) is now obtained:

$$\Delta p = k_0 \cdot \frac{L}{D^3} \cdot f_p(x), \quad f_p(x) = \begin{cases} x & |x| < 1 \text{ (laminar)} \\ k_1 \cdot x \cdot |x|^{0.75} & |x| \geq 1 \text{ (turbulent)} \end{cases} \quad (3.9)$$

Figure 3.3 shows the flow-pressure function for $k_1=1.477$ ($Re=2000$). In the laminar region bounded between $-1 < x < 1$, the function illustrated by the dashed red curve follows x . Outside the laminar region, the function follows the black line which represents the turbulent component as previously described in Equation (3.9). The flow-pressure function is discontinuous at the transition between laminar to turbulent at $x = 1$ and $x = -1$. This may cause some issues if the method is implemented numerically and where the function must be continuous. A proposed remedy to this problem is to introduce a relatively small distance Δx used for linear interpolation in the transition region. A detailed discussion about this remedy is provided in Paper VI.

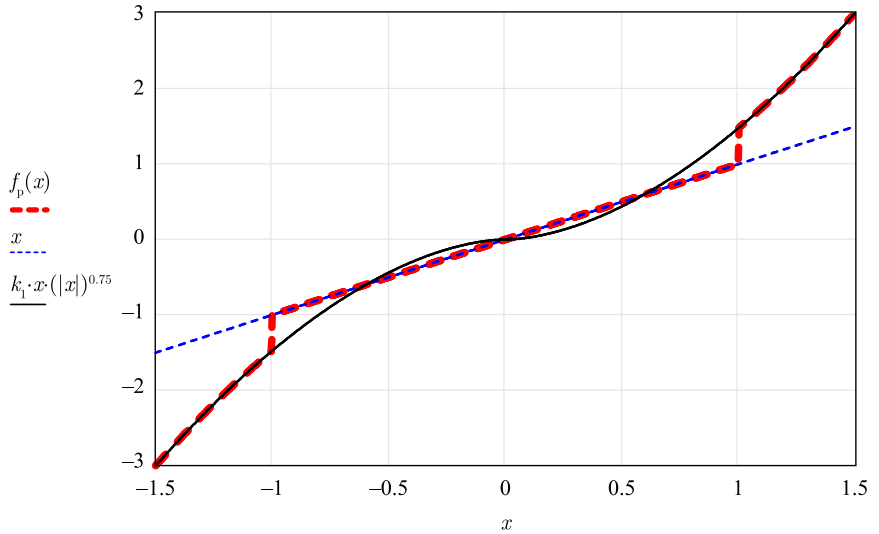


Figure 3.3 Flow-pressure function $f_p(x)$.

The presented flow-pressure function can be easily modified to account for the pipe roughness e that can be obtained using several equations such as Chen (1979), Churchill (1977), Haaland (1983), and Swamee and Jain (1976). The latter is adopted herein, and the flow-pressure function becomes:

$$\Delta p = k_0 \cdot \frac{L}{D^3} \cdot f_{\text{pSW}}(x, \acute{e}), \quad f_{\text{pSW}}(x, \acute{e}) = \begin{cases} x & |x| < 1 \\ \frac{\text{Re}_{\text{tr}} \cdot x \cdot |x|}{256 (\log(y))^2} & |x| \geq 1 \end{cases} \quad (3.10)$$

$$y = \frac{\acute{e}}{3.7} + \frac{5.74}{(\text{Re}_{\text{tr}} \cdot |x|)^{0.9}}, \quad \acute{e} = \frac{e}{D}$$

A new dimensionless flow-pressure function based on the Swamee-Jain equation is presented in Figure 3.4 for different values of relative roughness and up to larger x . It can be seen that in typical applications with smooth steel and plastic pipes ($e = 0.001 - 0.1$ mm), the pipe roughness has a quite small impact on the flow-pressure function.

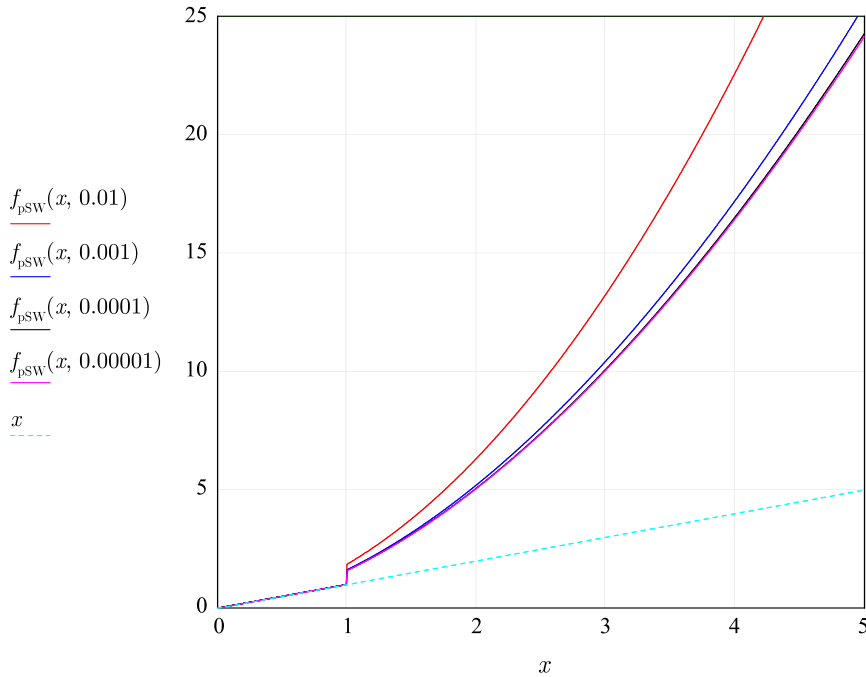


Figure 3.4 Flow-pressure function $f_{\text{pSW}}(x, \acute{e})$ based on the Swamee-Jain equation.

3.2.4 Bifurcation function

The bifurcation function $\Delta p_{\text{bf}}(\dot{m})$ is defined as the sum of pressure differences over a closed loop and is generally expressed for any number ν_{ps} of connected prosumers as:

$$\Delta p_{\text{bf}}(\dot{m}) = \sum_{\nu=0}^{\nu_{\text{ps}}} \Delta p(\dot{m}, \nu), \quad \Delta p(\dot{m}, \nu) = k_0 \cdot \frac{L_\nu}{D_\nu^3} \cdot f_p \left(\frac{\dot{m} - \Sigma_\nu}{k_2 D_\nu} \right); \quad (3.11)$$

$$\Sigma_0 = 0, \quad \nu \geq 1: \Sigma_\nu = \sum_{j=1}^{\nu} \dot{M}_j$$

The term Σ_ν denotes the sum of accumulated prosumer flows whereby the mass flow in a pipe segment ν becomes equivalent to $\dot{m} - \Sigma_\nu$.

To elaborate more on the meaning of the bifurcation function, consider the closed loop with a single prosumer shown in Figure 3.5. At the prosumer node, there is a bifurcation flow comprising two flows \dot{m}_0 in the upper pipe and $\dot{M}_1 - \dot{m}_0$ in the lower pipe. The bifurcation function has a single unique zero $\Delta p_{\text{bf}}(\dot{m}_0) = 0$ which is determined by applying a root solver. Accordingly, the bifurcation function determines the unknown mass flow \dot{m}_0 in any network to fulfil the network mass balance.

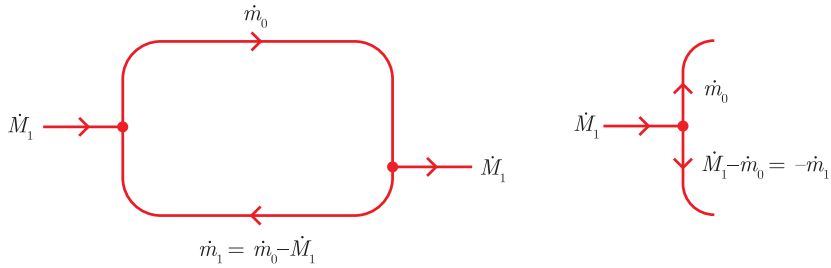


Figure 3.5 A simple closed loop with a single prosumer (left) and corresponding bifurcation flow (right).

Figure 3.6 shows the bifurcation function for the network with a single prosumer presented in Figure 3.5 with the following input data:

$$\begin{array}{l} \nu_{\text{ps}} = 1, \quad \dot{M}_1 = 10 \text{ (kg/s)}, \quad L_0 = 100 \text{ (m)}, \quad L_1 = 150 \text{ (m)}, \\ D_0 = D_1 = 0.25 \text{ (m)}, \quad \mu = 1.0 \cdot 10^{-3} \text{ (kg/(m} \cdot \text{s))}; \quad \Rightarrow \\ \Sigma_0 = 0, \quad \Sigma_1 = \dot{M}_1 = 10; \quad \Delta p_{\text{bf}}(0) < 0, \quad \Delta p_{\text{bf}}(\dot{M}_1) > 0 \quad \Rightarrow \\ 0 < \dot{m}_0 < 10 \end{array} \quad (3.12)$$

The blue dashed curve represents the pressure drop function for the upper pipe segment $\nu = 0$, whereas the black dashed curve represents the pressure

drop function for the lower pipe segment $\nu = 1$. The red curve shows the bifurcation function with the single unique zero which occurs at $\dot{m} = \dot{m}_0 = 5.572$ where the two pressure drop functions balance each other at the root.

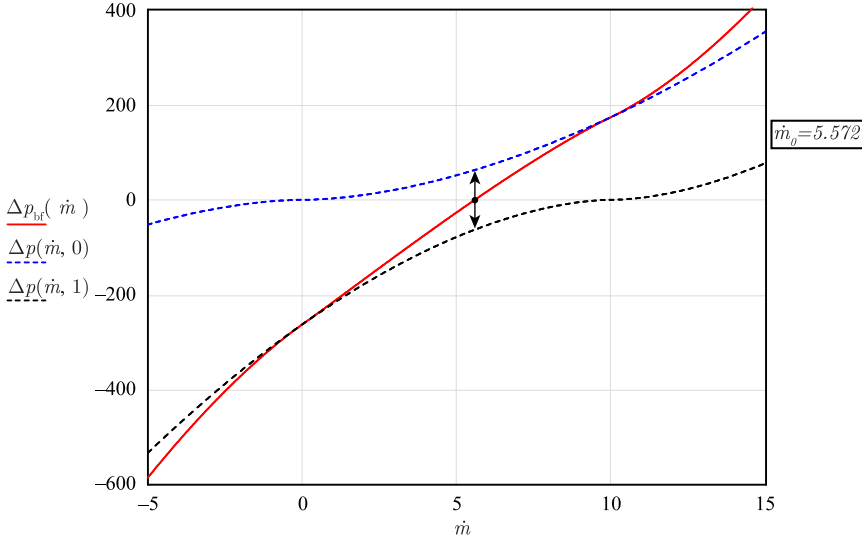


Figure 3.6 Bifurcation function with its two parts $\Delta p_{\text{bif}}(\dot{m}) = \Delta p(\dot{m}, 0) + \Delta p(\dot{m}, 1)$.

3.3 Steps for implementing the new analytical method

The new analytical method evaluates the hydraulic states in BLTNs with any number ν_{ps} of prosumers in terms of mass flows in each pipe segment in the closed loop and node pressures following the below eight simple steps:

Step 1: The input data required for the full solution include:

$$\rho, \mu, \text{Re}_{\text{tr}} (= 2000); \quad \dot{M}_{\nu} \text{ for } \nu = 1, \dots, \nu_{\text{ps}}; \quad L_{\nu}, D_{\nu} \text{ for } \nu = 0, 1, \dots, \nu_{\text{ps}} \quad (3.13)$$

Step 2: Three constants (k_0, k_1, k_2) are defined according to Equation (3.7).

Step 3: The accumulative prosumer flows in the network are determined as:

$$\Sigma_0 = 0, \quad \nu = 1, \dots, \nu_{\text{ps}} : \Sigma_{\nu} = \sum_{j=1}^{\nu} \dot{M}_j \quad (3.14)$$

Step 4: The flow-pressure function for a pipe segment is defined as in Equations (3.9) and (3.11).

Step 5: The bifurcation function gives the pressure drop around the closed loop of pipes as a function of the unknown mass flow $\dot{m} = \dot{m}_0$:

$$\Delta p_{\text{bf}}(\dot{m}) = k_0 \cdot \sum_{\nu=0}^{\nu_{\text{ps}}} \frac{L_{\nu}}{D_{\nu}^3} \cdot f_p \left(\frac{\dot{m} - \Sigma_{\nu}}{k_2 D_{\nu}} \right) \quad (3.15)$$

Step 6: The unknown flow in the first pipe segment $\nu = 0$, \dot{m}_0 is the value where the bifurcation function becomes zero:

$$\Delta p_{\text{bf}}(\dot{m}_0) = 0, \quad \left(\sum_{\nu=0}^{\nu_{\text{ps}}} (p_{\nu+1} - p_{\nu}) = p_{\nu_{\text{ps}+1}} - p_0 = 0 \right) \quad (3.16)$$

Step 7: All pipe mass flows are now determined from the root \dot{m}_0 :

$$\nu = 0, 1, \dots, \nu_{\text{ps}} : \dot{m}_{\nu} = \dot{m}_0 - \Sigma_{\nu} \quad (3.17)$$

Step 8: The pressure in each node is finally calculated as:

$$p_0 = 0, \quad \nu = 0, 1, \dots, \nu_{\text{ps}} : p_{\nu+1} = p_{\nu} + k_0 \cdot \frac{L_{\nu}}{D_{\nu}^3} \cdot f_p \left(\frac{\dot{m}_{\nu}}{k_2 D_{\nu}} \right), \quad (3.18)$$

$$\left(p_{\nu_{\text{ps}+1}} = p_0 \right)$$

It was mentioned earlier in the motivation section that in actual applications of BLTNs the network is firstly constructed as a single closed loop. As the network expands, a meshed network consisting of multiple closed loops is likely to be formed. The presented analytical method is capable of solving meshed networks with multiple loops. This case is discussed extensively in Paper V.

3.4 Summary

Advanced technologies of district heating and cooling systems enable connecting multiple heat prosumers to the same network. Consequently, the fluid in the piping network and the energy carried by the system are no longer restricted to flow in one direction. A new fast and accurate analytical method for modelling network hydraulics in district systems with bidirectional mass and energy flows was developed. The solution sequence is

straightforward and mainly includes the definition of a simple flow-pressure function and a bifurcation function. To summarise, the newly developed analytical method offers several major advantages for modelling BLTN hydraulics compared to traditional numerical methods. First, the analytical method can solve any network topology with any number of connected prosumers without describing the system graphically in much detail. Second, the robust and simple solution sequence makes the analytical method easy to implement in any simulation software. Third, issues in numerical methods related to zero or near-zero values, execution of iterative algorithms, and reaching solution convergence are all avoided in the new analytical method. Finally, the newly developed analytical method supports rapid evaluation of the hydraulic states as well as the plotting of pressure gradient curves which in turn supports safe hydraulic design and operation.

Chapter 4

Model applications

This chapter demonstrates the applicability of the developed multi-domain model on two existing and operational systems with advanced district heating and cooling technologies and one system currently under construction. The technical concept for each system is firstly described and the system performance is subsequently analysed through simulations. The chapter also presents the application of the newly developed analytical method for modelling hydraulics in terms of its validation and the understanding of pressure propagation in bidirectional networks.

4.1 Case study I

The system presented in Figure 4.1 shows what is regarded as the first Swedish district network with simultaneous heating and cooling delivered through decentralised heat pumps and chillers. The system is designed to connect 15 buildings in a campus area, nine of which have been considered while performing the analysis. The buildings were constructed in the 1970s and have different usage including offices, research facilities, conference rooms, sport halls, and dining areas. The energy supply system consisted of

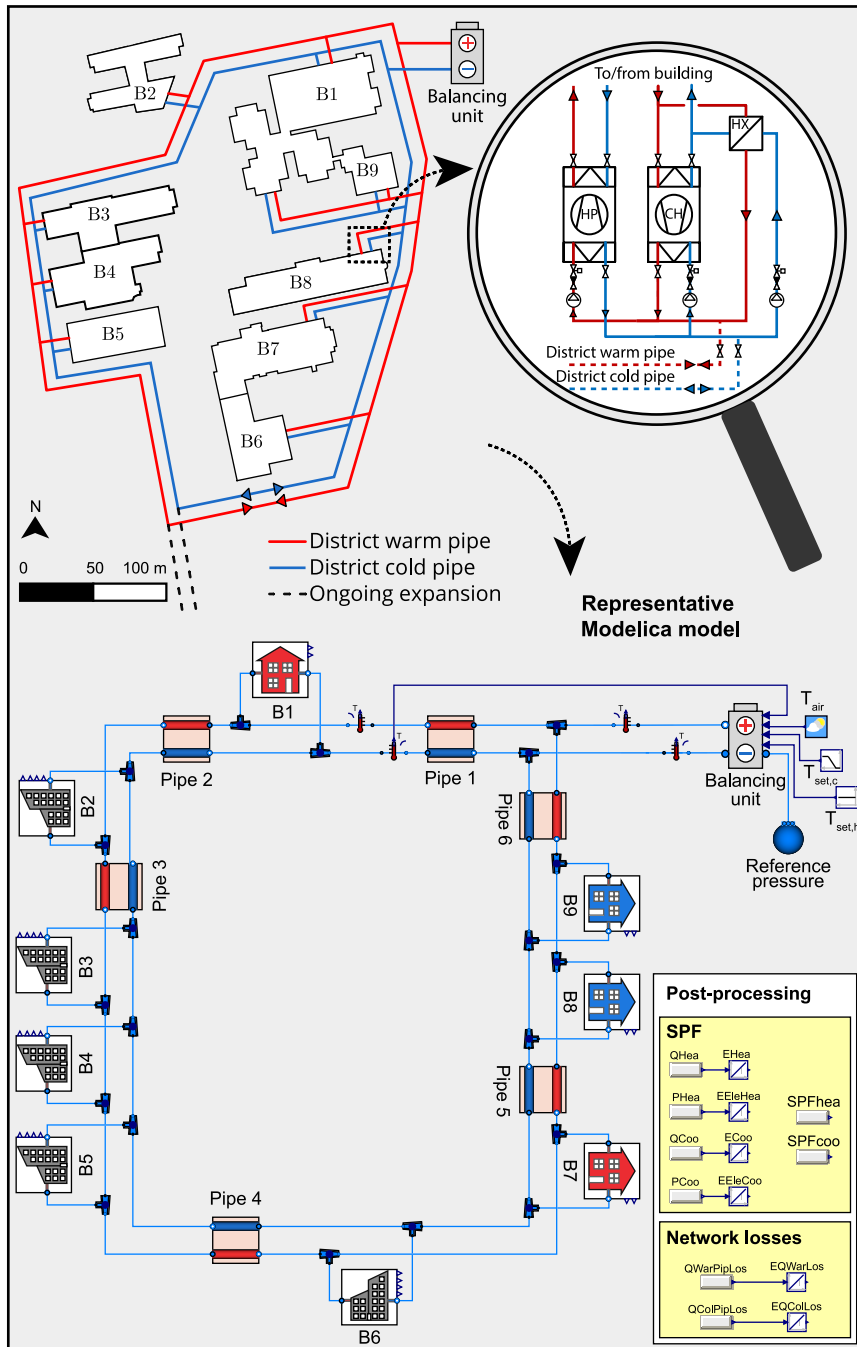


Figure 4.1 Illustration of Case study I (top) and the representative Modelica model (bottom).

traditional district heating and cooling with four pipes in total indicating supply and return.

In 2018, the energy system was renovated to feature a 5GDHC system with a new two-pipe distribution network, new decentralised substations, and a new energy source and/or sink referred to as a balancing unit. The balancing unit is equipped with an accumulator tank, cooling towers, and a large reversible air-source heat pump that maintains the network temperature within prescribed temperature levels according to a free-floating control strategy. The motivation behind retrofitting the energy system was that the new 5GDHC system would cover most of the energy demands by utilising power-to-heat technologies and by establishing synergies between the connected buildings. The entire campus area has a heated floor area of around 105,000 m² with measured yearly demands in 2017 near 10.8 GWh of heating and 4.7 GWh of cooling.

As shown in the magnified part of Figure 4.1, the new decentralised substations incorporate heat pumps, mechanical chillers, and free-cooling heat exchangers which all allow local energy sharing within the substation as well as between the connected buildings. The new piping network is made of uninsulated plastic pipes with an average nominal size of 200 mm and a total length of 1,710 m. The balancing unit includes a reversible air-source heat pump, cooling towers, and a 150 m³ accumulator tank used to provide enough static pressure to ensure adequate flow to all connected buildings.

Measurement data taken between August 2020 and July 2021 have been used to validate and simulate the system using the developed Modelica model. The measurements have been obtained from thermal energy meters located at the district side inside each substation. Model validation has been performed using the probabilistic validation described in Section 2.3. The three sources of errors including the error of the calculator of the thermal energy meter, the error of the temperature sensor pair, and the error of the flow sensor have been propagated to a maximum permissible error equivalent to 9 %. This value has been used as a benchmark level to compare the probability of the model error. Overall, validation results using different benchmark levels suggest that the model has high accuracy in modelling heat flow rates, which enables evaluating the system performance with high confidence.

Figure 4.2 shows annual hourly simulation results at different system levels. Figure 4.2(A) indicates changes in the system state with regard to the ambient air and soil temperatures. The total network demands are presented

in Figure 4.2(B) showing a peak power for heating and cooling of about 1 MW and annual heating and cooling energy of 4.2 and 1.4 GWh, respectively. The network temperature floats between 5 and 40 °C as shown in Figure 4.2(C). At times of dominant heating demands as shown in winter months, the network temperature is at its lowest due to the dominant heat extraction. Conversely, the heat injected into the network due to the cooling needs causes the network temperature to rise as shown in summer months. Flow reversal can be clearly understood by looking at Figure 4.2(D) where a positive sign indicates a flow direction from the warm to the cold pipe when heating demands dominate. The thermal power provided by the balancing unit to maintain the network temperature is shown in Figure 4.2(E) and the corresponding network losses per unit length are shown in Figure 4.2(F). It can be seen that the warm pipes lose heat to the ground throughout the year while the cold pipes gain heat from the ground due to the lower fluid temperature of the latter.

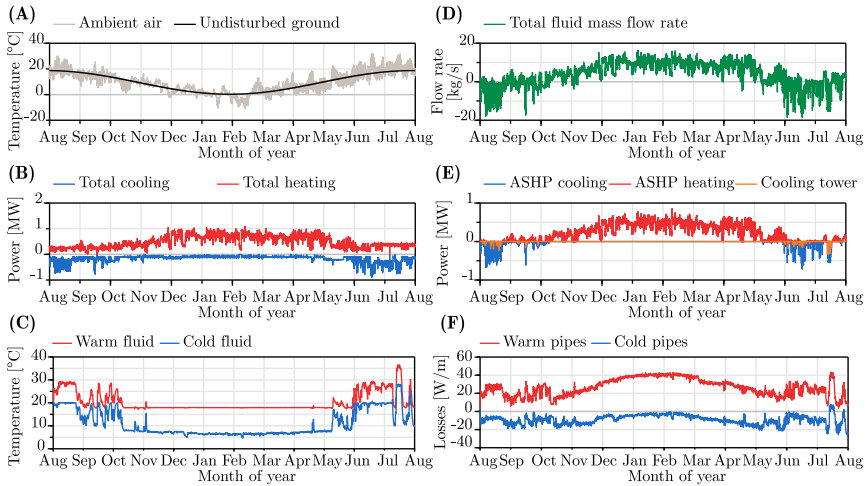


Figure 4.2 Annual hourly simulation results of Case study I showing boundary conditions (A), network demands (B), network temperature (C), network mass flow rates (D), thermal power provided by the balancing unit (E), and network heat losses (F).

From an overall system perspective, the annual Seasonal Performance Factor (SPF) defined as the ratio between the total delivered thermal power and the total used electric power was found to be 4.1 and 7.3 for heating and cooling, respectively. Several factors could have a direct impact on improving the system performance. First, the obtained measured data used for system analysis highlighted some of the current challenges for adequate

instrumentation and data recording. For example, the placement of the energy meter does not necessarily represent the conditions of the heat pump, especially in situations where multiple heat pumps are installed in one substation and where different streams are mixed. This factor points to the limitation of the developed model where only one heat pump with infinite capacity is used, which may cause a large error between modelled and measured heat flow rates at around 20 %. The second factor is related to maximising the utility of the free-cooling heat exchangers. Because of the low return temperature from the building cooling system, free-cooling was inadequately utilised based on the operating conditions described in the controller shown in Figure 2.3. Another improvement factor is associated with the pipe insulation. Due to the network dominant heating demands throughout the simulated year, insulating only the warm pipes may reduce network losses by up to 90 % and further improve the system performance. It should also be pointed out that the newly constructed 5GDHC system can materialise an additional benefit if connected to the existing third generation DH. Such a connection would make the traditional network act as a heat source to the new network while at the same time it would increase the capacity of the traditional network without changing the flow.

4.2 Case study II

The second analysed system presented in Figure 4.3 consists of 15 single-family detached houses located in Denmark. A unique aspect of this system is that it is in a rural area far from existing infrastructure of traditional district networks. Traditionally, DHC systems are considered beneficial in urban areas with high heat densities. The evaluation of the presented system in this section could therefore open new opportunities for DHC to penetrate market segments that were not possible before.

The buildings are connected through a plastic uninsulated two-pipe network to a shallow geothermal borefield. The houses were built in 2018 to meet the requirements of the Danish building code with a yearly heating consumption of 8 MWh for a typical single-family house of 130 m². Each house is equipped with a single heat pump used for both space heating and domestic hot water (DHW). In a space heating mode, the heat pump extracts the heat-carrying fluid coming from the borefield through the district pipe and supplies hot water to the building heating system. The heat-carrying fluid in the borefield and the distribution network is brine with 30 % mass

fraction of propylene glycol in water. Once or twice a week, the heat pump operates at a high supply temperature at around 60 °C for legionella protection.

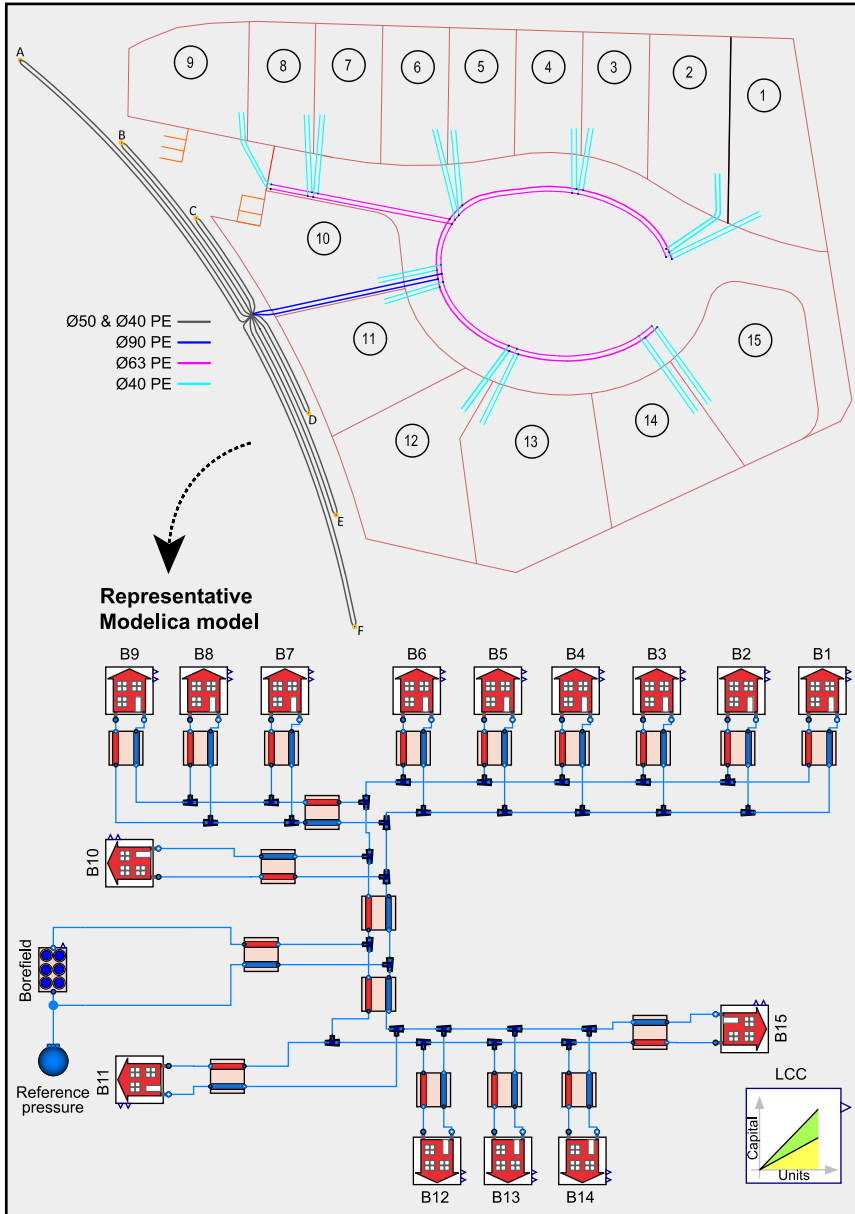


Figure 4.3 Illustration of Case study II (top) and the representative Modelica model (bottom).

The energy source consists of six boreholes connected in parallel as shown in Figure 4.3. Each borehole is 120 m deep and has a radius of 75 mm. An in-situ thermal response test was performed, and the borehole thermal resistance was found to be 0.12 (m·K)/W with an effective thermal conductivity of 2.36 W/(m·K). The distribution network has a total length of 484 m and includes three different pipe sizes for the boreholes' main pipe, the branch pipes, and the connection to houses with respective diameters of 90, 63, and 40 mm.

Construction work began in 2018 and the houses were connected to the network at different stages. Thus, the obtained measured data for a total period of four years do not have a uniform time series with matching start and end dates. The obtained measured data include four variables representing the temperature levels at the inlets and outlets of the heat pump evaporator and condenser sides. The installed heat pumps are standard for single-family houses and typically operate with a constant flow where the heating power is derived accordingly (Liu et al., 2020). In 14 out of the 15 connected houses, the installed heat pump has a nominal capacity of 5.8 kW. The supply temperature from the heat pump is controlled based on a temperature compensated curve that varies according to the outside weather and the room setpoint. The remaining heat pump in the last house has a nominal capacity of 10.3 kW with a similar operation.

A Life-Cycle Costing (LCC) analysis was performed before the system was built in 2018 to assess the system's economic feasibility. A Modelica model for the LCC analysis was therefore developed and implemented alongside the system model as shown in the lower right corner of Figure 4.3. The LCC model is based on the Net Present Value (NPV) that was applied to compare the capital investment and cash flows over a lifetime as:

$$NPV = \sum_{t=0}^N \frac{CM}{(1+i)^t} = \sum_{t=0}^N \frac{(\text{Revenue} - \text{Costs})}{(1+i)^t}$$

where CM is the contribution margin, i is the discount rate, t is the time of the cash flows, and N is the number of life cycle years. The breakdown of revenue (positive cash flows) and costs (negative cash flows) is provided in detail in Table 4.1.

Results for the simulated year between January 2021 and December 2021 are presented in Figure 4.4. The temperatures of the ambient air and undisturbed ground at the pipe burial depth are shown in Figure 4.4(A). The aggregated demands of all buildings including space heating and DHW are

Table 4.1 Breakdown of revenue and costs for the performed LCC analysis in the year 2018.

Description	Value	Unit
LCC		
Interest on loan	2.6	[%]
Discount rate	3.0	[%]
Life cycle years	20	[-]
Revenue		
Heat selling price	350	[DKK/MWh _{th}]
Heat meter rent fee	840	[DKK/ unit]
Facility contribution (related to cooperative networks)	2,400	[DKK/house]
Fixed fee	15.2	[DKK/m ²]
Costs		
1. Production costs		
Electricity price excluding taxes	689	[DKK/MWh _{el}]
Water treatment cost	5	[DKK/MWh _{th}]
Piping cost	6	[DKK/MWh _{th}]
Maintenance cost	1,750	[DKK/house/year]
Servicing cost	250	[DKK/house/year]
Administration costs	400	[DKK/house/year]
2. Investment costs		
Drilling cost	79,746	[DKK/borehole]
Heat pump cost excluding VAT	58,867	[DKK/unit]
Earthwork cost	136,693	[DKK]
Piping network cost	147,188	[DKK]
Excavation for house connection	6,600	[DKK/house]
Electric unit to heat pumps	8,220	[DKK/unit]
Heat meter cost	3,120	[DKK/unit]
Subsidies and allowance (negative costs)	-73,537	[DKK/house]

shown in Figure 4.4(B). The peak demand occurs in February with about 80 kW, which corresponds approximately to the peak of all 15 buildings combined given the nominal capacity of each installed heat pump. The average borefield temperature is shown in Figure 4.4(C) indicating the heat extraction from the ground according to demand and outside weather. The total mass flow rate of the brine entering and leaving the borefield is represented by the green line in Figure 4.4(D) and corresponds to the sum of mass flows from all connected buildings. Network losses are shown in Figure 4.4(E). It should be noted that in systems with only heating demands like the one analysed herein, heat gains from the ground to the piping network (presented in a negative sign) cause the distribution network to act as a horizontal heat exchanger with the ground and are therefore beneficial. Heat gains in the cold pipes are relatively larger than in the warm pipes due to the higher temperature difference between the undisturbed ground and the heat-

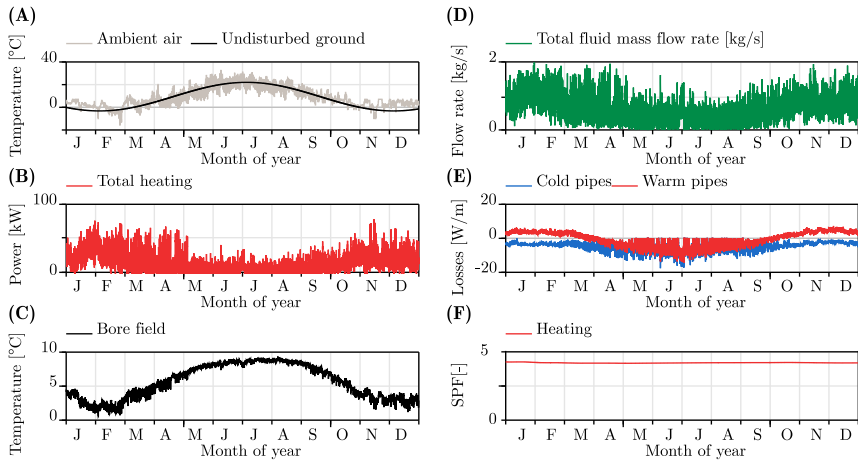


Figure 4.4 Annual hourly simulation results of Case study II showing boundary conditions (A), network demands (B), average borefield temperature (C), network mass flow (D), network heat losses (E), and system seasonal performance factor (F).

carrying fluid. Throughout the simulated year, heat gains amounted up to 20 % of the total delivered heat to all buildings with a total seasonal performance factor of 3.3 as shown in Figure 4.4(F).

Figure 4.5 is used to study the impact of continuous heat extraction on the borefield temperature and the profitability of the system over the 20 years lifetime. The left diagram highlights the ground depletion over four years due to the continuous heat extraction and the lack of ground balancing, see Figure 4.4(B). The right diagram of Figure 4.5 establishes the relationship between the NPV and the system seasonal performance factor. Given the cost structure provided in Table 4.2, a breakeven point is found at an SPF of around 3.3. It can also be seen that throughout the life cycle, the system does not yield high economic gains given the provided revenue and cost structure. It is worth noting that in regulated district heating markets such as in Denmark, prices are determined based on the ‘non-profit’ principle which holds that the final heating price for the end-user comprises the total accumulated costs for heat, generation, distribution, and service (Brown et al., 2022).

Based on the presented analysis, potential system improvements may exist in two areas related to the heat pumps and the borefield. In the former case, a stable heat pump supply temperature would further increase its efficiency. This can be achieved by adjusting the temperature compensated curve which currently gives high and quick variations in the required supply temperature

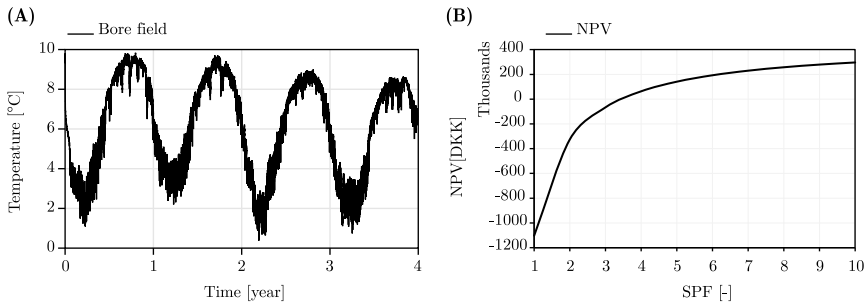


Figure 4.5 Evolution of borefield average temperature over four years (A) and impact of system performance on profitability (B).

from the heat pump. It should also be noted that due to the lack of complete measured data, the modelled heat pumps were assumed to operate with a constant mass flow. Therefore, an improved measurement plan that considers both the source side of the district network and the supply side of the building heating system is necessary to reduce uncertainty and gain a holistic understanding of the system. The second improvement area can be attained by providing direct space cooling to the connected houses, which would improve comfort and at the same time increase the system performance by injecting heat from the houses into the ground to improve ground thermal balance, and in turn the supply temperature to heat pumps in winter.

4.3 Case study III

The last case study presented in this section is based entirely on simulated demand profiles as the system is currently under development. Simulating the system at this stage would enable evaluating the potential of energy sharing through a geothermal DHC network and comparing the system performance with different types of connected buildings. The concept is based on the energy sharing community like the one shown in Figure 4.6. Each decentralised substation has its own borefield which acts as an energy source and/or sink where one substation may serve single or multiple buildings. The concept has prominent advantages as it provides energy independence to each building through the included borefield while at the same time it connects buildings within a community through a distribution network for possible energy exchange. Such a connection would not only

improve the technical performance of the system, but it would also increase social participation and awareness about energy related questions.

Inside each substation, a number of control valves determine whether energy can be shared between the borefields. The control strategy for the energy sharing concept has been previously described in Section 2.2.3. Heat pumps have three modes of operation to provide DHW, space heating, and space cooling. In the latter case, the cold side of the heat pump is connected to the free-cooling heat exchanger for direct cooling supply where the waste heat at the hot side is injected into the borefield. The heat pump model is parametrised with a Carnot efficiency obtained based on the actual installed product. The system is designed for new energy-efficient buildings aiming to achieve level gold by the Swedish environmental certification system Miljöbyggnad version 3.0 (Sweden Green Building Council, 2017). A gold level is reached when the energy use in residential and office buildings is reduced respectively by 70 and 60 % compared to the existing requirements in the Swedish building code (Boverket, 2020). Substation 1 shown in Figure 4.6 serves two buildings with both heating and cooling demands. The two buildings consist of office spaces and conference rooms, and construction work is expected to finish in October 2023 which consist of. The second substation serves a residential elderly home with only heating demands and is expected to open in early 2024. In these kinds of buildings, it is expected that the demand for domestic hot water will exceed the demand for space heating. In total, the three buildings have a heated floor area of around 25,200 m². Borefield 1 has 30 boreholes, each is 300 m deep and has a thermal resistance of 0.1 (m·K)/W and an effective thermal conductivity of 2.0 W/(m·K). On

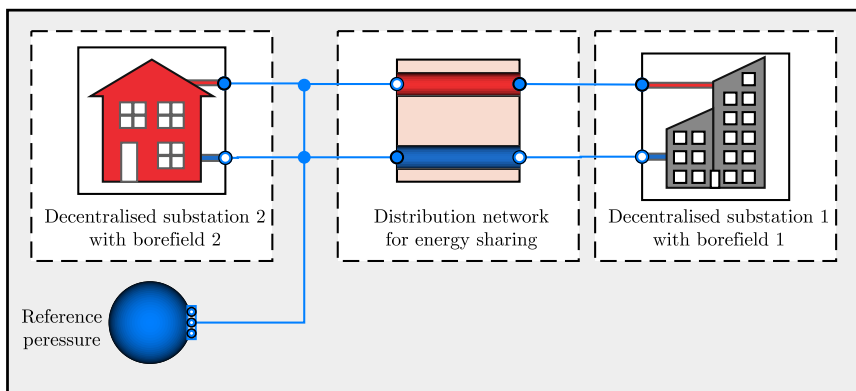


Figure 4.6 Representative Modelica model of Case study III based on the sharing energy concept described in Figure 2.6.

the other hand, borefield 2 has 12 boreholes, each is 285 m deep with a similar thermal resistance and effective thermal conductivity.

Demand profiles obtained from simulations using IDA-ICE software for whole-building energy simulation were provided by system designers. The demand profiles have been used as inputs to the Modelica model to simulate the entire energy community comprising the two substations. Figure 4.7 shows annual simulation results of the system including different variables. The peak heating demand occurs in January at about 0.4 MW, of which almost 0.13 MW is related to DHW production, as shown in Figure 4.7(B). The average temperature of each of the two borefields is shown in Figure 4.7(C). The impact of summer heat injection into the ground can be seen in substation 1 with both heating and cooling demands which causes the average borefield temperature to rise. The situation is different in borefield 2 as substation 2 receives a warmer fluid from borefield 1 due to the established energy sharing presented in Figure 4.7(D). A positive mass flow direction indicates a flow from substation 1 to substation 2 according to the fluid ports shown in Figure 4.6 and based on the Modelica sign convention introduced earlier in Figure 2.1 and Figure 2.2. The flow direction lays down the following explanations: since the return temperature from the buildings in substation 1, or the borefield leaving temperature, is higher than the borefield

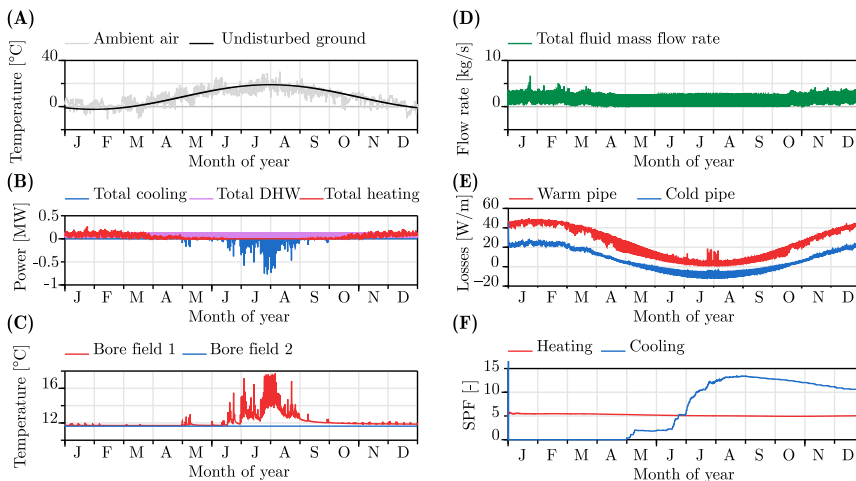


Figure 4.7 Annual hourly simulation results of Case study III showing boundary conditions (A), network demands (B), average borefields temperatures (C), network mass flow (D), network heat losses (E), and system seasonal performance factors.

temperature in substation 2 with heating demand, the fluid flows along the distribution pipe to substation 2 to improve its heat pump performance. The same principal applies in summer when the fluid continues to flow in the same direction as DHW demands exist in the residential building. Network losses per unit length are presented in Figure 4.7(E) and amount to about 5 % of the total delivered energy for heating and cooling. The system SPF is shown in Figure 4.7(F) with values around 4.8 and 11.0 for heating and cooling, respectively.

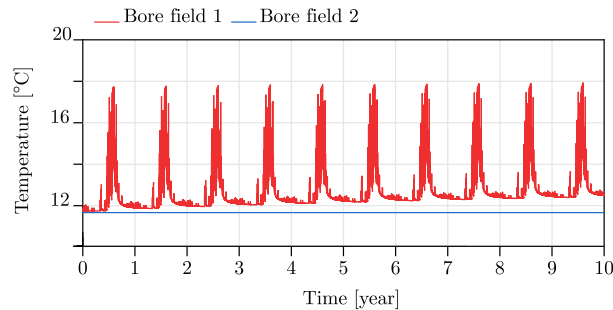


Figure 4.8 Evolution of borefield average temperature over ten years.

To study the impact of demand profiles on the temperature evolution in both two borefields, Figure 4.8 shows 10-year simulation results using the same demands presented in Figure 4.7(B). The existing cooling demands and the established energy sharing between the two substations have two advantages. First, the injected heat into borefield 1 due to the cooling demands causes its temperature to increase over the simulated period. Second, the shared energy from borefield 1 reduces the heat build-up and balances the temperature of borefield 2 which would otherwise experience ground depletion due to the lack of local heat injection.

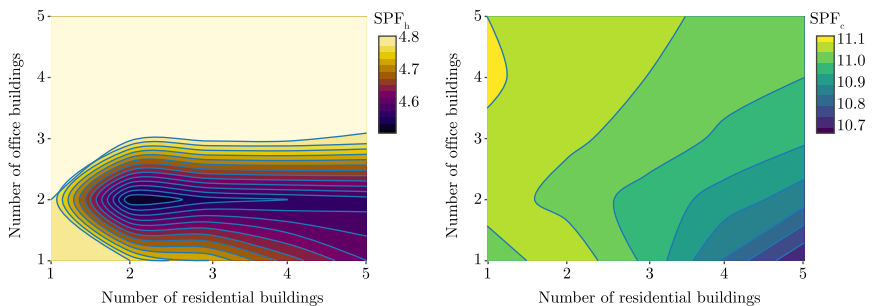


Figure 4.9 Contour maps for heating and cooling performance factors at different building clusters.

The analysis performed on the energy sharing concept sheds light on the important role of demand variation between connected buildings. Figure 4.9 shows contour maps for the changes in heating and cooling seasonal performance factors with different building clusters. Residential and office buildings refer in this context to buildings with the same demand profiles as presented in Figure 4.7(B). The contour maps support the decision-making during network expansion to find favourable building clusters and show that greater gains can be attained by connecting more office buildings due to the injected or shared heat into the ground or between buildings. Both the heating and cooling SPF can be increased by 6 and 4 % respectively when the ratio between office to residential buildings is 5:1. Overall, the dominant demand type across the year determines which performance factor should be favoured over the other to reduce the total purchased energy within the energy community.

4.4 Hydraulic applications

This section presents two approaches for validating the new analytical method for modelling hydraulics in BLTNs. The first approach involves an experimental investigation using a lab test bench, while the second compares the analytical method against three established numerical methods using a set of predefined validation tests. The section ends with an explanation of the pressure propagation in BLTNs with the help of pressure gradient curves.

4.4.1 Experimental investigation

The laboratory at the Division of Building Services at Chalmers University of Technology in Sweden is equipped with several facilities to test the operation and control strategies for borehole thermal energy storage, ground-source heat pumps, chilled beams, air handling units, among others (Javed and Fahlén, 2011). Each of the facilities is connected through piping networks that couple different supply and delivery systems. The type of the heat-carrying fluid and the pipe connections can be changed to modify or design new test setups.

A new facility was built as shown in Figure 4.10 to test flow reversal and prosumer's differential pressure in BLTNs with a two-pipe system. The facility is comprised of six prosumers, three on the right side and three on the left side. A tank ensures enough pressurisation in the pipes at around 1.2 bar. From the tank, the main copper pipe with an outer diameter of 42 mm

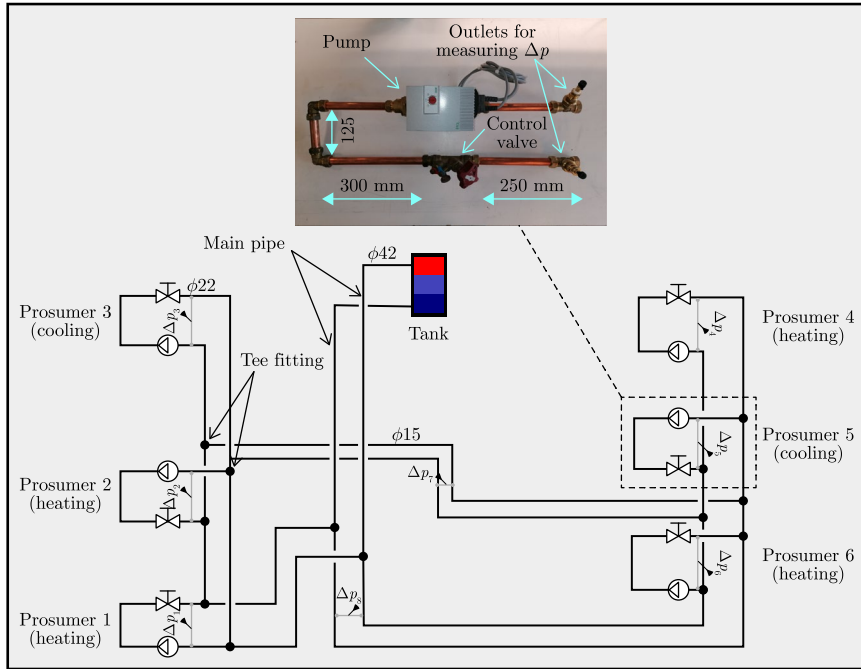


Figure 4.10 Schematic layout of the laboratory setup showing the eight positions for measuring Δp .

distributes the water to the two sides of the network whose outer pipe diameter is 22 mm. Another pipe with an outer diameter of 15 mm connects the two sides to study flow bifurcation at varying flows.

The demand type in each prosumer is determined based on the connection side of the circulation pump. For instance, the circulation pump in Prosumer 5 extracts water from the cold pipe to represent a building with cooling demands. The control valve is mainly used to measure the flow and the differential pressure across the valve to validate the measuring instruments prior to measuring the differential pressure at the prosumer's connection. In total, differential pressure was measured at all six prosumers in addition to two positions indicating the main and new pipes. Measuring differential pressure was performed using the instrument TA-SCOPE which consists of two parts. The first part is the differential pressure sensor that has two hoses connected to the measuring outlets shown in Figure 4.10. The second part is the display unit which features wireless communication with the differential pressure sensor. The instrument has an uncertainty that is equal to the highest between 0.1 kPa or 1 % of the reading.

A total of nine test cases were designed to represent different network operating conditions by varying the pump speed and the valve position in each prosumer. Measurements from the lab test bench have been compared against results obtained using the newly developed analytical method and a numerical Modelica model that represents the built system. Measurements of flow and differential pressure across the valve have been in excellent match with the modelled values. However, large discrepancies have been found when comparing differential pressure measurements across the prosumer's connection, as shown in Figure 4.11. The results show significant errors between measured and modelled values for most of the cases. Reasons for such large errors can be related to the relatively small pipe sizes compared to actual applications of DHC systems and the large number of bends and T-junctions. Losses due to pipe fittings are usually difficult to quantify. They can be either estimated using, e.g., the equivalent length method suggested by ASHRAE (2017), or through product catalogues. In both approaches, simplifications are made to approximate losses in pipe fittings and a wide range can be attained.

Findings from the experimental investigation reveal the challenges in measuring differential pressure which can be ascribed to either, or all, of the following reasons: 1) pressure waves travel along the pipe at the speed of sound at approximately 1400 m/s and is therefore difficult to record at a stable condition, 2) fitting losses are difficult to estimate especially in small-scale systems with large number of fittings, and 3) the model's level of accuracy is directly influenced by the simplifying assumptions made to represent the actual system. Due to the abovementioned reasons, a study based on comparative validation against established hydraulic modelling tools was conceptualised to validate the newly developed analytical method.

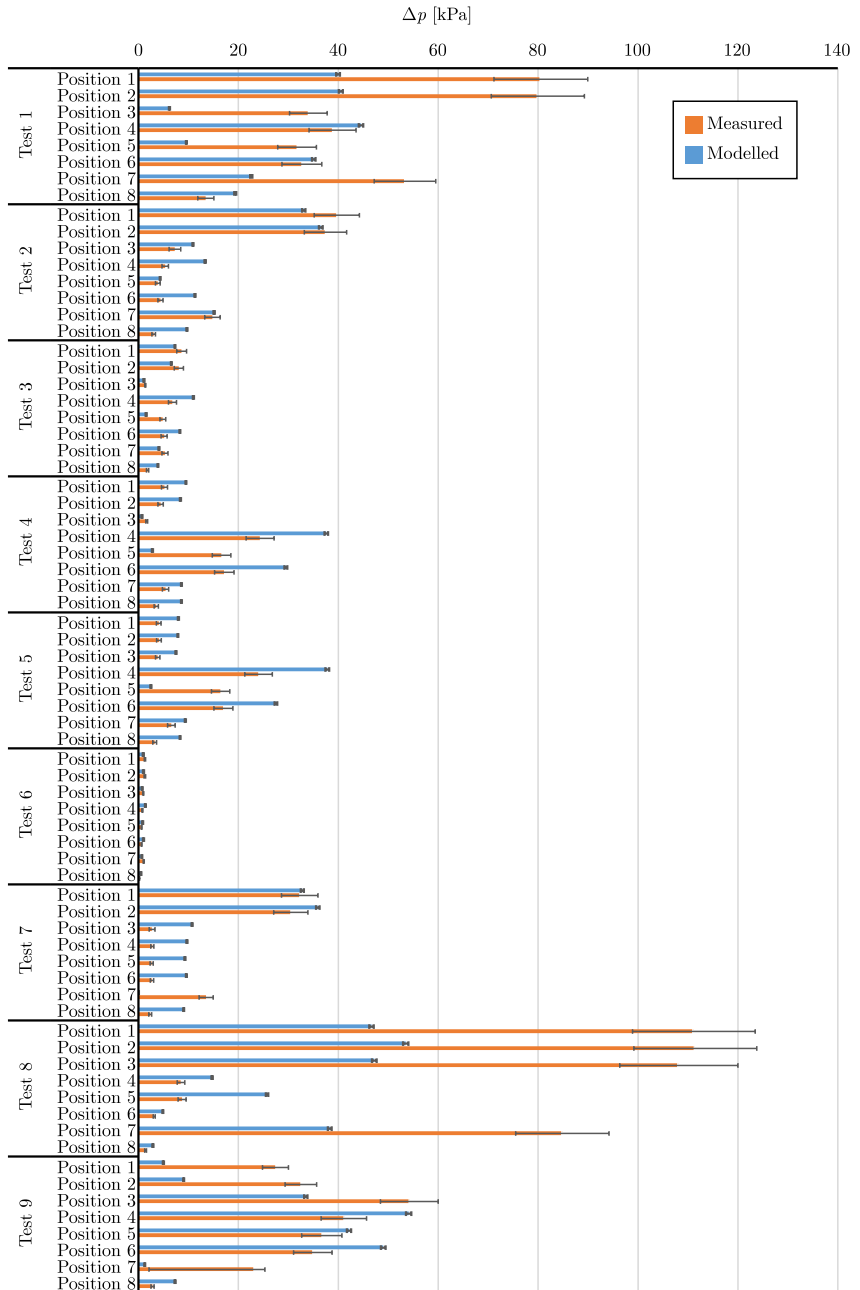


Figure 4.11 Measured and modelled pressure difference based on the laboratory test bench. Error bars denote measurement uncertainty.

4.4.2 Comparative validation

This section is based on Paper VI.

This section presents the approach for validating the new analytical method against three established numerical methods, namely Modelica, Pipe Flow Expert (PFE) software, and Program Flow System (PFS) software. The theoretical background of how each method evaluates the hydraulic states in fluid systems is provided in appended Paper VI. A network example has been used and modelled using all four methods to perform nine validation tests. The BLTN shown in Figure 4.12 consisting of two loops with warm and cold pipes is used in all test cases. Loop 1 connects Buildings 1 to 6 and is used in tests 1 to 7. Loop 2 on the other hand indicates the case of network expansion with five new buildings connected to the network and is used in tests 8 and 9.

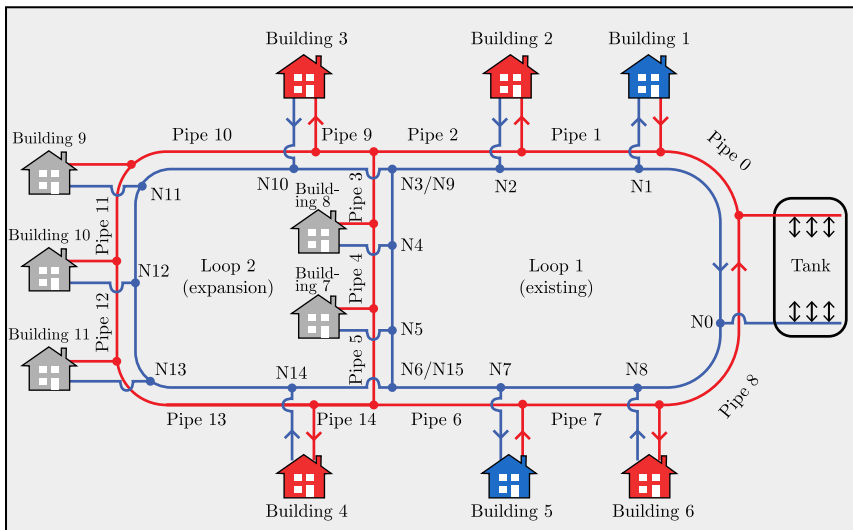


Figure 4.12. Illustration of the BLTN used for comparative validation showing the assumed positive flow direction. Note that the demand type in buildings 7 to 11 change from one test to another and hence are presented in grey colour.

The description of each test case is provided in Table 4.2. In tests 1 to 7, Loop 1 connects six buildings with different thermal demands to an accumulator tank. Four buildings have only heat demands and two have only cooling demands. For tests 8 and 9, five new buildings are connected, and a two-loop system is formed. The demands in the newly connected buildings

vary from one test to another to analyse the impact of different demand profiles on the pressure propagation along the network length.

Table 4.2 Description of the comparative validation tests.

Test number	Description
Test 1	Nominal operating conditions with mass flows based on the building's size and typology.
Test 2	Peak winter conditions with only heat demands.
Test 3	Peak summer conditions with only cold demands.
Test 4	Dominant heat demands in spring/autumn.
Test 5	Dominant cold demands in spring/autumn.
Test 6	Operation in only the upper side of the loop (Building 1, 2, and 3).
Test 7	Operation in only the lower side of the loop (Building 4, 5, and 6).
Test 8	Network expansion with two closed loops, five additional buildings, and dominant heat demands.
Test 9	Network expansion with two closed loops, five additional buildings, and dominant cold demands.

Results from the comparative validation showed that the new analytical method can model hydraulics in bidirectional networks accurately and yet quickly. In all considered test cases, the analytical method had marginal differences compared to the other three numerical methods with coefficient of determination R^2 being always greater than 0.99. As for the NMBE and CV(RMSE) validation metrics, the ASHRAE-140 guidelines (ASHRAE, 2004) suggests that a model is considered valid when these metrics have a value of less than 10 and 30 %, respectively. Once again, the analytical method showed excellent agreement based on these suggestions.

In terms of computational efforts, the analytical method is considered more favourable compared to its numerical counterparts for several reasons. First, numerical methods usually require a graphical representation of the network such that it will be decomposed into different elements and equation systems. This time-consuming effort is minimised since a detailed description of the network using the analytical method is no longer required. Second, numerical errors stemming from zero mass flows and convergence issues are typically avoided. Finally, the analytical method is straightforward and easy to implement in any simulation tool according to the preference of the modeller and the end-user.

4.4.3 Pressure propagation in bidirectional networks

To gain a deeper understanding of the pressure propagation in BLTNs, Figure 4.13 presents pressure gradient curves for the nine validation tests obtained using the analytical method. It can be generally noticed that the

pressure level between the warm and cold sides of the network is solely determined by the dominant demand type across the network. For instance, in situations where heating dominates, circulation pumps at the prosumer levels dominantly extract water from the warm pipe and inject the water into the cold pipe after energy exchange, causing the pressure level in the cold pipe to increase.

Another finding is related to the special case of network expansion shown in Test 8 and Test 9. Here, the position at which the new loop is connected to the existing network plays a crucial role in determining the start and end pressure levels in the new loop. This point is of major importance due to its role in deciding whether a booster pumping station is required in the new loop. Overall, the results indicate that the newly developed analytical method supports quick design and analysis of different hydraulic configurations.

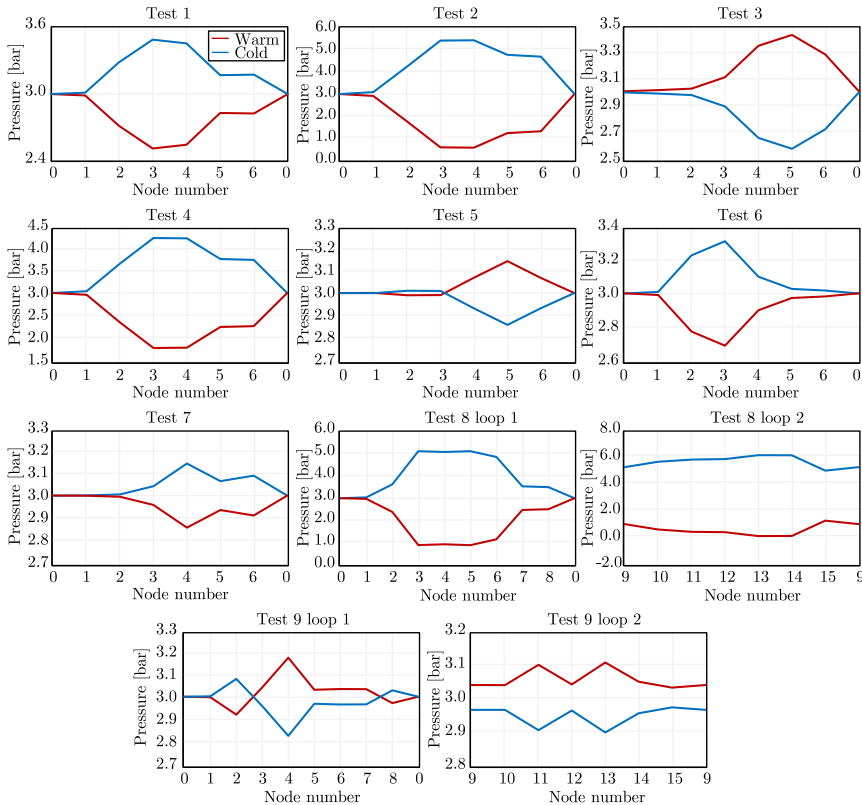


Figure 4.13 Pressure gradient curves for each validation test. Note that the diagrams do not have a uniform scale.

4.5 Summary

This chapter first presented simulation-based analyses of three real-world case studies using the developed model presented in Chapter 2. A summary of the three cases is provided in Table 4.3. From all the analysed cases, a general finding can be outlined. Because district heating and cooling systems consist of several subsystems and a multitude of components, a holistic approach to improving energy efficiency is necessary. Such approach includes, e.g., improving the building envelope, retrofitting the building energy systems, analysing the impact of pipe insulation on the network heat losses and gains, and combining multiple energy sources and sinks to provide capacity for peak loads while at the same time providing simple and stable operation.

The chapter then presented an experimental study conducted to validate the newly developed analytical method for modelling hydraulics in BLTNs explained in Section 3.2. However, challenges in obtaining stable measurements of differential pressure led to performing comparative validation against three established numerical methods. The comparative validation highlighted several advantages of the new analytical method including, fast and robust hydraulic modelling, ability to model different network topologies, and ease of implementation.

Table 4.3 Summary of the three modelled case studies.

Measure	Case study I	Case study II	Case study III
General description			
Location	Sweden	Denmark	Sweden
Number of connected buildings	9	15	3
Total heated floor area [m ²]	82,000	1,950	25,200
Energy source and/or sink	ASHP, cooling towers, tank (150 m ³)	6 BHEs (each 120 m)	42 BHEs (12,420 m)
Distribution network			
Pipe insulation	N/A	N/A	N/A
Pipe material and average nominal size	PE, \varnothing 200	PE, \varnothing 63	PE, \varnothing 180
Network length [m]	1,710	484	184
Annual supply-demand structure			
Delivered heating [GWh/y]	4.2	0.12	0.36
Delivered cooling [GWh/y]	1.4	N/A	0.14
Delivered DHW [GWh/y]	N/A	0.0779	0.52
Pumping energy [MWh/y]	21.14 (0.38 % of total delivered energy)	0.18 (0.16 % of total delivered energy)	36 (3.5 % of total delivered energy)*
Distribution losses (% of total delivery, negative sign indicates heat gains)	10 %	-27 %	5 %
System performance			
Annual heating SPF [-]	4.1	3.3	4.8
Annual cooling SPF [-]	7.3	N/A	11.0
Simulation performance			
Resolution of demand profiles	Hourly	Hourly	Hourly
Simulation time [year]	1	4	10
CPU time** [min]	4.56	33.41	25.21

*The high ratio of pumping energy is related to the low demands in the simulated new energy-efficient buildings. This finding is consistent with that of Buffa et al. (2019).

**Simulations performed using a desktop computer with 12 physical cores and 24 logical processors with a maximum speed of 3.50 GHz (AMD Ryzen Threadripper 2920X) and 32 GB of RAM running under Windows 10 Pro 64 bit using Dymola software version 2022. The CPU time is mainly influenced by the evaluation of the g-function and the number of distribution and connection pipes.

Chapter 5

Transition pathways

5.1 Background

This section is based on Paper IV.

District heating and cooling systems transition does not only entail advances in technology solutions, it rather encompasses a wider perspective that includes social and political aspects as well. Thus, the term socio-technical solution is frequently used to imply the interplay between a technical solution and its impact on society. For instance, a technical solution might be deemed to be feasible in terms of its security of energy supply, yet the same technical solution might negatively impact the environment and may not be economically feasible. It is therefore important to analyse the impact of technical solutions from different aspects.

One way of addressing technical and non-technical implications of DHC systems transition is by using the common *top-down* and *bottom-up* approaches (van Vuuren et al., 2009). The former approach includes governmental agencies and policy makers who enact policies to improve energy efficiency and reduce carbon dioxide emissions. These policies are communicated further down to citizens and practitioners to reach national

compliance with laws. The bottom-up approach, on the other hand, originates from individuals and small to medium organizations who exert efforts to create a change. A third complementary approach is referred to as the *middle-out* in which industry professionals are regarded as the main drivers of change towards successful DHC systems transition (Janda and Parag, 2013). In this context, industry professionals include architects, district heating and cooling companies, property owners, and builders who will be referred to as middle agents.

Middle agents can influence DHC systems transition in three distinct but compatible directions (Horsbøl and Andersen, 2021). In the first direction, they provide expertise and feedback *upstream* towards governmental bodies and policy makers. The second direction involves offering advice *downstream* towards citizens on the most technically and economically feasible solutions suitable according to citizens' needs. Middle agents also communicate *sideways* towards peer professionals to improve and promote the industry. Given their important role in the systems transition, middle agents have three indicative roles: 1) to enable (or disable) the implementation of new technologies, 2) to mediate the required modifications of the technology to suit specific cases, and 3) to aggregate the gained experience from different projects. In the following sections, transition pathways are outlined based on collected opinions from middle agents.

5.2 Qualitative data collection and interpretation

A mixed-method combining best practice and roadmapping workshops was used to invite middle agents and collect their opinions on DHC systems transition. A total of 19 participants joined the two workshops that took place during a full working day at the Faculty of Engineering at Lund University in Sweden. In the first workshop, a series of seven presentations was given to share lessons from existing advanced DHC concepts. The second part included a roadmapping exercise designed specifically to address different questions related to DHC systems transition. The participants were divided into three groups representing system planners, district heating companies, and heat pump experts and were asked to join separate break-out rooms for each group. A digital roadmapping template was provided to each

of the three groups and a group leader was responsible for documenting the discussion and presenting the group’s roadmap at the end of the workshop.

Both the presentations and the roadmapping workshops were audio recorded and subsequently transcribed. The digital roadmaps from each group were collected to perform a thematic analysis to identify the main themes discussed by each group. Afterwards, all discussed themes were juxtaposed against each other to elicit common patterns that are useful in outlining the transition pathways. A brief summary of the discussed points by each group is provided in Figure 5.1.

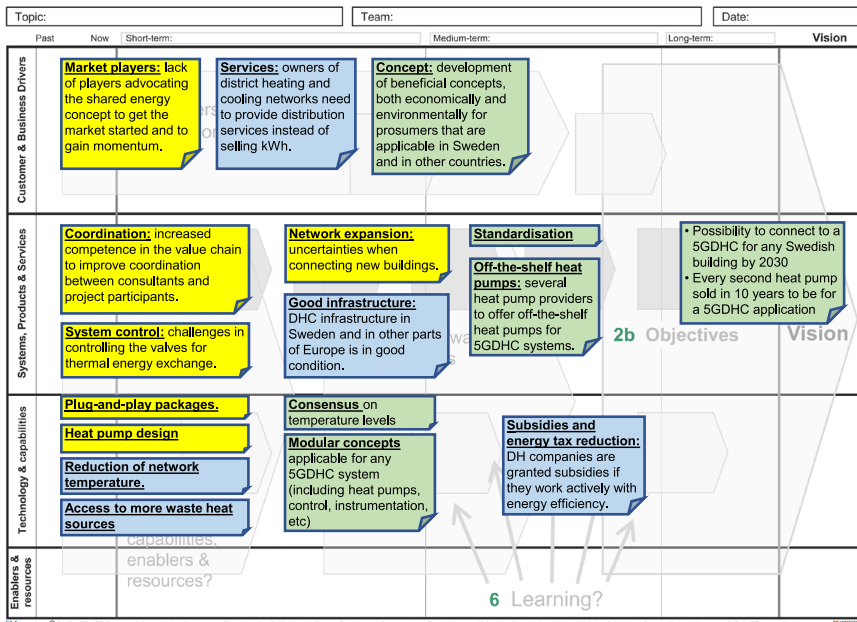


Figure 5.1 Summary of the main discussed themes in the roadmapping workshop superimposed on the digital roadmapping template. Different colours denote themes discussed by each of the three groups: yellow = system planners, blue = district heating companies, and green = heat pump experts.

System planners pointed out the lack of market players for the shared energy concept and difficulties in coordinating projects, as knowledge in advanced DHC concepts needs to increase. The group highlighted the technical challenges seen in designing similar systems to cover the peak capacity, controlling the system in different demand profiles, and deciding which set of buildings can be connected during network expansion. Moreover, the group discussed the current need to improve heat pump

design and the provision of plug-and-play packages for implementing advanced DHC concepts such that in the fifth generation.

The second group representing district heating companies noted the need for network operators to change the current business models which heavily rely on selling energy into providing distribution services instead. Additionally, the group accentuated the important aspect of third-party access to district networks to increase waste heat utilisation. As this aspect requires reducing the network operating temperature in most of the existing systems to allow for the recovery of low-grade urban waste heat, the group finally discussed the need for new schemes of governmental subsidies that motivate district heating companies to work actively on energy efficiency.

Heat pump experts first talked about the importance of developing beneficial concepts for all involved parties in DHC systems that connect both heat producers and consumers. They also mentioned that having a consensus on network temperature levels is necessary to design heat pumps that are reliable for low temperature lifts. The group pointed out the need to establish industry standards that promote several identified concepts for better product development. Accordingly, off-the-shelf heat pumps can be offered to suit specific modular concepts, which could achieve the group's vision of connecting any Swedish building to a 5GDHC network by 2030.

5.3 The dynamics of systems transition

The transition of district heating and cooling systems from the predominantly existing high-temperature third-generation systems to low-temperature networks with high integration of renewable energy sources poses practical implications encompassing technology, society, and policy. In this section, some of the important factors and drivers for DHC systems transition are discussed based on the analysed case studies presented in Chapter 4 and based on the roadmap envisaged by the middle agents provided in Section 5.2.

From a technology point of view, a multitude of advanced DHC concepts exist which all in common exploit the value of power-to-heat technologies and pave the way to fully decarbonise district heating and cooling. However, extensive electrification of thermal networks will impact the resilience of power grids as the demands for capacity production increase. Additionally, the associated risks of electrification on energy security have gained fresh prominence especially when the mix for energy production is heavily

dependent on imported oil, gas, and coal. Therefore, the transition to a production mix based on renewable sources with intermittent generation is currently ongoing. This will create more need for grid services such as frequency-regulation services where heat pumps can have a leading role in phasing out fossil energy sources. The year 2022 saw a record in heat pump sales in Europe with around 3 million units added to the market, bringing the total stock to about 20 million units (EHPA, 2023). When combined with district heating and cooling systems, the development of heat pumps is influenced by two factors. The first is the network temperature levels which directly impact the performance of the heat pump. Variations in the source temperature can lead to changes in the capacity of the evaporator and condenser for the same heat exchanger size, causing incorrect refrigerant charge by the expansion valve. It is therefore necessary to develop heat pumps with low temperature lifts as buildings are becoming more energy efficient and require low-temperature heating. The second factor that influences the development of heat pumps is the expected ban of several refrigerants under new PFAS chemical restrictions and F-gas regulations proposed to the European Commission (EHPA, 2022). Refrigerants such as R134a and R125 are some of the targeted refrigerants set to be included in the restrictions. The proposal may enter into force in 2025 if it has become accepted. An exemption for heating, ventilation, and air-conditioning equipment has also been proposed due to the lack of current available alternatives. Such evolving discussions could undermine the rate of systems transition as the use of natural refrigerants in heat pumps is currently considered an ongoing research effort (ATMOsphere, 2022).

The social implications of DHC systems transition can be categorised into two main points related to energy security and financial schemes for energy communities. The electrification of thermal networks can offer flexibility by coupling the power and heat sectors. As this aspect may create more opportunities for small towns to have a security of energy supply when an established DHC infrastructure is lacking, it may pose risks in large cities if failures in the power system occur and all connected buildings become affected. Nevertheless, the risks may become acceptable when energy communities with advanced DHC concepts are created and energy poverty is alleviated due to the secure energy supply to all connected buildings within the community. Moreover, advanced DHC concepts that adopt the energy sharing principle can reduce the financial burden on tenants. As more extensive energy retrofitting projects are taking place, the rental cost is

increasing and tenants with different socio-economic status are impacted differently (von Platten et al., 2022). This issue highlights the second implication of DHC systems transition on society where different business models and financial schemes can be adopted to involve representatives from the energy community in the decision-making process. Examples of possible business models for such applications are the local energy markets and the third-party sponsored communities. In the former type, all community members are decision-makers and distribute the revenues from the DHC system equally among them. The community members have a common goal to increase autonomy and reduce trading with external energy providers. In the latter type, community members search for a third-party to finance energy community projects. As DHC systems are deemed to offer the lowest price for heating and cooling in the long run compared to other alternatives, they require large capital investment which might be difficult for community members to finance. Alternative financing schemes including, e.g., grants and subsidies, loans, or even crowdfunding may motivate citizens to be part of energy communities.

The last discussed element in the dynamics of DHC systems transition is the establishment of policy frameworks and industry standards. There have been methodical and continuous enhancements of the European frameworks aiming to reduce energy consumption and related greenhouse gas emissions. Examples of these are the Energy Efficiency Plan (European Commission, 2011) and the Clean energy for all Europeans package (European Commission, 2019). The latter contains four directives that set out common principles for national regulatory frameworks. Within the Electricity directive, empowering citizens in the energy market is acknowledged through the concept “Citizen energy communities”. Some of the key elements of the Citizen energy communities are the self-generation, sharing, and storage of electricity within the community. Moreover, energy communities are entitled to own, establish, or lease the distribution network while maintaining the rights and obligations of the energy community members to, e.g., switch supplier and establish rules on network charges and balancing (Spasova and Braungardt, 2022). Putting these policy frameworks in line with the presented case studies in Chapter 4 and the roadmap provided in Section 5.2 highlight the practical need for establishing industry standards. These standards have vital roles in elaborating the industry requirements and filling the gap in skills shortage, which are all necessary for a successful DHC systems transition.

5.4 Summary

This chapter presented transition pathways for district heating and cooling systems. Qualitative data using a mixed-method combining best practice and roadmapping workshops were collected and interpreted. Thematic analysis was performed to identify common opinions about DHC systems transition across middle agents representing architects, district heating and cooling companies, property owners, and builders. The dynamics of DHC systems transition from third generation to low-temperature networks with advanced technologies were discussed based on their technical, social, and political implications. Due to the high degree of heat pump utilisation in new technologies of DHC, the development of heat pumps to suit low-temperature lifts and to shift to natural refrigerant are regarded as the most important directions where efforts need to be placed. It was found that citizen energy communities can accelerate DHC systems transition given their intrinsic values in ensuring energy security, alleviating energy poverty, and equal distribution of risks and roles across all community members.

Chapter 6

Concluding discussion

This thesis aims to evaluate district heating and cooling systems transition by: 1) developing a multi-domain simulation model for advanced concepts featuring low network temperature, simultaneous supply of heating and cooling, decentralised heat pumps at the building level, and bidirectional mass and energy flows, and 2) exploring existing challenges and future possibilities from a holistic point of view taking into account technical, social, and political aspects.

The thesis is structured as themed chapters linking theory and practice. The theoretical part included in Chapters 2 and 3 covers the development of the multi-domain simulation model as well as the development of a new analytical method for modelling hydraulics in district systems with bidirectional mass and energy flows. The practical part contained in Chapters 4 and 5 includes the assessment of several advanced technologies of DHC with the shared energy concept and the framing of transition pathways based on technical, social, and political implications. The overall research findings, limitations, and possible directions for future research are listed in the below sections.

6.1 Research summary and overall findings

A multi-domain simulation model has been developed for the design and analysis of advanced DHC concepts featuring simultaneous supply of heating and cooling, combining district and heat pump technologies, and bidirectional mass and energy flows. The model incorporates thermal, hydraulic, and control components to simulate the systems in one integrated environment using the Modelica language. The model is divided into three main subsystems representing the decentralised substation, the distribution network, and the energy source/sink. The substation model includes component models for heat pumps, mechanical chillers, and free-cooling heat exchangers. Control strategies for the operation of these equipment are described together with a novel control strategy for the energy sharing concept between several substations. The model for the distribution network is based on a double buried uninsulated pipe with a free-floating temperature control strategy. The components in the energy source/sink varies based on different design choices and a detailed description of the geothermal bore field model has been provided.

A new analytical method for modelling network hydraulics in district systems with bidirectional mass and energy flows has been presented and validated. The solution sequence for the new method is elaborated based on the definition of the *flow-pressure* and *bifurcation* functions. The first function establishes the relationship between the mass flow and pressure drops in a circular pipe, while the bifurcation function gives the sum of pressure differences over a closed loop. An attempt to validate the new analytical method experimentally has been carried out. Challenges related to obtaining stable measurements of differential pressure, difficulties in estimating fitting losses accurately, and the simplifying assumptions made to represent the actual system all limited the possibilities of the experimental validation. Consequently, a comparative validation against established numerical methods was performed and showed that the analytical method can offer better performance over its numerical counterparts due to its explicit nature, ease of implementation in any design or simulation tool, and flexibility to represent and model the network quickly.

Detailed analyses of three real-world DHC systems with advanced concepts have been performed using the developed Modelica model. Overall,

the analyses accentuate the promising potential of advanced DHC concepts to decarbonise the building sector by the electrification of thermal networks using power-to-heat technologies. The learned lessons from the three analysed cases to improve the system performance can be summarised into two main points. First, new concepts of DHC systems yield higher performance and are more favourable when energy-efficient buildings with low-temperature heating and high-temperature cooling are connected to the network. This would allow a high degree of free-cooling utilisation and increase the performance of heat pumps due to the low temperature lift. Moreover, connecting modern energy-efficient buildings would increase the capacity of the energy source to cover peak loads. To achieve this, a holistic approach based on system-level design including the building envelope, building energy systems, distribution pipes, energy sources and sinks is extremely necessary. The second point for improving the system performance is related to the distribution pipes. Simulations reveal that in networks with only heating demands, the uninsulated pipes act as a horizontal heat exchanger and the heat gains from the ground can contribute up to one-fourth of the total delivered heat. On the other hand, insulating only one side of the two pipes can reduce network losses by 90 % in networks with simultaneous heating and cooling, according to the analysed systems.

The technical, social, and political implications of DHC systems transition have been analysed based on the opinions of middle agents representing system planners, district heating companies, and heat pump experts who participated in best practice and roadmapping workshops. From a technical perspective, it is expected that the resilience of power grids will be impacted as a result of massive electrification of thermal networks, which will create more demands for capacity production. As more renewable sources with intermittent generation are used in the production mix, combining district and heat pump technologies would improve grid flexibility by providing frequency-regulation services in addition to phasing out fossil energy sources. Efforts in the development of heat pumps should be placed in two areas. The first is the provision of heat pumps for low temperature lifts that ensure stable and reliable operation. The second is the shift to natural refrigerants as more regulations to stop the use of chemical refrigerants are currently being proposed and are expected to enter into force in the coming few years. It has been argued that the social implications of advanced DHC systems with the shared energy concept can increase citizen awareness and contribute to wider implementation of similar concepts. There is a growing maturity of

beneficial business models such as local energy markets and third-party sponsored communities to involve all parties in the community and to find suitable financing schemes. More importantly, communities with the shared energy concept ensure a secure supply of heating and cooling to all connected buildings and can, therefore, alleviate energy poverty and reduce financial burdens on tenants. Given the current policy frameworks that offer drivers for the growth of DHC market, there is still a need to establish industry standards to promote the industry, to fill the gap of skills shortage, and to propose best practices and design recommendations which all contribute to successful systems transition.

6.2 Research limitations

The major limitations of this thesis are related to five areas. First, the thesis does not engage with detailed modelling of buildings and building energy systems to generate demand profiles. Because building energy models typically have large time constants, coupling these with control systems which have dynamic response of seconds would produce a stiff system that requires implicit solvers to find a numerical solution and where the simulation performance becomes computationally taxing. Second, the heat pump model is limited to scaling its coefficient of performance based on the Carnot efficiency. This approach was followed due to the lack of manufacturer data for heat pumps with low temperature lifts and to avoid extrapolation errors when performance curve models are used. Third, the model for distribution pipes considers steady-state heat losses without heat storage in the pipe wall or in the soil where the soil temperature is uniform. Fourth, numerical simulations with Modelica use heat-carrying fluids with constant density, thermal conductivity, and viscosity. The issue of varying viscosity with varying medium temperature is handled by the newly developed analytical model and is analysed in considerable detail in appended Paper V. Finally, the full description of economic parameters and the determination of heat and electricity prices to perform life cycle cost analysis go beyond the scope of the thesis.

6.3 Future research

Future research directions can focus on three areas related to improving the developed model, performing experimental validation, and analysing the

electrification of district heating and cooling networks. In the first research direction, the model presented in Chapter 2 can be improved by including heat pump models with performance curves. This point is of particular importance as it increases the model accuracy by avoiding approximations based on the Carnot efficiency. Such improvement can be achieved once enough performance data for heat pumps with low temperature lifts are provided by manufacturers. Moreover, developing a model for dynamic heat losses in the distribution pipes is necessary due to the thermal transients which are expected to play a significant part in uninsulated pipes. The impact of pipe insulation under different demand profiles and temperature levels should also be investigated to provide guidelines for system planners and design engineers. Furthermore, the borefield model can be improved by implementing better performing methods for calculating the borehole thermal resistance. Examples of these methods with a comprehensive comparison can be found in the work of Javed and Spitler (2017).

The second research direction may focus on the experimental validation of the newly developed analytical method for modelling hydraulics in bidirectional low temperature networks. Performing the experimental validation using an actual system scale with lower number of fittings would circumvent many of the issues that typically occur in lab setups. However, it is essential to make an instrumentation and data management plan to measure, record, and retrieve data accurately.

Another future research direction could analyse the impact of district heating and cooling electrification. Because the impact of electrification largely depends on the mix of energy production, available future scenarios for the power system can be utilised to assess the techno-economic feasibility of the electrification of district heating and cooling based on predicted spot price data. The assessment would benefit the planning of future energy systems both from a national level as well as for countries that have cross border agreements for electricity trading.

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Paper I





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Bibliographic analysis of the recent advancements in modeling and co-simulating the fifth-generation district heating and cooling systems



Marwan Abugabbara ^{a,*}, Saqib Javed ^a, Hans Bagge ^b, Dennis Johansson ^a

^a Department of Building and Environmental Technology, Division of Building Services, Lund University, Lund 221 00, Sweden
^b Department of Building and Environmental Technology, Division of Building Physics, Lund University, Lund 221 00, Sweden

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ABSTRACT

District heating and cooling systems have evolved through several development stages in order to improve their energy efficiency. The latest development reached the fifth generation where customers can be producers and/or consumers of thermal energy flows towards the network. The variety and complexity of system configurations and interactions between connected customers poses a challenge in adopting a suitable modeling paradigm capable of simulating each design case. Modelica language and the Functional Mock-up Interface standard are computational tools opted by the International Energy Agency for simulating building and community energy systems. This work aims to analyze the current status in literature where these tools are utilized in building and energy simulation with focus on district heating and cooling systems. Bibliographic maps and networks are presented to analyze the literature based on different bibliometrics. Among others, the analysis shows that coupled simulation between district and building energy models is a novel research area and can benefit in reducing the oversizing of space heating and cooling systems. In addition, the analysis demonstrates that the fifth generation district heating and cooling systems require advanced control strategies. These strategies need accurate and upfront specifications to decide a proper control strategy for each design case.

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1. Introduction

District Energy Systems (DES) offer the possibility to increase the exploitation of renewable energy and hence they are at the forefront of the engineering research [1–5]. The broad term of

* Corresponding author at: Faculty of Engineering, Lund University, Box 118, 221 00 Lund, Sweden.
 E-mail address: marwan.abugabbara@hvac.lth.se (M. Abugabbara).

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DES encompasses electrical, gas and thermal systems that are constructed in urban areas to distribute energy flows through power grids and pipe networks. District Heating and Cooling (DHC) systems are thermal application of DES and deemed most feasible in urban areas with high heat density [2]. The latest figures show that a growing number of the world's population is shifting from rural to urban areas. In 2018, the percentage of the world's population residing in urban areas reached 55%, a figure that is projected to increase up to 68% by 2050 [6]. As urbanization involves transformations in the built environment and infrastructure to meet the needs of shifting the spatial distribution of a population from rural to urban, DHC systems are expected to play a major role in this area. A survey carried out in 2017 by Euroheat & Power showed that there are about 6000 DHC networks currently in operation in Europe supplying about 12% of the total heat [7]. The previous figures suggest that DHC systems are therefore appropriate thermal energy applications that have potential enhancements that could attain greater benefits. One of these benefits, for example, could be the integration of multiple producers of thermal energy to the network [8].

DHC networks have evolved over time in order to achieve maximum energy efficiency and low distributions losses. Pellegrini and Bianchini [9] provided a background on the evolution of DHC generations. The first generation DHC systems were introduced in the United States in the late 19th century. The pipeline in these networks used steam as a heat carrier, which was later replaced by pressurized hot water with temperature over 100 °C to establish the second generation DHC networks. The authors also mentioned in their review that lowering the supply temperature in district heating networks to about 80 °C was needed since traditional residential buildings were heated using radiators that operate in this temperature range. This lowering in supply temperature led to the reengineering of the second generation DHC networks into the third generation that is currently widely applied [10]. Several technical and operating issues emerged in the third generation DHC networks. First, despite the high efficiency in energy production due to centralization, distribution losses in the network account for about 10–30% and pipeline insulation increased the cost [11,12]. Another issue is related to the sustainability of the technical components included in the systems. Components such as heat exchangers, valves, pumps and pipe material had to operate under high temperature conditions which affect their durability [13]. Furthermore, this generation limits the integration of low heat source renewables as high temperature sources are only suitable for integration [14]. The previous challenges have led to the inauguration of the fourth generation DHC networks which are usually characterized by supply temperatures in the range 50–70 °C. The main limitations in the fourth generation DHC system are: (i) separate pipes are needed to provide both heating and cooling and (ii) the production of energy is still centralized, which restricts the ability for network expansion due to design constraints. These are the main challenges that are addressed by today's fifth generation DHC systems.

The term "fifth generation" DHC systems has been firstly proposed in the H2020 project [15] and used in a number of studies, including [16,17]. Buffa et al. [18] provided an extensive review of existing applications of the fifth generation DHC systems in Europe. An example of such systems is seen at ETH Zurich Campus Höggerberg [19]. The system at present supplies heating and cooling to four building clusters but is rapidly being expanded. The grid operates between 4 and 22 °C and is connected with three underground storages and four substations with distributed heat pumps. The maximum heating and cooling outputs of the system at present are 5.5 and 4.5 MW, respectively. A similar project in Lund, Sweden is currently in operation and being expanded [20]. The project consists of 14 buildings with a total heated floor area

of 110,000 m². The energy demands in 2018 were 11 GWh heating and 5 GWh cooling. Currently six buildings are connected to the grid and the performance of the system is being evaluated. Generally, these systems can have different classifications depending on the method of heat rejection/extraction and the thermal energy flow from/towards the network. In its most simplified generic form, the fifth generation DHC system harnesses the shared energy concept which is realized in a network that connects "prosumers". The term "prosumer" refers to each customer connected to the network where they play the role of producer and/or consumer of thermal energy flows distributed through the network. A low-grade heat source is connected to a bidirectional pipe network that allows the simultaneous use of heating and cooling through a low temperature thermal network. Decentralized substations, typically heat pumps, are installed at the building level to boost and/or decrease the medium temperature to the desired levels each building requires.

Typically, modeling these systems involve components from various domains such as thermodynamics, fluid mechanics and controls. This results in a hybrid system of continuous time, discrete time and discrete events. Physical systems are described by differential algebraic equations consisting of derivatives with respect to time and space. On the other hand, digital control systems are described by discrete equations with time-, state- and step-events [21,22]. A problem that arises when attempting to model and simulate these heterogeneous systems is the requirement for a multi-domain platform that enables the evaluation of the dynamic behavior of the system in various design settings and configurations.

The International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC) Annex 60 called for an international project in 2012 to develop free open non-proprietary, new generation computational tools for building and community energy systems based on the Modelica, Functional Mock-up Interface (FMI) and Building Information Modeling standards [23]. Modelica is an equation-based object oriented modeling language that allows modeling physical systems involving multiple domains such as electrical, mechanical, thermodynamics and controls [24]. The FMI is a tool independent standard used for co-simulation of various dynamic models. By exploiting the outcomes of IEA-EBC Annex 60, the simulation of the fifth generation DHC systems can be realized. Moreover, the interoperability issues among different simulation tools can be alleviated.

Modelica language was developed through an international effort in 1996 benefiting from acausal modeling and advances in object-oriented constructs [25]. Models are described by differential, algebraic and discrete equations using a standardized interface that encapsulates the mathematical relations of a model between its interface variables and represent them graphically by an icon [26]. At the lowest level of abstraction, the mathematical equation describes the relationship between variables. At higher level of details, components are composed graphically through drag-and-drop and the externally visible variables called connectors are connected by a line between two connections. A connection defines another set of equations, one for each variable in the connector. By exploiting acausal modeling, the input/output relationship between system components is usually absent [27]. In such approach, a code generator is responsible for determining the input and output variables by employing symbolic algebra to determine an optimal solution sequence [28]. The use of Modelica has an extent use over variety of applications, we focus in this study on applications with respect to energy in buildings.

The complexity of modeling heterogeneous multi-domain systems yields a problem where no single simulation tool is capable of reproducing the behavior of the model [29]. One approach to surmount this problem is to model the system as subsystem mod-

els in different simulators which suit best for the specific domain [30]. However, to model and understand the dynamic behavior of the complete system, the need for integrated simulation becomes increasingly important [31–34]. Beausoleil-Morrison et al. [35] provided four options for integrated building performance simulation to extend the capabilities of existing tools: (i) add new features to existing tools; (ii) integrate the source code of one tool into another; (iii) develop a new building performance simulation tool and (iv) the use of co-simulation approach. Co-simulation offers a pragmatic solution to the problem of integrated simulation without demanding more resources.

The term co-simulation may cause confusion due to its several interpretations across different domains. Hafner and Popper [36] did an outstanding work in clarifying the semantics pertaining co-simulation and distinguished the different methods used in the context of co-simulation. They provided definitions for basic terms related to the field of modeling and simulation which we now introduce and suggest being used henceforth to avoid any ambiguity. A *model* refers to the mathematical representation of a system entities or process. A *simulation* is an experiment performed on a model. *Solver* refers to the solution algorithm which is applied to a specific simulation model. A *simulator* is a tool that allows the implementation and simulation of models. Co-simulation is an abbreviation for cooperative simulation or coupled system simulation [37,38] where two or more simulators are coupled to exchange data that depend on state variables in order to solve differential equations [39,40]. The coupled simulators differ in either solver algorithm or step size, hence, a master algorithm acts on the top level to organize the communication and data exchange between the coupled tools which are called slaves [22,36,41,42]. Master algorithms are not standardized, they can be developed both as a separate tool as well as an included feature of an existing simulation tool which plays the role of the master [43].

The aim of this study is to analyze the current status in literature where Modelica and co-simulation are utilized in modeling and simulation of DHC systems. The study is synthesized around five focal points. Section 2 explains the method used in the literature study. The literature findings including applications of Model-

ica and co-simulation in building energy simulation are introduced in Section 3. Bibliographic maps and networks are presented in Section 4 aiming to explore the literature based on different bibliometrics. Detailed discussion is covered in Section 5. Finally, conclusions are drawn in Section 6.

2. Method for literature analysis

A list of relevant publications had been compiled from six literature sources including journal articles and conference proceedings. The reader is asked to refer to the attached supplementary material to view the table of included publications. All publications included in this study were published before 1 October 2019. Fig. 1 shows the six literature sources together with the percentage of total number of publications each source accounts for. Out of a total number of 150 publications, proceedings of the International Modelica Conferences accounted for most of the literature in the list. The second largest set of publications were retrieved from a multistep query carried out in Scopus database. With nearly equal number of publications from the search in Scopus database, proceedings of the International Building Performance Simulation Association (IBPSA) Conferences comprised the third largest group of publications in the list. Other regional meetings such as the American and Japanese Modelica Conferences and the Equation-based Object-Oriented modeling Languages and Tools (EOOLT) workshops accounted together for 4% of the publications included in the list. The first International Modelica Conference took place in Lund, Sweden in October 2000. The conference then started to be organized about every other year in different locations. The International Modelica conference has reached its 13th event which took place in Regensburg, Germany in March 2019. Since its inauguration, the conference expanded its scope to cover wider themes and topics such as automotive, aerospace, electrical power, mechanics and transport, numerical methods and other subjects related to applications of Modelica. In this study, our primary focus was on proceedings related to the following topics: buildings, power and energy, thermodynamics and Functional Mock-up Interface.

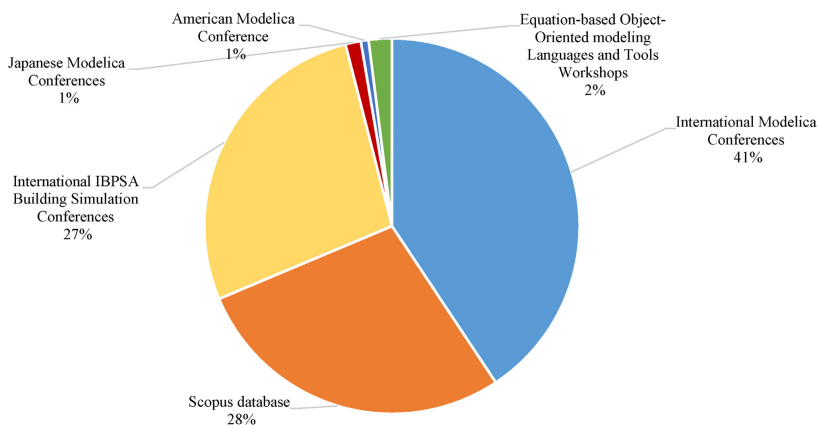


Fig. 1. Literature sources included in this study and their contribution to the list of publications.

Table 1
Literature search strategy and its corresponding keyword categories.

Keyword category 1	modelica OR fmi OR fmu OR functional mock* OR co-simulation
Boolean operator	AND (title-abstract-keywords)
Keyword category 2	energy OR "building energy" OR dist* energy OR shar* energy OR grid OR network
Boolean operator	AND NOT (title-abstract-keywords)
Keyword category 3	chemi* OR vehicle OR solar OR mechat* OR maritime OR aircraft OR nuclear OR medical OR medicine OR "embedded system" OR hardware OR robot OR mechat* OR atom* OR motor OR optical OR "smart artifact" OR starch OR "speed train" OR infection OR processor OR military OR supermarkets
Boolean operator	AND NOT (source title)
Keyword category 4	nuclear OR ipbsa OR "Conference of the International Building Performance Simulation Association OR cardio"
Boolean operator	AND NOT (title)
Keyword category 5	workshop

The multistep query carried out in Scopus database is described in Table 1. The query is divided into five main keyword categories that aim to include and/or exclude specific topics when performing the request. The first two keyword categories attempt to combine studies where Modelica and co-simulation have been utilized in applications for district and building energy systems. A large set of articles that are not related to the scope of our study was ensued as a result of searching keywords in category 1 and 2. Therefore, the latter three categories in Table 1 aim to narrow down the search by limiting these unrelated topics. In each keyword category, the OR Boolean operator is used so that the search engine can find articles where at least one of the keywords listed in the category is contained. The asterisk symbol denotes the truncation search technique. In this technique, the asterisk symbol is added to the beginning or end of a word to retrieve word variations. For example, *dist* energy* may find the words *district energy* and *distributed energy*. Moreover, the double quotation mark indicates the search for loose phrases where multiple words appear together in the designated search field. This technique is shown for example in keyword category 2 when searching for "building energy" to emphasize the importance for these two words to appear together.

Once all the literature have been collected, a bibliographic database file was created in order to generate bibliographic maps and networks by employing the software VOSviewer [44]. These maps and networks are presented in detail in Section 4. The database file followed the structure of a Comma-Separated Values (CSV) file exported from Scopus database. In total, 13 variables were considered and imported to VOSviewer for the all 150 publications. The variables in the database file are shown in Table 2 together with

Table 2
Data structure of the bibliographic database file.

Variable	Format	Separator character	Example
Author	Text string	Comma	Hong T., Sun H., Chen Y., Taylor-Lange S.C., Yan D.
Title	Text string		An occupant behavior modeling tool for co-simulation
Year	YYYY		2016
Source title	Text string		Energy and Buildings
Volume	Integer		117
Issue	Integer		
Page start	Integer		272
Page end	Integer		281
Cited by	Integer		77
DOI	Character string		https://doi.org/10.1016/j.enbuild.2015.10.033
Link	URL		https://www.sciencedirect.com/science/article/pii/S0378778815303480
Affiliation	Text string	Semicolon	Lawrence Berkeley National Laboratory, United States; Tsinghua University, China
References	Text string	Semicolon	reference 1; reference 2; (...); reference 56

their format and separator character in addition to an example that clarifies the definition of the 13 variables for an example article. It is worth mentioning that Scopus export function does not support accented characters. Hence, a look up process for accented characters, as explained in [45] was followed in order to remedy inadvertent inconsistencies between the original information and the exported ones. The number of citations for each publication was retrieved from Google Scholar. Missing publications in Google Scholar were assigned to a citation number equal to zero. Less than 9% of the total number of publications included in the list had a missing number of citations.

VOSviewer offers the possibility to explore bibliographic maps based on different types and units of analysis. We limited the generation of maps and networks to three types of analysis due to the following two reasons. Firstly, the reference string in the created bibliographic database file has harmonization problems. Different publications yielded different reference styles and therefore VOSviewer was prone to pitfalls in completely parsing a cited reference [46]. However, singular elements inside a cited reference such as authors, source title and year were able to be distinguished. Another reason to limit the types of analysis was related to the definition of different types of analysis and what they may refer to. For instance, the metric *bibliographic coupling* focuses on groups of items, e.g. authors, publications, etc., which cite the same publication. On the other hand, *co-citation analysis* measures the frequency of references coming in pairs [47]. We are primarily interested in identifying items with frequent occurrence within our literature list. These facts led us to focus more on specific types and units of analysis than others.

3. Literature findings

This section presents the findings derived from the included 150 publications. They are divided into two main areas related to Modelica language and co-simulation. The former focuses on the utilization of Modelica language in building performance and district energy simulation. The latter presents several co-simulation approaches and reviews applications between different simulation platforms.

3.1. Modelica in building energy simulation

Before delving into the review of previous applications of Modelica, we briefly discuss the open-source Modelica libraries that relied on the International Energy Agency Annex 60 and mentioned in [48]. RWTH Aachen [49] demonstrated the applicability of the *AixLib* library for building performance simulation on building and district scale. The library can also be used for both high and low order model of buildings with provided reference models for

heating, ventilation, and air-conditioning components. The *BuildingSystems* library developed by UdK Berlin [50] can be used for single or multi-zone buildings or entire city districts. The *Buildings* library from Lawrence Berkeley National Laboratories [51] supports the design and operation of building energy and control systems. It also includes tools for pre- and post-processing, regression tests, co-simulation and real-time data exchange with building automation systems. KU Leuven developed the *IDEAS* library [52] for integrated district energy simulations. The library allows simultaneous transient simulation of thermal, control and electrical systems at both building and feeder levels. Source code of these libraries and implemented models can be edited and/or expanded to adapt changes for different use cases. These libraries had been extensively validated in modeling DHC systems and were reported in Annex 60 final report [53].

Since the primarily focus of this study is to review the use of Modelica in simulating District Heating and Cooling systems (DHC), few of the Modelica applications with respect to this subject are herein introduced. Ljubijankic et al. [54] developed the *FluidFlow* library to model complex thermal energy supply systems focusing on heating and ventilation systems, solar thermal, and DHC systems. The library has been validated empirically and against computational fluid dynamics simulations. EDF R&D in France developed *BuildSysPro* library [55] for modeling buildings and energy systems consisting of building envelope, building energy system, heating and ventilation systems, domestic hot water, solar panels, weather conditions and indoor comfort. Arce et al. [56] shared lessons learnt from modeling a low heat density District Heating (DH) system. They provided a detailed comparison of the different water models in the Modelica Standard Library (MSL) and motivated their decision to develop a new water model. The *DistrictHeating* library [57] was developed and used for accurate and robust simulation of DHC systems. The *Buildings* library and MSL had been used together to build a power-based model of a heating station for DH systems [58]. The dynamic behavior of DH networks using Modelica models was evaluated in [59] with a framework to parameterize these models with Geographic Information System data. Mans et al. [60] used Python and Modelica for automated generation and simplification of DHC networks by either reducing the total number of pipes in the model or by using static pipe models for short pipe sections. A Modelica library for low temperature thermal networks was developed [61] and the simulated system resulted in reduced energy losses between pipes and ground, an additional electrical load due to heat pumps was however observed. Different models of heat pumps has been presented in [62–67]. Approaches in developing the previous heat pump models involved for example a black box model connected to a module that calculates heat flow and compressor power by using look-up tables from manufacturer data. Another approach relied on a simplified mode of a vapor compression cycle with five refrigerant states. Many of the applications presented in the literature utilized co-simulation to benefit from the different capabilities of various tools through interoperable integrated simulation.

3.2. Co-simulation between building performance simulation tools

Many co-simulation frameworks have emerged over time. A comprehensive study and comparison among those is mentioned in [68]. We focus on two specific frameworks due to their wide application in the field of building performance simulation. The Building Controls Virtual Test Bed (BCVTB) [39] developed at Lawrence Berkeley National Laboratory is a middleware tool that allows connecting different simulation programs to exchange data during the time integration. It has features capable of and not limited to: (i) smaller computation time for data transfer compared to the

individual simulation programs when performing a co-simulation for a whole building; (ii) modularity and tool-independency that can couple for example Modelica, EnergyPlus [69], MATLAB [70] and online visualization tools of variables; (iii) communication over the internet and across different operating systems including Microsoft Windows, Linux and Mac OS X and (iv) running with a graphical user interface or as a console application without user integration. The presence of the additional layer, i.e., middleware, in the BCVTB in addition to the proficiency required in familiarizing the tool increase the complexity of the coupled system [68]. The Functional Mock-up Unit (FMU) import removed the concept of middleware and introduced a standardized interface between coupled programs.

In 2008 a consortium was initiated and organized under the Information Technology for European Advancement (ITEA2) project MODELISAR to develop a tool and vendor independent standard for the exchange of dynamic models and for co-simulation using a combination of eXtensible Markup Language (XML) files and compiled C-code [71,72]. The first version of the standard called Functional Mock-up Interface (FMI) was established by the automotive sector and released in 2010 and followed by version 2.0 in 2014 [73,74]. The use of the standard has expanded to other industries and engineering domains where now over 100 tools support FMI for model exchange or co-simulation [75]. The interactions between the tools abiding to the FMI standard happen in two ways [43]:

1. Model exchange: One simulation environment establishes the equations of one component and pass them over to another simulator which collects all component models and simulates all equations together.
2. Co-simulation: Each component's simulator solves its own equations whilst values which belong to more than one component are exchanged. Here the simulators have to be synchronized. Model exchange is the base for co-simulation as the same data for model exchange are needed.

A component that implements the FMI is called an FMU [22,72,76]. It consists of one zip-file containing the following files:

1. An XML-file contains the definition of all variables and model description of the FMU that is exposed to the environment in which the FMU shall be used.
2. A small set of easy to use C-functions are provided for all model equations for model exchange. For the FMI for co-Simulation, C-functions are also provided in source and/or binary form to initiate a communication with a simulation tool, to compute a communication time step and to perform the data exchange at the communication points.
3. Further data can be included in the FMU zip-file such as a model icon (bitmap file), documentation files, maps and tables needed by the model and/or shared libraries that are utilized.

To couple simulation tools, there exists two strategies to choose from [76,77]. First, in the *quasi-dynamic coupling* also called *loose coupling* or *ping-pong coupling* strategy, the distributed models run in sequence and simulators use data from preceding time steps where no iteration is required between the coupled simulators. The second strategy is a *fully-dynamic coupling* also called *strong coupling* or *onion coupling* in which the distributed models iterate within each time step to satisfy a predefined convergence criterion. The former strategy allows the use of multiple time steps in co-simulation whereas the latter can only use equal simulation time steps. Several previous studies have utilized co-simulation between different building performance simulation tools. This approach allows the use of the extensive features each single tool

is providing instead of using a monolithic simulation environment with limited capabilities.

An FMU-import was implemented in EnergyPlus and described in [78]. Two use cases were presented: modeling of a heating, ventilation and air-conditioning system and a shading controller in Modelica which were exported as FMU to EnergyPlus. A detailed building energy model was created using NANDRAD simulation tool [79] and exported as an FMU and integrated into a Modelica environment containing a heating and ventilation model. The study also investigated the co-simulation approach between the two tools using MASTERSIM [80] as a middleware for co-simulation and master algorithm. Since importing the FMU depends on functionalities specific to the simulator environment, a study by Chen et al. [81] aimed to provide a generic FMU interface for any Modelica simulator. Integrated modeling between TRNSYS [82] and Modelica was demonstrated in [27]. The Occupant Behavior Functional Mock-up Unit (obFMU) was developed and used to include stochastic functionality in modeling occupants while analyzing their impact on a building energy model in EnergyPlus [83]. Plesis G. et al. [84] managed to use the FMI to couple occupant behavior between SMACH, an agent-based platform developed by EDF R&D in France, and BuildSysPro library in Modelica for a building energy model. A specified use case of coupling a building's thermal envelope model in SIMULINK [85] with BRAHMS [86] model for multi-agent occupant behavior modeling was introduced in [73]. An approach that relied on using Java to model occupant behavior as a master simulation with a slave EnergyPlus building model was established in [32]. Several other attempts to couple building energy performance with computational fluid dynamics simulation tools are found in [42,87], while another study used the FMI to assess a ventilated double-skin fenestration system coupled with a compact fan-coil-unit [88]. Based on this literature review, integrated co-simulation of the fifth generation district heating and cooling systems including district and

building levels is necessary in order to recognize the various interactions between the decentralized substations and the pipes network.

4. Bibliographic analysis

Bibliographic maps and networks are created in order to provide the reader with a visual analysis of bibliometrics pertaining applications of Modelica and co-simulation for building energy simulation. By visually inspecting these maps, the reader can explore various metrics that link different items according to each type and unit of analysis. In this study, we limited our focus to three types of analysis due to the reasons previously mentioned at the end of Section 2. The three types of analysis are co-authorship, co-citation and co-occurrence. The maps and networks for the respective types of analysis are presented in Figs. 2, 3 and 4. To enhance visualization, character length in these figures was limited to 30 and network attraction and repulsion values were optimized. In addition, a cut-off for the largest connected items is only shown in these Figures. For example, map A in Fig. 2 shows the co-authorship network based on the authors unit of analysis. Out of 419 authors in the 150 publications list, 101 authors constitute to the largest set of connected authors and, hence, only those are shown in the map. Similarly, the authors correspond to 166 different organizations that are depicted in map B in Fig. 2. This map only presents the 65 largest connected organizations. Both map A and B in Fig. 2 have inherent information spread over two dimensions. The label size, i.e., circles, is proportional to the number of publications produced by the author or organization. The circle color indicates the time point where the literature was published. The circle color is interpreted according to the legend provided in the lower right corner of each map. A proliferation of publications can be seen over time, where years 2011 to 2015 marked significant events. Most of research institutions and organizations have

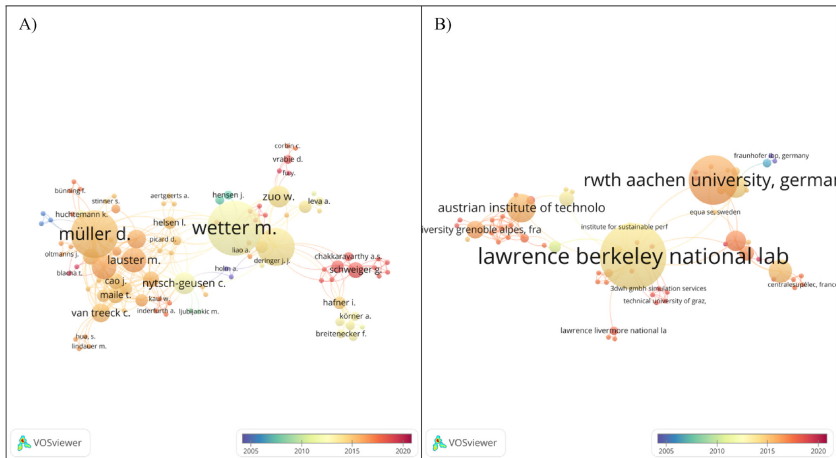


Fig. 2. Bibliographic maps and networks based on co-authorship type of analysis between authors (A) and organizations (B). For interpretation of colors and legends, the reader is referred to the web version of this article.

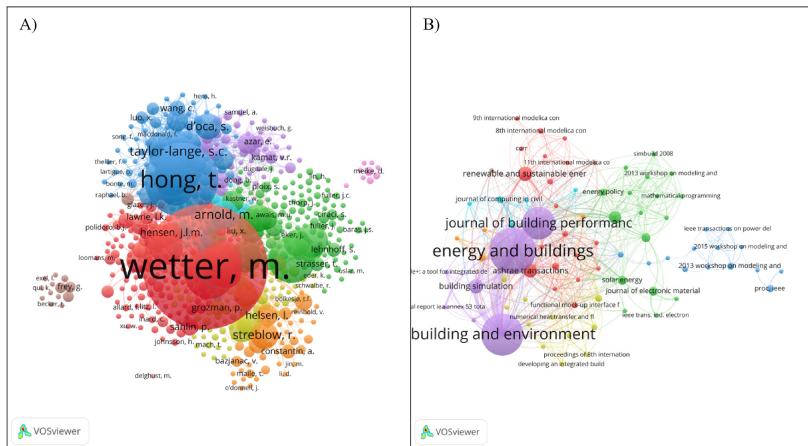


Fig. 3. Bibliographic maps and networks based on co-citation type of analysis between cited authors (A) and cited sources (B).

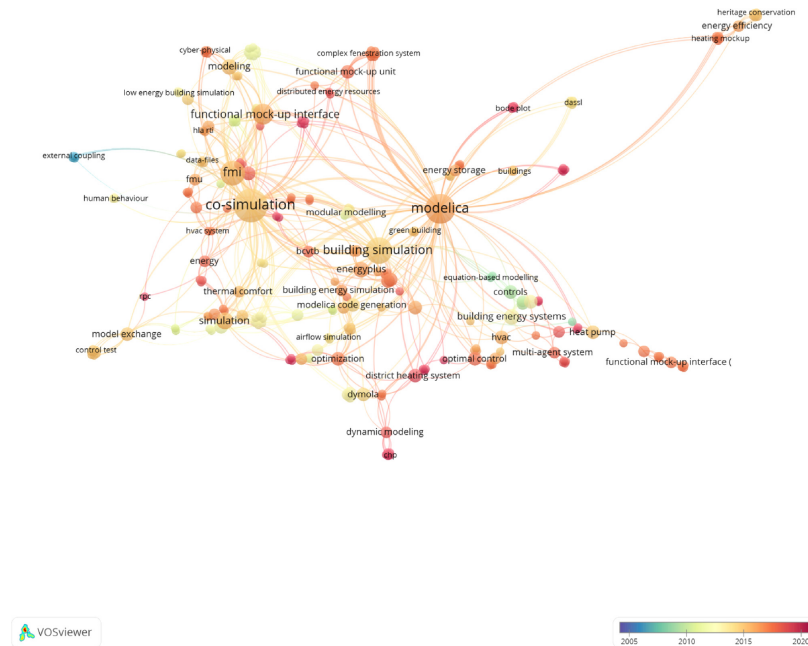


Fig. 4. Bibliographic map and network based on co-occurrence type of analysis and author keywords.

collaborated with Lawrence Berkeley National Laboratory in the United States where authors Wetter M. and Noudui T. S. are affiliated. Müller D. from RWTH Aachen University in Germany has also contributed to a copious number of publications within the literature list. The red circles indicate that other organizations such as Technical University of Graz in Austria, Pacific Northwest National Laboratory in the United States and 3dwh GmbH Simulation Services in Germany had published more documents in the recent years.

Shifting the focus to Fig. 3 which presents maps and networks based on co-citation type of analysis for cited authors and cited sources. The colors in maps A and B indicate the number of clusters produced by the clustering technique explained in [89] with a resolution parameter set to 1. No conclusions should be elicited between the clusters in the two maps as each was produced separately. In contrast to the maps in Fig. 2, the circles here are weighted by the number of citations for authors and source titles. With a total number of 106 citations, map A shows that Wetter M. was the most cited author within the literature list followed by Hong T. with almost half the number. The cited references were communicated through wide range of sources. Journals; Energy and Building, Building Environment and Journal of Building Performance Simulation accounted for the most frequent sources, as shown in map B. In general, the cited references seemed to be communicated through journals and conferences related to building energy modeling and simulation.

The map and network illustrated in Fig. 4 link the author keywords included in the literature list. A link between two or more keywords is established when the keywords appear together in the same publication. The distance between multiple keywords implies how different applications belong or relate to the same research area. The total number of keywords found in the literature list is 401. The map, however, shows the largest set of connected items consisting of 251 keywords. At the first glance, one can recognize that the map is centered around four main keywords, these are *co-simulation*, *Modelica*, *Functional Mock-up Interface (FMI)* and *building simulation*. The size of the circles corresponding to the four keywords is relatively large and is weighted by the occurrence of each keyword. For instance, the lower right corner of the map shows studies that include applications of *district heating systems*, *dynamic modeling*, *control*, *heat pump* and *functional mock-up interface* that are connected to *Modelica* and *building simulation* main keywords. The keywords in this region have prominent red circles, which by interpreting against the legend color signify that the research addressing these topics is novel and recently published. The lower left corner of the map provides information about studies that utilized *co-simulation for building simulation*. It is clearly seen that tools such as the *Building Controls Virtual Test Bed (BCVTB)* and *EnergyPlus* are used for co-simulation between models related to *energy*, *thermal comfort*, *optimization*, *occupant behavioral modeling* and *Heating, Ventilation and Air-Conditioning (HVAC)* systems. The upper left corner links studies that combined both *Modelica* and the *FMI*. Here, complex systems such as *distributed energy resources*, *fenestration system* and *cyber-physical systems* distinctly employ the *FMI* to distribute the models across different platforms. Finally, the upper right corner shows studies that have solely used *Modelica* to cover research areas related to; development of the *Modelica Buildings* library, *energy storage* and *Differential/Algebraic System Solver* known as *DASSL*.

5. Discussion

The literature showed prolific applications of Modelica and co-simulation for integrated building energy performance simulation. In addition, the literature confirms that the simulation of district

energy systems using Modelica and co-simulation has grown rapidly in the recent few years. These applications substantiate that Modelica language, together with co-simulation, form a reliable paradigm for simulating complex and multi-domain systems such as the fifth generation District Heating and Cooling (DHC) systems. However, Buffa et al. [18] concluded in their review that a little has been done regarding the control strategies of the fifth generation DHC systems. Moreover, and as shown in studies [68,77,79,90,91], simulation performance becomes computationally taxing when coupling models with high level of details. Therefore, we summarize current research challenges related to the modeling and simulation of the fifth generation DHC systems to the following two categories: (i) optimal control strategies and operation and (ii) integrated simulation including building energy performance. The former challenge requires the specification of different system design settings and the impact of parameter estimation on control logics, while the latter involves investigating the simulation performance and speed when attempting to couple building models with DHC models. These are our main discussion points and are therefore in need for further elucidation.

5.1. Control strategies and operation

Basic control strategies in the fifth generation DHC systems differ from traditional ones. In traditional DHC systems, differential pressure control and supply temperature control are implemented in heat supply units, whereas in the fifth generation DHC systems these are absent [18]. The control logic depends on the system configuration in each design case. For instance, consider a closed-loop system where the heat carrier exchanges the thermal energy with a ground heat source. Here, the temperature is let to fluctuate freely. On the contrary, in open-loop systems the medium is discharged after exchanging thermal energy and therefore the supply temperature is dependent on the source. The differential pressure control, on the other hand, is found in design cases that involve a network with connected customers who are in need for heating while others are in need for cooling. In other cases, the direction and flow rate of the carrier medium are decided according to the interactions between the decentralized substations at each customer level. During the modeling and simulation of the fifth generation DHC systems in Modelica, parameter estimation is a key point that has a direct influence on the controllability and operation of the system. Parameters are one type of variables in Modelica models that are known before simulation starts and remain constant through the simulation. In the context of the fifth generation DHC systems, parameters may, for example, refer to the temperature difference between the two sides in the network or the fluid start temperature so that the simulation can be initialized. Depending on the simulated case, four possible outcomes may occur when one defines initial values for parameters [92]: (i) the solver may fail in trying to find consistent set of initial values if these are not fully specified; (ii) the solver produces errors due to an over specified system when a set of fixed inconsistent initial values are defined; (iii) the solver changes some of the initial values if they are guessed and (iv) the simulation may fail to converge when guessed inconsistent initial values are defined. Parameters affecting heat transfer between the soil and the pipes network should be given extra care. These include depth of burial, soil conductivity with respect to moisture and density, pipe insulation properties and distance between adjacent pipes [93]. Therefore, it is necessary to evaluate the impact of parameters estimation in order to choose fixed consistent initial values which would make the simulation more computationally efficient. Choosing a fixed consistent initial values has also the advantage of breaking algebraic loops [90] that are the artifact of multiple interdependent equations.

5.2. Simulation performance and accuracy

We begin discussing the simulation performance by revisiting the computational experiments reported in the International Energy Agency Annex 60 final report. A one-year simulation of a district energy grid connecting 6 dwellings required 1 day, 1 h and 49 min of CPU time. This reference simulation was performed completely using a single Modelica simulation environment. The best results were obtained by changing the solver tolerance and by using co-simulation together with parallel computing. This kind of simulation setup yielded a relative computation time of 0.37 when using two physical core CPU. The computation time can be further decreased with today's common multiple core processors. To improve the performance of simulating the fifth generation DHC systems, a few general remarks are here listed. First, although the entire building can be simulated in Modelica, it is recommended to avoid modeling buildings with high level of physical details [79] as buildings involve many components that result in thousands of differential equations. Second, the manual connection between building components involving equipment and control systems may be prone to errors as the level of details tends to increase. Moreover, Modelica language uses symbolic manipulation methods such as partitioning, tearing and inline integration [94–96] alongside conventional numerical solver methods in order to solve the unknowns in a system of equations. In building models with high level of detail, the code becomes large and the Modelica solver may be extremely slow in solving the unknowns. Another reason to avoid modeling buildings with high level of details is that buildings with heavy inertia can tolerate relatively large daily variations of heat supply from the district heating system while maintaining a good indoor climate [97]. In typical buildings, a 2 °C reduction in indoor temperature occurs after a few dozen hours of a 10% reduction in heat supply [57]. These figures indicate that building energy models have a time constant of hours where the resulting system model is not stiff. Non-stiff systems can be solved efficiently using explicit time integration algorithms [98]. However, when coupling building models with control systems which have dynamic response of seconds, the resulting stiff system requires implicit solvers to find a numerical solution. This point should be taken into consideration when choosing between loose or strong coupling strategies for co-simulation. In addition to the dynamic response of the system, shorter execution time is found in loosely coupled simulation, but for lower accuracy with increase of time step [77]. The accuracy decreases due to errors occurring in splitting the system and requirements for extrapolation during synchronization [36]. Integrated co-simulation of the fifth generation DHC systems would mitigate the current problem of oversizing heating and cooling systems at each building level. Space heating systems are designed based on the worst-case scenario, whilst during the full heating season the actual heating demand in the building varies between 0 and 80% of the design heat demand [99]. Co-simulation would also enable the analysis of how different types of buildings can contribute to the thermal energy flows in the network. This point can be achieved by simulating different occupant behaviors in order to derive the thermal demands for each building. Based on how much the building extract/reject heat from the network and how it affects the energy balance in the system, a decision can be made whether or not to connect the analyzed building to the network.

It follows from the discussion that it is highly required to prescribe the specifications with high level of details for each design case during the development process of a simulation model for the fifth generation DHC systems. Accurate specifications allow to analyze the dynamic behavior and numerical properties of the model from a model and global perspective. The former analyzes a specific configuration of the system, while the latter allows a

greater understanding of system performance under different configurations. Modelica language offers high flexibility in reusing and extending component models. This makes it a suitable modeling paradigm for modeling the various configurations in the fifth generation DHC systems. Component models such as heat pumps and bidirectional pipes need only to be developed once. A specific assembly of these pre-existing models arranges a specific configuration of the system. By modifying model parameters, a new configuration can be easily arranged using the same pre-existing models. This feature that Modelica offers saves modelers time when simulating different configurations and make component models less prone to errors. The process of sizing the system is accomplished by leveraging any of the co-simulation strategies. This enables the integration of buildings in the simulations during the initial design stage or when the network is being expanded.

6. Conclusions

This study aimed to analyze the status in the literature for simulating the fifth generation DHC systems. The technology behind these systems entails nontraditional installations and intricate interactions between connected buildings. The variety in system configuration and design cases required a modeling paradigm capable of predicting the dynamic behavior of the system for each simulated case. The simulation of the fifth generation DHC systems can be realized by utilizing Modelica and the Functional Mock-up Interface. The literature showed that these computational tools have a wide range of applications in building energy performance simulation. This work presented bibliographic maps and networks that link publications, authors, research organizations and research areas. The bibliographic analysis shows that employing Modelica and co-simulation for simulating district and building energy systems is novel but has some challenges that necessitate further research. Current research challenges in simulating the fifth generation DHC systems are the advanced control strategies and the integrated simulation including building energy performance. Decentralization of energy production and bidirectionality of energy flows make the control strategies differ in each design case. Co-simulation between district energy models and building models can help minimizing the oversizing of space heating and cooling systems. It also helps assessing the feasibility of connecting potential customers to the network by evaluating their contribution of thermal energy flows on the overall system efficiency. Coupling district and building energy models, however, conduces to a trade-off between simulation performance and model accuracy.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2020.110260>.

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Paper II



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Modelica-based simulations of decentralised substations to support decarbonisation of district heating and cooling

Marwan Abugabbara^{a,*}, Jonas Lindhe^a, Saqib Javed^a, Hans Bagge^b, Dennis Johansson^a

^a Department of Building and Environmental Technology, Division of Building Services, Lund University, 221 00 Lund, Sweden

^b Department of Building and Environmental Technology, Division of Building Physics, Lund University, 221 00 Lund, Sweden

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Abstract

District heating and cooling are considered effective solutions to decarbonise the energy use in the building sector. The latest generation of district heating and cooling also increases the potential of integrating heat pumps and chillers in each building substation. The benefits of such integration are the reduction of network temperature and distribution losses; the recovery of waste heat through a bidirectional network; and the decentralised production of heating and cooling. Sizing the network depends mainly on the heat flows between connected buildings. The substation performance and technical installations determine these heat flows. We present in this paper Modelica-based simulations of two design cases for substations. The first design case involves installed heat pump, chiller, and circulation pumps. Alternatively, the second design enables the heat pump to provide direct cooling through a heat exchanger. The models for these installations were developed using the Modelica language to perform continuous-time simulations. The performance in each design case was evaluated in terms of seasonal coefficient of performance and total electric energy use. An analysis on a cluster of 11 buildings suggests that the addition of the direct cooling heat exchanger can save up to 10% of the total annual electric energy use. Additional savings can be achieved by optimising the building supply temperatures and the district network temperature.

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1. Introduction

The new goals in the Swedish Climate Policy Framework adopted in 2017 aim at reaching zero net emissions of greenhouse gases by 2045 [1]. The country has also a promising target to achieve 100% renewable electricity production by 2040 [2]. To attain these goals, innovative solutions in different sectors are necessary. Heating and cooling of residential and commercial buildings account for almost 40% of the total final energy use in Europe and in Sweden [3]. This figure shows that there is a possibility to improve the energy-efficiency within the building

* Corresponding author.

E-mail address: marwan.abugabbara@hvac.lth.se (M. Abugabbara).

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sector. Waste heat recovery, security of supply, efficient heat distribution, and competitive price strategies are some of the current questions researchers attempt to address to improve energy-efficiency.

District heating and cooling (DHC) are considered effective solutions to decarbonise the building sector and can help reaching national and international energy-efficiency targets [4]. The systems are a common way for heating and cooling buildings in urban areas with an implementation rate exceeding 50% in Sweden, Denmark, Finland, Russia, and northern China [5]. Regardless of their popularity, conventional DHC systems have two main drawbacks. First, the centralised heat production results in higher distribution losses through the pipe network. Second, separate pipes are required for the supply of simultaneous heating and cooling. A possible solution to these problems is the integration of heat pumps and chillers in each building substation. The term *substation* refers to the link between the building side and the district network. A typical substation in a fifth-generation district heating and cooling (5GDHC) system mainly consists of a heat pump, chiller, circulation pumps, and heat exchanger for direct cooling. The outcomes of decentralised substations are the significant reduction in network temperature, and the simultaneous supply of heating and cooling through the same pipes.

1.1. Design and modelling of 5GDHC systems

A typical 5GDHC system leverages the synergies between connected buildings with different thermal demands. Hence, the heat carrier in the pipe can flow in either direction depending on the type of thermal demand at a given point in time. The system mainly comprises of the following three subsystems: (1) substations with installed heat pumps and chillers to modulate the temperature to the building desired supply levels, (2) low temperature bidirectional network with uninsulated pipes, and (3) balancing unit for energy storage and heat production. Previous work that investigated this generation can be seen in the comprehensive review by Buffa et al. [6]. For system design, Wirtz et al. [7] presented a mathematical model based on linear programming for the design of bidirectional networks. Another study by Abugabbara and Lindhe [8] demonstrated an analytical solution to balance energy flows between connected buildings and to size 5GDHC networks. An important aspect that is lacking in these studies is the ability to evaluate the system performance dynamically and for different design cases. In equation-based object-oriented modelling, large complex systems are composed by assembling smaller stand-alone subsystem models. These subsystem models can be easily reconfigured to simulate the system under different design cases.

The Modelica language offers high flexibility and reusability of component models across several domains. District heating and cooling systems involve components from thermo-fluid and control domains. A recent review by Abugabbara et al. [9] motivated the choice of Modelica for modelling and simulation of complex physical systems such as the 5GDHC systems. The free open-source Modelica *Buildings Library* [10] contains validated models for building and community energy systems. We use these models to construct larger models for decentralised substations. An investigation of different design cases and their impact on the system performance was carried out and the main findings are presented in this paper.

1.2. Paper objective

The objective of the paper is to evaluate the performance of substation installations in different design cases. The paper attempts to study the performance of two substations with different design cases. Fig. 1 presents the schematic diagram of the two considered substations. In substation A, the heat pump evaporator inlet is connected to the chiller condenser outlet to recover waste heat. Similarly, the heat pump evaporator outlet serves as a cold source to the chiller condenser inlet. Depending on the proportion between heating and cooling demands, heat is either extracted or injected from/to the bidirectional network. Substation B includes all previous installations in addition to a heat exchanger used for direct cooling. The heat exchanger reduces the electric power in the chiller's compressor. However, it decreases the potential to recover waste heat by the heat pump.

Heat pumps transfer thermal energy from a low temperature source to a higher temperature sink. The heat pump Coefficient of Performance (COP) increases to infinity when the temperature difference between sink and source approaches zero. Waste heat from the chiller raise the temperature at the heat pump source, hence, increasing the heat pump COP. Conversely, the direct cooling heat exchanger reduces the electric energy use for space cooling while also reducing the amount of recovered waste heat. We present in this paper the interactions between heat pumps, chillers, and the direct cooling heat exchanger on a cluster of 11 buildings in Lund, Sweden. The analysis was performed using Modelica continuous-time simulations where temperatures at each simulation time point were computed.

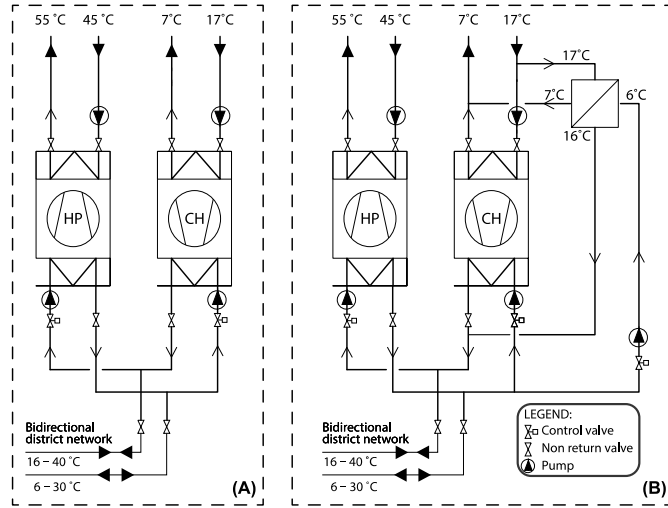


Fig. 1. Schematic diagram of a substation model with installed heat pump and chiller (A) and a substation with additional heat exchanger for direct cooling (B). Design value are presented according to the case study input parameters shown in Table 1.

2. Method

This section presents the approach for modelling the substations including heat pumps, chillers, circulation pumps, and direct cooling heat exchanger. The demand profiles in the case study together with the set of used input parameters are then presented. The performance indicators used for evaluating the substation performance are then described. The section ends with a description of the study assumptions and limitations.

2.1. Models for substations

Heat pumps and chillers were modelled as a Carnot refrigerant cycle. Adjusting the COP based on the Carnot efficiency avoids favouring any particular product [11]. The COP for a heat pump and a chiller is defined as

$$COP_{HP} = \eta_{Carnot} \frac{T_{condenser}}{T_{condenser} - T_{evaporator}} \quad COP_{CH} = \eta_{Carnot} \frac{T_{evaporator}}{T_{condenser} - T_{evaporator}} \quad (1)$$

Since the physical behaviour of chillers is almost identical to heat pumps, we will only present models for heat pumps. At each simulation time point, mass flow rates at the condenser and evaporator are computed as

$$\dot{m}_{condenser} = \frac{\dot{Q}_h}{c_p \Delta T_{condenser}} \quad \dot{m}_{evaporator} = \frac{\dot{Q}_h - W_{compressor}}{c_p \Delta T_{evaporator}} \quad (2)$$

where \dot{Q}_h is the building heat demand in Watts, c_p is the water specific heat capacity in J/kg·K, $\Delta T_{condenser}$ and $\Delta T_{evaporator}$ are the temperature difference between condenser and evaporator inlet and outlet, and $W_{compressor}$ is the heat pump electric power which is equivalent to

$$W_{compressor} = \frac{\dot{Q}_h}{COP_{HP}} \quad (3)$$

On the heat pump evaporator side, the circulation pump extracts water in the amount of $\dot{m}_{evaporator}$. The circulation pump electric power is derived as

$$W_{cirPump} = \frac{\dot{V}_{evaporator} \Delta p}{\eta_h \eta_m} \tag{4}$$

where $\dot{V}_{evaporator}$ is the volume flow rate in m^3/s , Δp is the pump pressure rise in Pa, η_h and η_m are the hydraulic and motor efficiencies of the circulation pump.

Lastly, the Carnot cycle models for heat pumps and chillers were used to construct models for substations.

Fig. 2 depicts the case of a substation with only heat demands and installed heat pump. Modelling systems in Modelica is realised by instantiating components and connecting them visually in a Lego-like approach. Connector lines interface component variables inside the model when seen from within, and from the outside when the component is externally connected. The right box in Fig. 2 provides a description of the components in substation model with only heating demand. Fluid ports 17 and 19 represent the connection to the respective district warm and cold pipes when the model is connected from the outside. The fluid transport delay in the substation is taken into account as shown in components 16 and 18. On the heat pump evaporator cold side, the circulation pump extracts water from the warm district pipe to the evaporator inlet. The cold water at the evaporator outlet then flows to the district cold pipe. On the heat pump warm side, mass flow rates at the condenser inlet are computed in components 01 to 06 based on the building demand. The condenser outlet is connected to the building sink shown in component 08. Finally, the substation total electric power and heating demand are interfaced externally through components 14 and 15 for processing results.

2.2. Case study

We analysed a cluster of 11 buildings to evaluate the substation performance in both design cases. The buildings are located in Lund, Sweden and have a total heated floor area of about 110,000 m^2 . Most of the floor area is used for offices, conference rooms, and labs. Other space usage includes restaurants and a sport centre. To understand the demand requirements in the cluster, Fig. 3 shows the yearly heating and cooling demand profiles. As clearly noticed, the cluster has simultaneous demands for heating and cooling throughout the year. The simultaneous demands increase the potential to exchange energy between connected buildings. However, the actual amount of exchanged energy depends on the COP of heat pumps and chillers. The substation and network design temperatures play an important role in determining the amount of exchanged energy within the cluster.

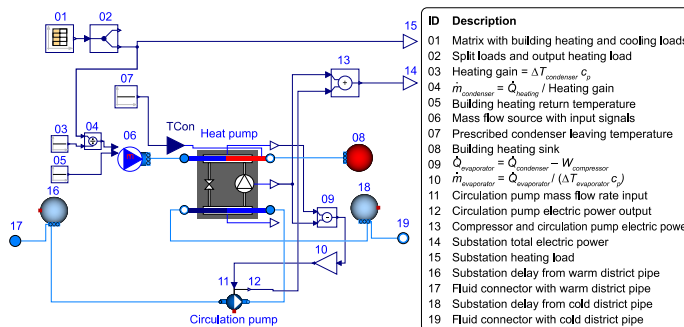


Fig. 2. Diagram view of a substation model with only heating demand. The right box describes the different components included in the model.

Table 1 provides an overview of the design parameters used in the simulations. On the district side, heating is injected to the network by the balancing unit when the warm pipe temperature drops below 16 °C. On the other hand, when the cold pipe temperature rises above 30 °C, the balancing unit supplies cooling to the network. The value of the parameter regarding water pressure drops over condenser and evaporator was chosen based on the

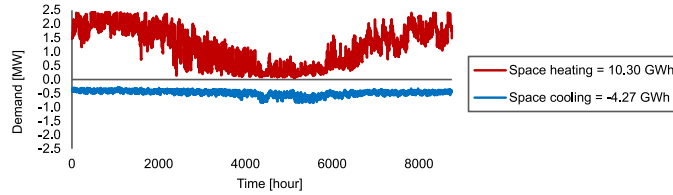


Fig. 3. Yearly heating and cooling demand profiles in the building cluster.

Table 1. Case study design input parameters.

Parameter	Value	Unit
Temperature range in warm district pipe ^a	16–40	°C
Temperature range in cold district pipe ^a	6–30	°C
Design supply temperature for space heating ^a	55	°C
Design supply temperature for space cooling ^a	7	°C
Evaporator temperature difference of the heat pump (outlet – inlet) ^a	–10	K
Condenser temperature difference of the chiller (outlet – inlet) ^a	10	K
Temperature difference between refrigerant and water outlet in condenser and evaporator	2	K
Water pressure drops over condenser and evaporator	30 000	Pa
Carnot efficiency	50	%
Pump hydraulic and motor efficiencies	70	%

^aThe reader is advised to refer to Fig. 1 to point the design values on the schematic diagram.

measurements reported in [12]. The global circulation pump efficiency was set to 0.49 for the assumed efficiencies shown in the table. Both design cases were simulated using with the same design input parameters.

2.3. Performance indicator

The case study was simulated for each of the two design cases presented in Fig. 1. For each simulation, the system performance was assessed based on the Seasonal Coefficient of Performance (SCOP). The SCOP for heating and cooling is defined as

$$SCOP_h = \frac{\sum_i \dot{Q}_{h,i}}{\sum_i W_{compressorHP,i} + W_{hCirPump,i}} \quad SCOP_c = \frac{\sum_i \dot{Q}_{c,i}}{\sum_i W_{compressorCH,i} + W_{cCirPump,i}} \quad (5)$$

For $SCOP_h$ in Eq. (5) the \dot{Q}_h denotes the total annual delivered heating energy by heat pumps, $W_{compressorHP}$ is the compressors total annual electric energy use in heat pumps, and $W_{hCirPump}$ is the total annual electric energy use in circulation pumps used for heating. The compressor electric power in heat pumps and chillers is derived from Eq. (3), whereas the electric power in circulation pumps is determined as shown in Eq. (4). It is worth noting that in a system with direct cooling, the chiller delivers thermal energy that corresponds to the difference between the cooling demand and the transferred heat in the heat exchanger.

2.4. Assumptions and limitations

When modelling the direct cooling heat exchanger, our primary interest was to utilise the available energy in the heat pump evaporator. In practice, the heat exchanger can also draw water from the district side depending on the temperature levels in the building return and the district pipes. The study did not include the temperature control between the heat exchanger and the district pipes. Therefore, direct cooling was realised when the heat pump is in operation and by assuming that the evaporator temperature satisfies the building cooling demand. Moreover, we did not model the building side of the heat exchanger. Instead, the heat transfer rate in the heat exchanger was set to be

equivalent to the heat flow in the heat pump evaporator. This approach was sufficient to model the heat exchanger and was also followed by Sommer et al. when they only modelled the district side of the heat exchanger [13].

Another assumption involved the connection points shown in Fig. 1. These points indicate fluid mixing and were modelled as mixing volumes that include the substation delay. The delay refers to the time it takes for the change in temperatures to be absorbed by the system. A time constant is used to describe this first-order lag and is defined based on engineering experience. We defined a time constant of 600 s similar to the district examples presented in the Modelica Buildings Library.

3. Results and discussion

This section presents the substation SCOP and electric energy use in the two design cases.

3.1. Substation SCOP

The variations in the cooling and heating SCOP throughout the year are shown Fig. 4. The left chart presents the performance for the design case without direct cooling, whereas the right chart shows the system performance when direct cooling is realised. At first glance, it can be noticed that both systems have somewhat a low heating SCOP. We have considered that heat pumps supply a constant temperature of 55 °C throughout the year. As a matter of fact, each heat pump adjusts the heating supply temperature based on the outdoor temperature and a control curve. The control curve varies from building to building and can be implemented into the model when provided. Including these curves mean that heat pumps would need to operate for lower temperature lifts compared to a constant supply temperature operation. This would result in an improved heat pump performance.

A discernible distinction between the two design cases is seen in the cooling SCOP. The addition of the direct cooling heat exchanger increased the annual cooling performance by about two and a half fold. Since heat pumps in this system were also utilised to provide cooling, chillers were running with much lower powers. In winter months where heat pumps covered most of the cooling demand, the compressor load in chillers was reduced. This can be seen by contrasting the cooling SCOP in both charts in Fig. 4. In summer months where heat pumps operate at much lower load ratios, chillers start to run to provide the required cooling. This resulted in a rapid decrease in the cooling SCOP in the system with direct cooling. In view of the fact that the building cluster has dominant heating demand throughout the year, employing direct cooling from heat pumps is regarded more favourable.

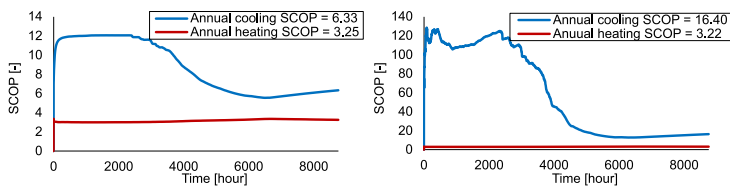


Fig. 4. Variation of heating and cooling seasonal coefficient of performance for a system with no direct cooling (left) and for a system with direct cooling (right). Note that the two charts do not have a uniform scale.

3.2. Substation electric energy use

Fig. 5 provides a better understanding of how each design case impacted the substation annual electric energy use. The top two figures A and B compare the compressor cumulative electric energy use. For heat pumps in the two design cases, the compressor electric energy use is almost identical. This accords with the presented heating SCOP in Fig. 4 since the seasonal performance was similar in the two designs. A notable difference between the two design cases is seen in chillers’ electric energy use. In the first design case, chillers run continuously throughout the year to provide the required cooling demand, as shown in Fig. 5(A). When direct cooling is realised, chillers only run when heat pumps can no longer fulfil the cooling demand through the evaporator ($Q_c > Q_{\text{evaporator}}$). Overall, direct cooling covered the entire cooling demand during almost one third of the yearly operation. Moreover, it decreased

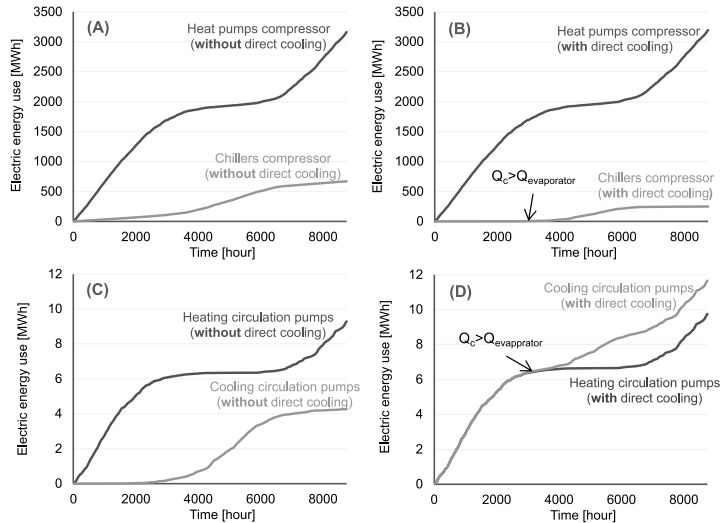


Fig. 5. Substation annual electric energy use. Figures (A) and (B) compare the electric energy use in compressors between the two design cases, while figures (C) and (D) compare the electric energy use in circulation pumps.

the operating capacity of chillers which consequently reduced the compressor annual electric energy use by about 63%.

The circulation pumps electric energy use is illustrated in Figs. 5(C) and 5(D). The two lines representing heating and cooling circulation pumps in Fig. 5(D) are superimposed on each other until a certain point. This shows that the same circulation pump is used for both heating and cooling which are provided by heat pumps. After reaching the maximum capacity of the direct cooling heat exchanger where $Q_c > Q_{\text{evaporator}}$, chillers start to operate. This is depicted in the diverging point in the grey line where other circulation pumps start to draw water to chillers. Taken together, the results suggest that the system with direct cooling yielded a reduction of 10% of the total electric energy use. The results, however, may differ from one building cluster to another depending on the simultaneity between heating and cooling demands. Previous studies aimed to investigate the simultaneous demands developed metrics such as the Diversity Index [11] and the Demand Overlap Coefficient [14]. Evaluating these metrics supports engineers to map potentially promising clusters in order to increase the efficiency of the district system.

4. Conclusions

We demonstrated in this paper Modelica-based simulations of decentralised substations with two different designs. The substations included models for heat pumps, chillers, and circulation pumps. The difference between the two designs was the utilisation of heat pumps to provide cooling from the evaporator to a direct cooling heat exchanger. We studied a cluster of 11 buildings with simultaneous heating and cooling demands to compare the two designs. The substation seasonal coefficient of performance (SCOP) and annual electric energy use were evaluated as performance indicators. The results show that the system design with direct cooling reduced the operation time of chillers by one third in addition to decreasing their operating capacity. To improve substation performance, we recommend implementing temperature controllers in both demand and supply sides. This may involve controlling the heating and cooling supply temperatures based on the outdoor weather, as well as controlling the district network temperature. The former would improve the performance of heat pumps and chillers, while the latter would increase the potential for direct cooling through the district network.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Paper III





A simulation model for the design and analysis of district systems with simultaneous heating and cooling demands

Marwan Abugabbara*, Saqib Javed, Dennis Johansson

Department of Building and Environmental Technology, Division of Building Services, Lund University, 221 00 Lund, Sweden

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ABSTRACT

Latest generations of district heating and cooling systems are characterised by low network temperature with uninsulated pipes, decentralised heat pumps and chillers to modulate the network temperature, and shared energy flows between interconnected buildings. This paper presents a simulation model for the design and analysis of these systems. The model was developed using the Modelica language and it consists of component models from thermal, fluid, and control domains. The model was employed to simulate and analyse the first existing Swedish district system with simultaneous heating and cooling demands and bidirectional energy flows. The system currently connects nine buildings with total respective annual heating and cooling demands of 4.2 and 1.2 GWh. Simulation results revealed several benefits for integrating district and heat pump technologies, including (1) sharing energy flows between interconnected buildings to cover 40 % of the total carried heat in the network, (2) reducing the total purchased energy by 69 % compared to a traditional four-pipe district system, and (3) reducing distribution losses by 28 % compared to traditional networks with insulated pipes. The model can be utilised to support future research and development of new advanced district heating and cooling systems.

1. Introduction

Heating and cooling demands in existing and future buildings will vary due to climate change, urbanisation, and the global increase of living standards [1,2]. The International Energy Agency has projected that space cooling demands will be tripled between 2016 and 2050 and that two-thirds of the world's households could potentially install systems for comfort cooling [3]. At the same time, the demands for heating will still exist for domestic hot water production and space heating. Therefore, the need for integrated heating and cooling systems becomes increasingly important.

The integration between district heating and cooling (DHC) and heat pump technologies is an effective solution that can offer several benefits, including, for example, (1) efficient decarbonisation of the building sector, (2) high and reliable security of supply to connected buildings, (3) lower risks for fire and gas explosions in buildings since individual heating and cooling systems with hazardous fuels are eliminated, and (4) increased community resilience by connecting buildings suffering from energy poverty to a district system [4–7].

District heating (DH) and heat pumps are the two largest heat sources that supply heat to Swedish residential and public buildings. The market share for DH in 2014 was about 55%, whereas heat pumps had 25% of the market share [8]. Sweden has also a large district

cooling (DC) market that delivered about 1 TWh in 2019 for both comfort and process cooling applications [9]. These figures indicate potential for leading the heating and cooling markets by leveraging the benefits of DHC and heat pump technologies.

1.1. Development of district heating and cooling

District heating networks have evolved through four generations that were categorised and defined by Lund et al. [10]. The first generation was introduced in Lockport in the United States in the late 19th century and used steam as a heat carrier [11]. Since steam systems had a high risk of explosion, the steam was replaced by pressurised water with high temperatures in the second generation. In the 1980s, building space heating was typically provided by radiators with a supply temperature of around 80 °C. This led to the development of the third generation which is commonly referred to as Scandinavian district heating since many of its components were prefabricated in Scandinavian countries [12]. Although the third generation is widely spread, a large share of the input heat is lost through the distribution pipes due to the high network temperature. The fourth generation addressed this issue by lowering the network temperature to around

* Correspondence to: Faculty of Engineering, Lund University, Box 118, 221 00 Lund, Sweden.
E-mail address: marwan.abugabbara@hvac.lth.se (M. Abugabbara).

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Nomenclature	
Abbreviations	
5GDHC	Fifth-Generation District Heating and Cooling
ASHP	Air-Source Heat Pump
BU	Balancing Unit
CDF	Cumulative Distribution Function
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
DSS	Decentralised Substation
FSM	Finite State Machine
Latin letters	
c_p	Specific heat capacity [J/kg K]
K_2	Constant for computing pipe pressure drops
\dot{Q}	Heat flow rate [W]
\dot{V}	Volume flow rate [m ³ /s]
\dot{m}	Mass flow rate [kg/s]
A	Amplitude
L	Pipe segment length [m]
B	Pipe burial depth [m]
C	Horizontal distance between centre of pipes [m]
D	Pipe outer diameter [m]
F	Factor for accounting pressure loss in pipe fittings
P	Power [W]
R	Thermal resistance [K/W]
Re	Reynolds number
T	Temperature [K]
Z	Absolute error [%]
d	Pipe inner diameter [m]
e	Pipe relative roughness [m]
k	Fixed flow resistance factor at nominal flow
y	Control signal
Greek letters	
ΔT	Temperature difference [K]
Δp	Pressure drop [Pa]
α	Thermal diffusivity [m ² /s]
β	Dimensionless resistance parameter
γ	Modified pipe wall friction factor
ϵ	Heat exchanger effectiveness
η	Efficiency
λ	Thermal conductivity [W/m K]
μ	Fluid dynamic viscosity [Pa s]
ρ	Fluid density [kg/m ³]
τ	Annual period length [s]

Subscripts	
a	Anti-symmetrical
c	Cooling/cold
CH	Chiller
$comp$	Compressor
$cond$	Condenser
dis	District
$evap$	Evaporator
h	Heating
HP	Heat Pump
hx	Heat exchanger
hyd	Hydraulic
lea	Leaving
mea	Measured
mod	Modelled
mot	Motor
ms	Mean surface
nom	Nominal
pri	Primary
ret	Return
s	Symmetrical
sec	Secondary
set	Setpoint
sup	Supply
ug	Undisturbed ground
w	Warm

absorption chillers with cold water as the distribution fluid. A third generation emerged in the 1990s to utilise diversified and decentralised cold sources as well as heat recovery from compression chillers and short-term cold storage. The future fourth generation is based on the synergy with other energy sectors such as the electricity and heating sectors. Several technologies such as electric heat pumps, absorption heat pumps, ambient sources, and cold storage are integrated into a smart energy system based on renewable energy sources.

During the latest few years, fifth-generation district heating and cooling (5GDHC) has been developed. It is characterised by additional reduction in the network temperature as well as the ability to supply simultaneous heating and cooling. A typical 5GDHC network operates at temperature levels close to the ambient temperature (<40 °C). Therefore, installing decentralised heat pumps and/or mechanical chillers is necessary to adjust the network temperature to the desired building supply temperatures. Such operating principle allows combining heating and cooling where energy can be shared between connected prosumers who produce/consume energy towards/from the network. Consequently, the potential for waste-heat recovery is increased and the energy efficiency of the district network is improved. Since the 5GDHC is a fairly new complex district heating and cooling concept, there is a lack of a common vocabulary as different names can be found in the literature [14,15]. These include, e.g., *fifth-generation district heating and cooling* [16–19], *ultra-low networks* [20–22], and *bidirectional networks* [23,24], among others.

Buffa et al. [25] reviewed existing 5GDHC systems in Europe. The current status and development of 5GDHC is reported by Jonas et al. [17]. Wirtz et al. [26] presented an optimisation approach for designing 5GDHC systems using mixed-integer linear programming. A topology analysis tool was developed by von Rhein et al. [27] using the Modelica language [28] to determine the most feasible way to connect prosumers to either existing or new 5GDHC networks. Sommer et al. [29] also used Modelica to compare a single-pipe 5GDHC network (referred to as the reservoir network) to a double-pipe 5GDHC network.

40 °C, which allowed the integration of low-enthalpy renewable energy sources such as solar and geothermal [10].

In a recently published paper, Østergaard et al. [13] have categorised similar four generations for DC systems. The first generation was introduced in the USA in the late 19th century as a pipeline refrigeration system to supply cooling to the food industry. The second generation was introduced in the 1960s to provide comfort cooling to commercial and public buildings by using large compression or

Millar et al. [30] generated demand profiles for several buildings with rarely occurring simultaneous heating and cooling and highlighted the need for energy storage to utilise the shared energy for later usage. Meibodi and Loveridge [31] evaluated the possible integration between energy geostructures (e.g., energy walls, energy piles, and energy tunnels) and 5GDHC systems.

Based on the literature, it can be noticed that previous research has investigated particular aspects of 5GDHC systems such as component sizing and network topology analysis. However, there is still a need to investigate these new advanced systems from a global perspective combining several technical aspects. Our research attempts to bridge this gap by presenting a simulation model for the design and analysis of 5GDHC systems including thermo-fluid and control components. To the authors' best knowledge, no previous work has investigated 5GDHC systems using a multi-domain approach with an analysis of network heat losses in uninsulated pipes. The model can therefore support the planning and analysis of new advanced DHC concepts.

1.2. Modelling of advanced district heating and cooling concepts

The literature review has shown that 5GDHC systems may incorporate several design options, such as the choice of network topology and the type of energy source. This poses challenges to model and analyse changes in the system which are expected to take place during the initial design stage or operation as well as future network expansion. Therefore, methods that support multi-domain modelling and provide flexibility in adapting changes in the model architecture are necessary. Modelica is regarded by the International Energy Agency as one of the new generation computational tools for modelling building and community energy systems [32]. It is also recommended by researchers, including Abugabbara et al. [33], for modelling 5GDHC systems.

Modelica is a free and open-source equation-based object-oriented modelling language that supports multi-domain modelling of complex physical systems. The behaviour of physical systems is described using differential-algebraic and discrete equations that are encapsulated inside an icon that represents the model [34]. To build models of large physical systems, smaller component models are connected through connection lines that exchange model variables through standardised interfaces. Therefore, there is no need for an explicit definition of input/output relationships between the models. Instead, the variables are computed by efficient solvers as long as the boundary conditions at the connection ports are sufficient to solve the system of equations.

Robust Modelica models for building and energy systems are available for free in several libraries, such as the Modelica *Buildings* library [35] developed at Lawrence Berkeley National Laboratories in the USA, *AixLib* [36] from RWTH Aachen in Germany, and *IDEAS* [37] from KU Leuven in Belgium. Component models from existing libraries can be used either directly or after customising them to suit the need of the end-user. Researchers and end-users alike can therefore utilise the available component models to develop a simulation model for advanced district systems such as 5GDHC systems.

1.3. Paper aims, contribution, and organisation

The aim of this paper is to present the development of a simulation model for the design and analysis of 5GDHC systems with two-pipe network topology and bidirectional energy flows, including main thermo-fluid components and control strategies. Additionally, the paper aims to present the potential and anticipated system performance under semi-ideal conditions. The paper contributes to the growing area of research on new and advanced district heating and cooling technologies by presenting and utilising the simulation model to analyse the first existing Swedish 5GDHC system. Additionally, the model can be utilised to monitor an existing 5GDHC system, analyse network losses in uninsulated distribution pipes, and forecast heat injection/extraction

into/from the network. The study findings could be used to explore future possibilities for a wider implementation of 5GDHC systems.

The development of the simulation model is firstly described in Section 2 following a gradual progression from modelling small components up to modelling the entire district system. Annual simulation results are then presented in Section 3 for an in-depth analysis of the system operation. This is followed by Section 4 discussing the main findings and practical recommendations for wider implementation of 5GDHC systems. Finally, conclusions and future work are outlined in Section 5.

2. Methods and material

This section provides a classification of the system components used in the simulation model. Next, the Modelica implementation of thermo-fluid components and control strategies is described. A 5GDHC network is then assembled using the system components. Finally, the model validation and limitations, and the system performance indicators are clarified.

2.1. System description

The description of a 5GDHC system at different levels of abstraction is illustrated in Fig. 1. The illustration can also be seen as a modelling hierarchy that supports dividing the large district system into smaller subsystems and further down to single components. At the highest level of abstraction, the district system connects prosumers through a ring network with two pipes denoted as warm and cold pipes. A balancing unit is responsible for injecting or rejecting heat into/from the network depending on the dominant demand type and the temperature levels in the network. This function is primarily achieved by a reversible air-source heat pump. In the heat rejection mode, a cooling tower is also realised. Another important function of the balancing unit is to pressurise the network such that it ensures sufficient delivery of flow. Thus, an accumulator tank is incorporated to provide a desired static pressure. The magnified part in Fig. 1 shows the main components in a prosumer's decentralised substation designed for simultaneous heating and cooling demands, and includes a heat pump, a chiller, and a free-cooling heat exchanger. In the subsystem level, the system is divided into three independent subsystems that can be modelled and tested separately. Finally, individual components are described by differential-algebraic equations using Modelica syntax. Components for building and energy systems are modelled by reusing or editing existing components from finished Modelica libraries. Components from the Modelica *Buildings* libraries version 8.1.0 were used in this study and the model for the district system was assembled following a bottom-up approach.

2.2. Models for thermo-fluid components

This section presents models for the main subsystems that constitute a 5GDHC network, i.e., decentralised substations, distribution pipes, and the balancing unit.

2.2.1. Model for decentralised substations

A decentralised substation (DSS) can serve an individual building or multiple buildings at the same time. The type of technical installations in any DSS depends on the building demand type. Fig. 2 shows a Modelica diagram view of the main components included in a typical DSS with both heating and cooling demands. The figure is assisted with number labels that are used to explain the model behaviour at different points. Data for heating and cooling demands, and supply temperatures are first prescribed at point 01. The heating and cooling mode controllers are placed at points 02 and 03, respectively. The building heating return temperature $T_{ret,h}$ is expressed at point 04 as:

$$T_{ret,h} = T_{sup,h} - \Delta T_{HP,cond} \quad (1)$$

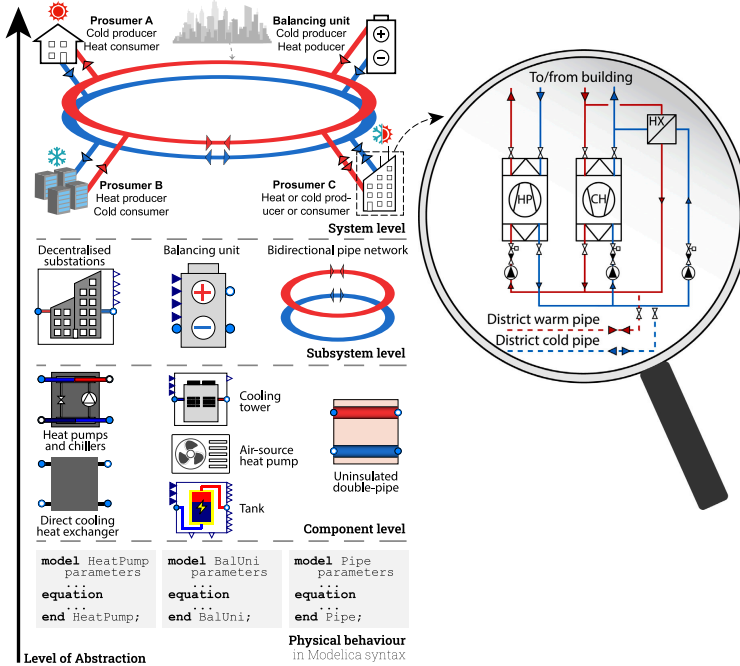


Fig. 1. Different levels of abstraction for a 5GDHC system.

where $T_{sup,h}$ is the heating supply temperature, and $\Delta T_{HP,cond}$ is the temperature difference between the heat pump condenser inlet and outlet. The circulation pump at point 05 draws water to the inlet of the heat pump condenser in the amount of:

$$\dot{m}_{HP,cond} = \frac{\dot{Q}_h}{\Delta T_{HP,cond} \cdot c_{p,water}} \cdot y_h \quad (2)$$

where \dot{Q}_h is the heat demand, $c_{p,water}$ is the specific heat capacity of water, and y_h is the heating mode control signal that determines the pump's state of operation. The required heating supply temperature defined at point 06 is equivalent to the heat pump condenser leaving temperature $T_{HP,cond}$, and the heat pump model shown at point 07 computes the coefficient of performance (COP) based on a prescribed Carnot efficiency η_{Carnot} as:

$$COP_{HP} = \eta_{Carnot} \cdot \frac{T_{HP,cond}}{T_{HP,cond} - T_{HP,evap}} = \frac{\dot{Q}_h}{P_{comp}} \quad (3)$$

where $T_{HP,evap}$ is the temperature of the heat pump evaporator, and P_{comp} is the compressor electric power. The building heating loop is then closed by including the heat sink shown at point 08. The heat pump delivered thermal power and the total electric power used by the compressor and the circulation pumps are marked at point 09 and 10, where the electric power of the circulation pump P_{pump} is defined

as:

$$P_{pump} = \frac{\dot{V} \cdot \Delta p}{\eta_{hyd} \cdot \eta_{mot}} \quad (4)$$

where \dot{V} is the volume flow rate, Δp is the pump pressure rise, and η_{hyd} and η_{mot} are respectively the hydraulic and motor efficiencies.

At the heat pump source side, two loops can be found to establish hydraulic separation between the building demand side and the district supply side for safe operation. Moreover, the heat pump evaporator may need to operate at a temperature difference and a flow rate different from that in the district loop to avoid freezing. As such, the mass flow entering the heat pump evaporator at point 11 equals to:

$$\dot{m}_{HP,evap} = \frac{\dot{Q}_h - P_{comp}}{\Delta T_{HP,evap} \cdot c_{p,water}} \cdot y_h \quad (5)$$

A similar procedure takes place when cooling demands exist. Unlike the heating mode where only the heat pump delivers all heating demand, cooling can be delivered either by the chiller or the free-cooling heat exchanger or a combination of both. The explanation provided below assumes that both the chiller and the free-cooling heat exchanger operate at the same time. In such mode, the chiller provides the amount of cooling that exceeds the capacity of the free-cooling heat exchanger. The return temperature from the building cooling loop $T_{ret,c}$ is described at point 13 as:

$$T_{ret,c} = T_{sup,c} - \Delta T_{CH,evap} \quad (6)$$

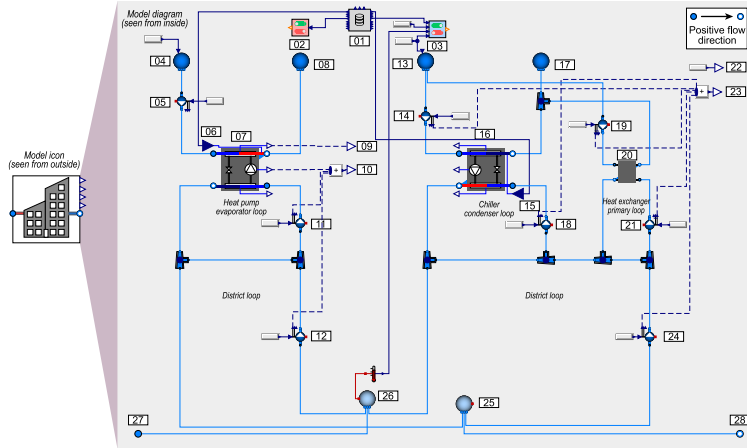


Fig. 2. Diagram view of a decentralised substation with heating and cooling demands. The diagram is assisted with number labels that correspond to the model description provided in Section 2.2.1.

where $T_{sup,c}$ is the cooling supply temperature, and $\Delta T_{CH,evap}$ is the temperature difference between the chiller evaporator inlet and outlet. The circulation pump at point 14 draws water to the inlet of the evaporator equivalent to:

$$\dot{m}_{CH,evap} = \frac{\dot{Q}_c - \dot{Q}_{hx}}{\Delta T_{CH,evap} \cdot c_{p,water}} \cdot y_c \quad (7)$$

where \dot{Q}_c is the cooling demand, \dot{Q}_{hx} is the heat transfer rate of the free-cooling heat exchanger, y_c is the cooling mode control signal that activates the corresponding circulation pumps.

The leaving temperature of the chiller's evaporator is prescribed at point 15 and the COP of the chiller shown at point 16 is determined as:

$$COP_{CH} = \eta_{Carnot} \cdot \frac{T_{CH,evap}}{T_{CH,cond} - T_{CH,evap}} = \frac{\dot{Q}_c}{P_{comp}} \quad (8)$$

The cold water is then supplied to the building cold sink marked at point 17. The circulation pump at point 18 draws water from the district loop to the warm side of the chiller as:

$$\dot{m}_{CH,cond} = \frac{\dot{Q}_{CH,cond}}{\Delta T_{CH,cond} \cdot c_{p,water}} \cdot y_c \quad (9)$$

Similarly, the pumps at the secondary and primary sides of the free-cooling heat exchangers marked respectively at points 19 and 21 draw:

$$\dot{m}_{hx} = \frac{\dot{Q}_c}{\Delta T_{hx} \cdot c_{p,water}} \cdot y_c \quad (10)$$

The corresponding heat transfer rate of the free-cooling heat exchanger becomes:

$$\dot{Q}_{hx} = \varepsilon \cdot \dot{m}_{hx} \cdot c_{p,water} \cdot (T_{pri,in} - T_{sec,in}) \quad (11)$$

where ε is the heat exchanger effectiveness that is computed based on the number of transfer units, the ratio between minimum to maximum flow rate, and the flow regime; $T_{pri,in}$ is the inlet temperature at the primary side; and $T_{sec,in}$ is the inlet temperature at the secondary side.

Finally, the delivered cooling power and the corresponding electric power are expressed at points 22 and 23, respectively.

Energy is shared locally inside the decentralised substation at the fluid volumes shown at points 25 and 26. At times when the DSS has dominant heating demands, it extracts water from the warm district pipe connected to the fluid port depicted at point 27. On the contrary, the DSS extracts water from the cold district pipe at point 28 when cooling dominates.

2.2.2. Model for distribution pipes

The model for distribution pipes is divided into two parts based on thermal and hydraulic aspects. The pipes are discretised into n segments along the flow path. For each segment, the thermal part is described using steady-state heat losses that are calculated according to Standard SS-EN 13941-1 [38] and adapted for uninsulated pipes. The calculation is based on the multipole method originally described in [39]. In such a method, heat losses are calculated based on a superposition of a symmetrical problem (interaction between pipes and surroundings and not with each other) and an anti-symmetrical problem (interaction between pipes and not with the surroundings). Fig. 3(a) illustrates the problem, and the equivalent resistance model adopted from van der Heijde et al. [40] is shown in Fig. 3(b). The Modelica implementation is then shown in Fig. 3(c).

The zero-order multipole formulae for the symmetrical resistance R_s is expressed as:

$$R_s = \frac{1}{2 \cdot \pi \cdot \lambda_{soil}} \cdot \left[\ln \left(\frac{4 \cdot H_o}{D} \right) + \beta + \ln \left(\sqrt{1 + \left(\frac{2 \cdot H_o}{C} \right)^2} \right) \right] \quad (12)$$

where λ_{soil} is the soil thermal conductivity, H_o is a corrected depth taking into account the ground surface resistance as $H_o = H + R_o \cdot \lambda_{soil}$, D is the pipe outer diameter, β is a dimensionless resistance parameter equivalent to:

$$\beta = \frac{\lambda_{soil}}{\lambda_{pipe}} \cdot \ln \left(\frac{D}{d} \right) \quad (13)$$

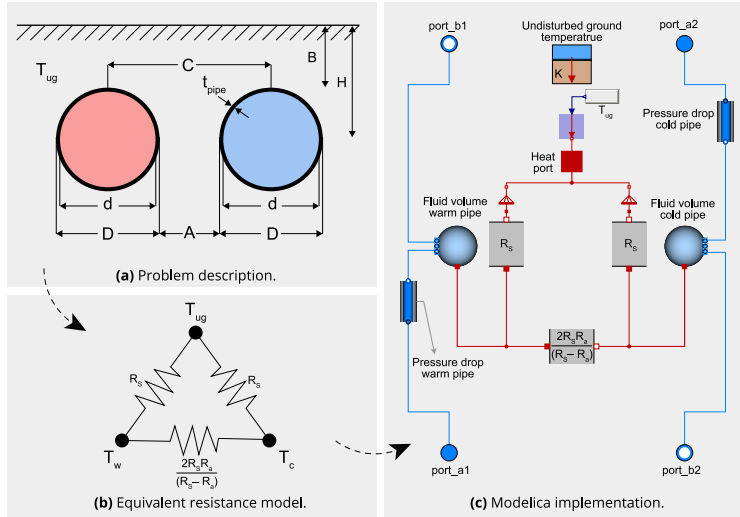


Fig. 3. Description of a steady-state heat loss problem in a double buried pipe. The Modelica implementation is presented for one discretisation element along the pipe path.

where λ_{pipe} is the pipe material thermal conductivity and d is the pipe inner diameter. On the other hand, the anti-symmetrical resistance R_a is expressed as:

$$R_a = \frac{1}{2 \cdot \pi \cdot \lambda_s} \cdot \left[\ln \left(\frac{4 \cdot H_g}{D} \right) + \beta - \ln \left(\sqrt{1 + \left(\frac{2 \cdot H_g}{C} \right)^2} \right) \right] \quad (14)$$

Once the resistances are defined, the temperatures of the warm and cold fluids are simulated dynamically and interfaced with the resistances at the heat ports denoted in red squares in Fig. 3(c). Finally, the undisturbed ground temperature at the pipe burial depth B is described based on site weather parameters and according to the following formula presented in the ASHRAE District Heating guide [41]:

$$T_{ug,B} = T_{ms} + A_s e^{-B \sqrt{\frac{\pi}{\alpha \cdot \tau}}} \sin \left(\frac{2\pi(t - t_{lag})}{\tau} - B \sqrt{\frac{\pi}{\alpha \cdot \tau}} \right) \quad (15)$$

where T_{ms} is the site mean annual surface temperature, A_s is the surface temperature amplitude, B is depth, α is the soil thermal diffusivity, τ is the annual period length, t is the calculation timestep, and t_{lag} is the phase lag of the soil temperature.

Heat losses (or heat gains) in each segment of the warm pipe can now be expressed as the arithmetic sum of the symmetrical and anti-symmetrical components as:

$$\dot{Q}_{loss/gain,w} = \left[\frac{1}{R_s} \cdot (T_w - T_{ug}) + \frac{R_s - R_a}{2 \cdot R_s \cdot R_a} \cdot (T_w - T_c) \right] \quad (16)$$

where T_w is the warm fluid temperature, T_c is the cold fluid temperature, and T_{ug} is the undisturbed ground temperature. Likewise, heat losses in the cold pipe are described as:

$$\dot{Q}_{loss/gain,c} = \left[\frac{1}{R_s} \cdot (T_c - T_{ug}) + \frac{R_s - R_a}{2 \cdot R_s \cdot R_a} \cdot (T_c - T_w) \right] \quad (17)$$

In the expressions provided in Eqs. (16) and (17), a negative sign indicates heat gains.

As for the second part of the distribution pipes model, the pipe pressure drop is calculated based on the following relationship between the mass flow rate and the pressure drop:

$$\dot{m} = k \cdot \sqrt{\Delta p} \quad (18)$$

where k is a fixed flow resistance that depends on nominal design parameters. The nominal pressure drop in each pipe segment is expressed as:

$$\Delta p_{nom} = F \cdot K_2 \cdot \gamma(Re, e) \quad (19)$$

where F is a factor that includes the pressure losses of the pipe fittings, K_2 is a constant that takes into account the pipe geometry and the fluid properties, and γ is a modified pipe wall friction factor that depends on Reynolds number Re and the pipe relative roughness e . The constant K_2 is equivalent to:

$$K_2 = \frac{L \cdot \mu^2}{2 \cdot d^3 \cdot \rho} \quad (20)$$

where L is the length of one pipe segment, μ is the fluid dynamic viscosity, d is the pipe inner diameter, and ρ is the fluid density.

The modified friction factor γ is intended for a robust numerical description of the pipe wall friction factor to avoid divisions by zero. A detailed description of the approach followed in Modelica to compute the modified friction factor can be found in the online documentation available in Ref. [42].

2.2.3. Model for system balancing unit

Fig. 4 shows Modelica diagram views of the component models included in the balancing unit (BU) at different levels of abstraction. The reference static pressure is described in the middle diagram at port_a1. The cold and warm district pipes are connected to port_a and port_b, respectively. The BU includes three main components, i.e., a reversible air-source heat pump (ASHP), an accumulator tank, and

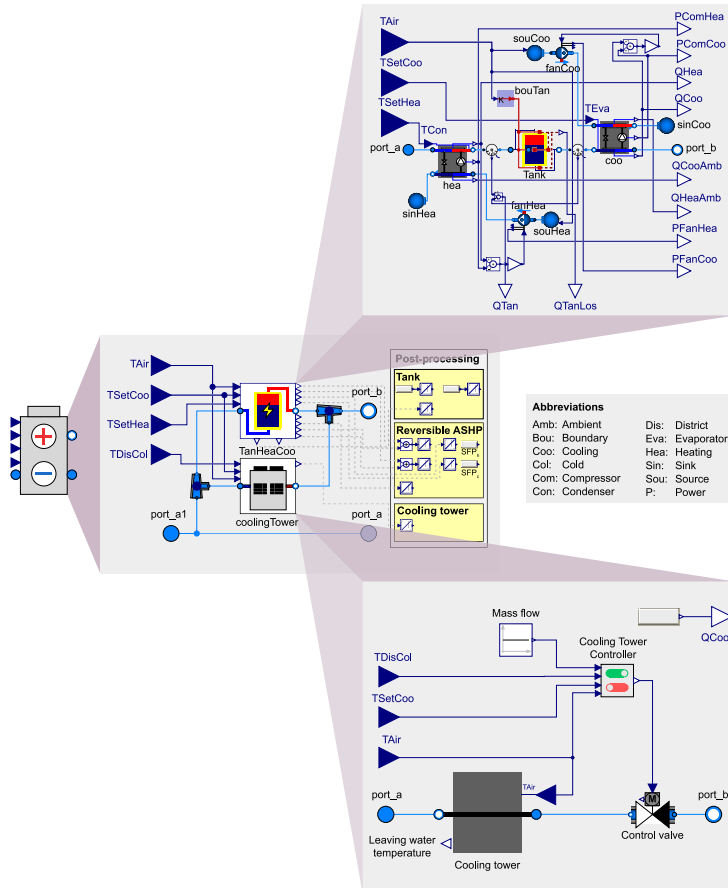


Fig. 4. Diagram view of a balancing unit which includes reversible air-source heat pump, accumulator tank, and cooling tower. Blue arrows denote input control signals, while white arrows interface output variables for post-processing.

a cooling tower. The ASHP and the tank are configured such that the ASHP maintains the temperature in the tank within the network temperature setpoints. The district network is a closed system and, therefore, the total mass flow (after local energy sharing inside the DSS) circulates through the balancing unit.

In the heating mode, the balancing unit activates the ASHP to ensure that the temperature of the warm pipe does not fall below a prescribed heating setpoint. Similarly, the balancing unit controls the temperature of the cold pipe such that it does not exceed a prescribed cooling setpoint. Priority in the cooling mode is given to the cooling tower over the ASHP as long as the operating conditions of the cooling tower

are satisfied. The cooling tower is modelled with a constant approach temperature ΔT_{APP} as:

$$\Delta T_{APP} = T_{water,lea} - T_{air,in} \quad (21)$$

where $T_{water,lea}$ is the temperature of the leaving cold water, and $T_{air,in}$ is the air inlet temperature. The heat removed from the water by the cooling tower $\dot{Q}_{cool,tower}$ is equivalent to:

$$\dot{Q}_{cool,tower} = m \cdot c_{p,water} \cdot (T_{water,lea} - T_{dis,w}) \quad (22)$$

where $T_{dis,w}$ is the temperature of the warm district pipe. The reversible ASHP is activated in a cooling mode when the cooling tower is not in

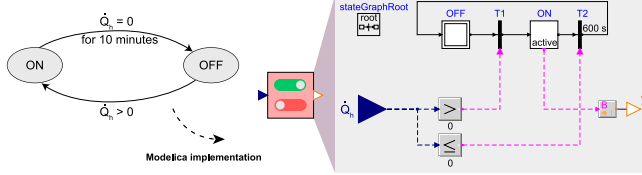


Fig. 5. State graph for the heating mode controller (left) and equivalent Modelica implementation (right).

operation or when additional cooling power is required. From the fluid ports shown in the model icon of the balancing unit, one can interpret the flow direction. For instance, the flow direction from *port_a* to *port_b* indicates dominant heating demands with heat injection into the network, while a flow direction from *port_b* to *port_a* denotes dominant cooling demands with heat rejection from the network.

2.3. Control strategies for component and system operation

This section defines the logics behind controlling the different system components and the entire district system.

2.3.1. Control of decentralised substations

Heating and cooling equipment in DSS are controlled using the finite state machine (FSM) algorithm. This kind of algorithm is convenient for modelling discrete events and reactive systems where the controlled equipment is decomposed into different modes of operation, i.e., states. The controlled equipment is allowed to be only in one state at a time, and the transition between the different states is determined by the controller based on a set of logical conditions [43]. FSM has been previously used by many researchers to control building and energy systems. Fu et al. [44] implemented an FSM algorithm to control a chiller in a data centre. Another FSM control logic was developed by Hinkelman et al. [45] for the operation of a central cooling plant in a district cooling system. For any FSM algorithm, the representation of the different states and the logical conditions is achieved with the aid of a state graph.

Fig. 5 shows a state graph for the heating mode controller in a DSS and the controller implementation is shown on the right side. The initial OFF state of the heating mode is denoted by the double square. The transition T1 from OFF to ON state is triggered when $\dot{Q}_c > 0$ and a subsequent heating signal y with an integer value of 0 or 1 activates the heating circulation pump. A delay time forces the heating mode to remain active for 10 min before the transition to the OFF state to avoid short-cycling between the states.

A similar principle with additional states is seen in the cooling mode controller presented in Fig. 6. Unlike the single heating equipment that provides all required heating demands, cooling can be provided either directly by the free-cooling heat exchanger (Free Cooling mode), by fully using a mechanical chiller (Full Mechanical Cooling mode), or by a combination of both (Partial Mechanical Cooling mode). The state graph on the top of Fig. 6 describes the conditions that determine the transition between the states. The initial OFF state is also denoted here by the double square shown in the Modelica diagram. The reader is reminded that cooling demands are denoted by a negative sign, hence cooling is activated when $\dot{Q}_c < 0$. At a particular point in time when cooling is required, the transition between the different states is mainly determined based on the temperature of the district warm pipe $T_{dis,w}$ and the return temperature from the building cooling loop $T_{ret,c}$. When the condition $T_{dis,w} < T_{set,c}$ holds, the transition T2 triggers and the FC mode is activated. If the required cooling demand is larger than the capacity of the free-cooling heat exchanger $\dot{Q}_{hx} >$

\dot{Q}_c , the transition T4 activates the PMC state where the mechanical chiller covers the additional cooling demand. In case the temperature of the district warm pipe is no longer suitable for direct supply, the transition T6 activates the FMC mode where cooling is provided solely by the mechanical chiller. The cooling control signal determines which circulation pump should be activated according to the arrangement of the cooling equipment shown previously in Fig. 2.

2.3.2. Control of the balancing unit

The balancing unit is controlled based on the dominant demand type across the network. At times of dominant cooling demands, the BU rejects the excess heat from the network. This is achieved by the cooling tower and the reversible ASHP which provide the required cooling according to the following control sequence. First, the operation of the cooling tower is determined by the controller shown in Fig. 7 when the following two conditions hold:

$$T_{air} < T_{dis,c} \quad \text{and} \quad \text{bandwidth} \quad (23)$$

$$T_{set,c} < T_{dis,c} + \frac{\text{bandwidth}}{2} \quad (24)$$

where T_{air} is the ambient air temperature, $T_{dis,c}$ is the temperature of the cold district pipe, $T_{set,c}$ is the network cooling setpoint, and the bandwidth makes the reference temperature passes over a certain predefined value (typically 1 °C) to induce a lag effect. The cooling tower is then activated and the output signal y shown in Fig. 7 controls the opening of the valve placed at the inlet of the cooling tower. Second, if at any point in time the capacity of the cooling tower is not sufficient to provide the required cooling power, the reversible ASHP is activated in a cooling mode such that:

$$T_{evap,lea} = T_{set,c} \quad (25)$$

where $T_{evap,lea}$ is the evaporator leaving temperature.

In the other situation when heating demands dominate, the reversible ASHP is activated in a heating mode to maintain the temperature of the district warm pipe such that:

$$T_{cond,lea} = T_{set,h} \quad (26)$$

where $T_{cond,lea}$ is the condenser leaving temperature and $T_{set,h}$ is the network heating setpoint.

2.4. Case study

The previously presented models for thermo-fluid systems and control logics have been used to assemble an entire district system. Fig. 8 shows a Modelica diagram view of the district system used in this study which is located in south Sweden. The buildings were previously connected to a traditional district heating and cooling network with a four-pipe network topology. Initial work to retrofit the energy system in the presented nine buildings to a 5GDHC network began in 2018 and the system is currently going through continuous expansion. The spaces in the buildings have different uses, including open offices, conference rooms, research labs, and sports halls. Overall, the facility

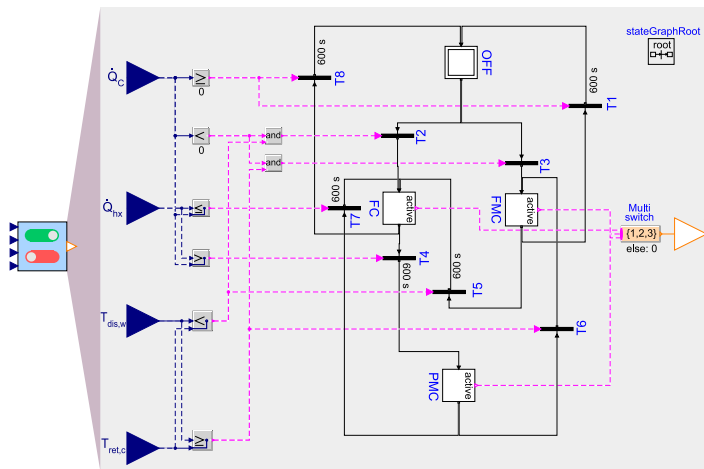
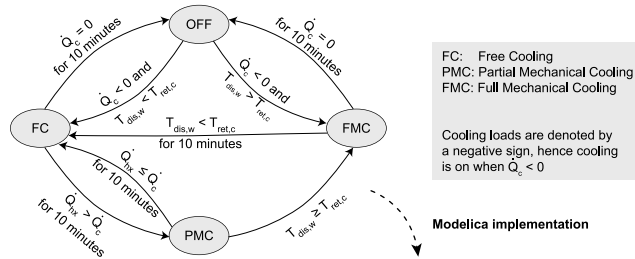


Fig. 6. State graph for the cooling mode controller (top) and equivalent Modelica implementation (bottom).

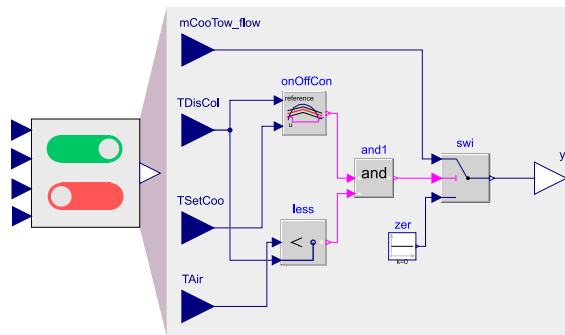


Fig. 7. Cooling tower controller.

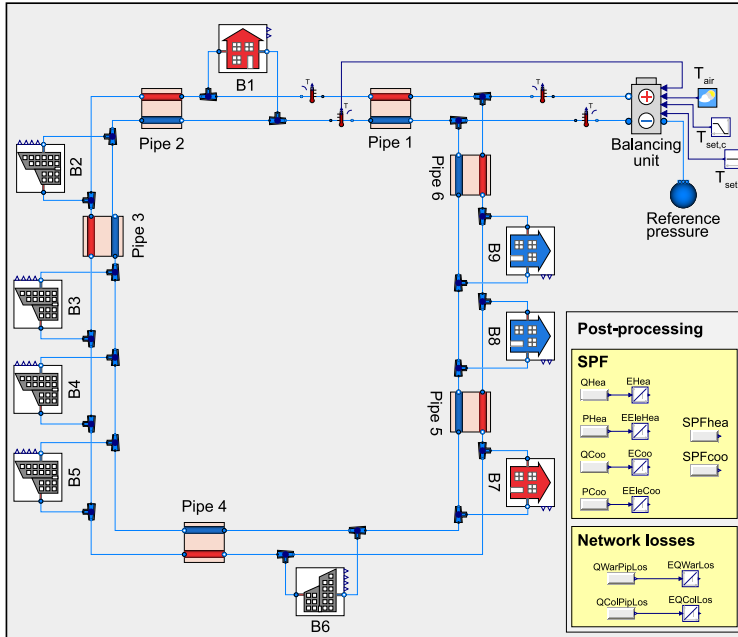


Fig. 8. Modelica diagram view of the studied district system showing the ring network topology, the nine connected buildings, and the balancing unit. The different pipe models indicate changes in the pipe size.

has simultaneous requirements for heating and cooling throughout the year.

All presented icons in Fig. 8 encapsulate the components which represent the model and exchange its variables with the connected models. For instance, the BU requires the following four variables to be prescribed: the temperature of the cold district pipe, the temperature of the ambient air, and the heating and cooling setpoints. The cold pipe temperature variable was obtained based on the feedback from the sensor located on the left side of Pipe 1 to break algebraic loops. The different pipe models indicate changes in the pipe size.

The model for the studied district system takes as inputs annual hourly measured data for buildings' heating and cooling demands and supply temperatures. Component models are parametrised based on actual design values and engineering assumptions. The tables in Appendix A provide an overview of the parameter values used in the models for decentralised substations, distribution pipes, and the balancing unit.

The district system was simulated on a desktop computer with 12 physical cores and 24 logical processors with a maximum speed of 3.50 GHz (AMD Ryzen Threadripper 2920X) and 32 GB of RAM running under Windows 10 Pro 64 bit. Dymola version 2022 [46] was used as the Modelica simulation environment since it offers a user-friendly interface for model development and post-processing. The CVODE integration algorithm was selected due to its efficiency in simulating thermo-fluid systems [47]. Simulations were performed for one year with one hour interval and tolerance of 1×10^{-6} .

2.5. Model probabilistic validation

Model probabilistic validation is used to study the impact of uncertainty on the model error since both measured data and model output have uncertainties [48]. Instead of directly determining mismatches between modelled and measured quantities, model probabilistic validation aims at establishing a relationship between error and probability. For this purpose, the cumulative distribution function (CDF) has been used to establish such relationship by following the steps shown in Fig. 9. The CDF is a continuous function bounded between 0 and 1 and provides the probability that a continuous random variable is less than or equal to a certain value. In this context, the CDF gives the probability that the absolute error Z between modelled and measured heat flow rate is less than or equal to an error benchmark level. The error Z is calculated as:

$$Z = \left| \frac{Q_{mod} - Q_{mea}}{Q_{mea}} \right| \cdot 100 \quad (27)$$

where Q_{mod} and Q_{mea} are respectively the modelled and measured heat flow rates.

The first estimation of a reasonable error benchmark level can be equal to the maximum permissible error (MPE) of the thermal energy meter. The MPE of thermal energy meters is quantified in accordance with Standard SS-EN 1434-1 [49] and the sensor characteristics which are provided in Table B.1 in Appendix B. Evaluating the probability at

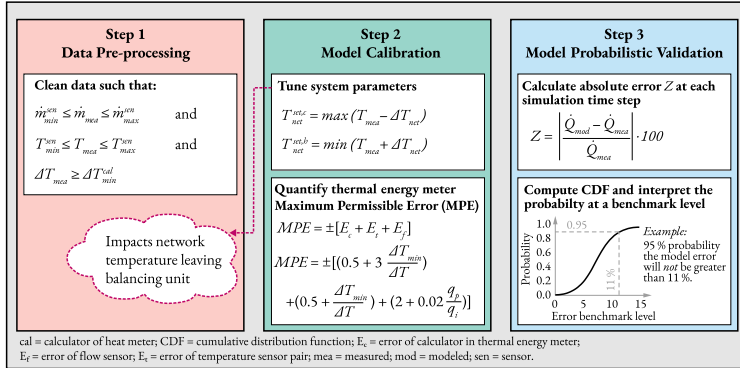


Fig. 9. Steps for performing model probabilistic validation.

different error benchmark levels is also useful to account, when possible, for other sources of uncertainties and to analyse the distribution of the error.

The model is validated using one-year data of heat flow rate from thermal energy meters located at the district side in each DSS. The heat flow rate is derived from measured entering and leaving temperatures as well as the measured mass flow rate. If the model calculates the heat flow rate with high confidence, an evaluation of the system performance can be made since the heat flow rate represents the actual exchanged heat between the DSS and the district system. In the first step shown in Fig. 9, data were pre-processed to exclude unrepresentative and faulty measurements. Depending on the characteristics of the thermal energy meter, faulty data were identified. For instance, data points with values that fall outside the range of the flow and temperature sensors were not considered. Moreover, data points with negative temperature differences yielded zero mass flow and zero heat flow rate. The second step involved determining a set of candidate parameters that can be used for model calibration. Because the calculation of the heat flow rate depends on the inlet and outlet temperatures, calibrating the network heating and cooling setpoints would directly impact the temperature in each DSS. Finally, the absolute error was calculated for each timestep and the probability of the model error was computed.

2.6. Performance indicators

The heating and cooling seasonal performance factor (SPF) are used as performance indicators. The SPF for all DSS is described according to the following boundaries:

$$SPF_{DSS} = \sum_{t=0}^n \sum_{i=0}^{8760} \frac{\dot{Q}}{P_{comp} + P_{pump,1,oa} + P_{pump,1,d,1s} + P_{pump,2,d,1s}} \quad (28)$$

where n is the number of buildings, t is the simulation time in hours, \dot{Q} is the delivered thermal power, P_{comp} is the compressor electric power of the heat pump or the chiller, $P_{pump,1,oa}$ is the electric power of the circulation pump at the building load side, $P_{pump,1,d,1s}$ and $P_{pump,2,d,1s}$ are the electric power of the two circulation pumps located on the district side. Fig. 2 should be consulted to point out the location of these circulation pumps.

As for the BU, the heating and cooling SPF are calculated as:

$$SPF_{BU} = \sum_{t=0}^{8760} \frac{\dot{Q}}{P_{comp} + P_{fan}} \quad (29)$$

where P_{comp} and P_{fan} are the respective compressor and fan electric power of the reversible ASHP.

The SPF for the entire district system is defined as:

$$SPF_{system} = \sum_{t=0}^{8760} \frac{\dot{Q}_{DSS} + \dot{Q}_{BU}}{P_{DSS} + P_{BU}} \quad (30)$$

where \dot{Q}_{DSS} is the total delivered thermal power by all DSS, \dot{Q}_{BU} is the delivered power by the BU, P_{DSS} and P_{BU} are respectively the electric power used in the DSS and the BU.

2.7. Model simplifications and limitations

The presented models are subject to several simplifications and limitations that may influence the interpretation of the results. Firstly, the building demands and the supply from the BU are provided only by the component models presented in the previous sections. Auxiliary energy systems such as conventional DH that cover peak demands are therefore not considered in the analyses to limit the performance evaluation to the components that are typically included in a 5GDHC network. Secondly, models for heat pumps and chillers have unlimited capacity and deliver thermal power based on the required demand. This makes it easier to model DSS with multiple heat pumps or multiple chillers by aggregating the demands into individual components. Additionally, we limited model validation to the measured heat flow rate at the district source side since it would suffice for the validation of decentralised heat pumps and chillers according to the definition of the Carnot cycle. Moreover, the calculations of heat losses in the uninsulated pipes are for steady-state operation with no heat storage in the pipe wall or the soil. The temperature surrounding the pipes is assumed to be uniform. Finally, the heat carrying fluid in the district and building loops is incompressible water with constant properties.

3. Results

This section presents simulation results of the district system for aspects related to simulation performance, network supply-demand structure, network temperature and heat losses, and the overall system energy balance.

Table 1
 Model statistics for a SGDHC system comprising nine buildings.

Model statistic	Value
Number of components	5126
Number of equations	23 544
Number of parameters	29 028
CPU time for annual simulation [min]	4.56

Table 2
 Probability of model error in calculating annual hourly heat flow rate at different locations and for different error benchmark levels.

Location of district supply thermal energy meter	Probability of model error \leq Benchmark level (BL)		
	9% BL	14% BL	19% BL
Building 1 heating	0.424	0.918	0.945
Building 2 heating	0.957	0.971	0.978
Building 2 cooling	0.062	0.313	0.591
Building 3 heating	0.824	0.928	0.960
Building 3 cooling	0.950	0.968	0.971
Building 4 heating	0.900	0.983	0.993
Building 4 cooling	0.959	0.977	0.992
Building 5 heating	0.481	0.590	0.676
Building 5 cooling	0.971	0.991	0.995
Building 6 heating	0.947	0.967	0.976
Building 6 cooling	0.975	0.975	0.977
Building 7 heating	0.971	0.976	0.980
Building 8 cooling	0.896	0.993	0.999
Building 9 cooling	0.956	0.987	0.995

3.1. Model and simulation performance

Information about model statistics and the probability of model error are provided in Tables 1 and 2, respectively. The complexity of the model is directly associated with the required computational efforts to perform simulations. The results show that simulating the entire district system for a period of one year took less than five minutes. The short simulation time highlights the benefits of using Modelica for further research on district energy technologies. The model probabilistic validation shown in Table 2 presents the probability of model error at different error benchmark levels. A benchmark level of 9% corresponds to the Maximum Permissible Error (MPE) of the thermal energy meter which was quantified according to the formulas shown in Fig. 9. The two additional benchmark levels enable gaining greater insights into the probability of model error if more sources of uncertainty are considered. What stands out in the table is the high accuracy of modelled heat flow rates at several substations. Exceptions were found at three locations: *Building 1 heating*, *Building 2 cooling*, and *Building 5 heating*. The substations in these three locations have more than one heat pump or more than one chiller that are connected in series and, hence, the measured heat flow rate was influenced by the performance of each individual heat pump/chiller. Since the model for DSS includes only a single heat pump and a single chiller, this limitation could explain the difference between the modelled and measured heat flow rates in these three substations. Taken all together, comparing the probability of model error between the different benchmark levels reveals that the model has a probability of at least 95% where the error is less than 14% for most of the measurement locations. These results suggest that the model is in good agreement with the measurements and further analyses on the system performance can be carried out.

3.2. Breakdown of system supply-demand structure

Fig. 10 presents a breakdown of the simulated district supply-demand structure at different system levels. The ambient air temperature and the modelled soil temperature at the pipe burial depth are presented in Fig. 10(a). The air temperature affects the system control, e.g., the operation of the cooling tower, while the soil temperature

impacts the heat losses (or gains) in the distribution pipes. Looking at Fig. 10(b), the illustrated total network demands show that the district system has a simultaneous requirement for heating and cooling throughout the year, with peak power for heating and cooling of about 1 MW. In Fig. 10(c), the total network mass flow is presented and can be interpreted as the total flow entering or leaving the BU in the direction towards or from the connected buildings. For instance, a negative mass flow would indicate a flow direction from the network to the BU. In other words, the dominant network cooling demands can lead to excess heat that flows from the network to the BU where the latter rejects the excess heat by the cooling tower and/or the reversible ASHP. On the other hand, a positive mass flow direction would denote a flow direction from the balancing unit towards the network. This situation can be realised when the network has dominant heating demands and the reversible ASHP injects heat into the network. Fig. 10(d) complements the system supply-demand structure where heating and cooling powers provided by the BU are presented. A comparison between the power provided by the cooling tower and the ASHP shows that the former can cover small portions of the required cooling power. This, in turn, would suggest that most of the cooling provided by the BU is achieved by compressors. The simulation results also show that no cooling is provided by the BU during the period from early November to mid-May. This implies that although the connected buildings have cooling demands, the network temperature remains below the cooling setpoint and therefore no network cooling is needed. A detailed analysis of the network temperature is covered in the following section.

3.3. Network temperature and heat losses/gains

In Fig. 11, the simulated annual hourly network temperature and network heat losses are presented. The network temperature shown in Fig. 11(a) is maintained between prescribed heating and cooling setpoints. The presented temperatures correspond to the temperature of the heat carrying fluid in the BU. As such, the BU maintains a constant warm fluid temperature at a setpoint of 18 °C during winter between November and April when network heating demands dominate. The effect of the network heat losses/gains on the warm fluid temperature during winter cannot be seen since the presented temperature corresponds to the fluid leaving the BU before distribution losses take effect. In contrast, the effect of the network heat losses/gains on the cold pipe temperature in the same winter period can be noticed since the fluid has already travelled along the pipes before entering the balancing unit. The calibrated cooling setpoint varies between the two summer periods. A cooling setpoint of 20 °C is used in the first summer period in August 2020, while a setpoint of 28 °C is used in July 2021. During spring and autumn, the fluid temperature changes more frequently as these are the periods where the dominant demand type changes within short intervals. As a consequence, the mass flow in the network reverses its direction depending on whether the balancing unit is injecting or rejecting heat, as Fig. 10(c) also shows. Although the network is designed for a 10 K temperature difference, the results suggest that such temperature difference is not always maintained due to the impact of network losses/gains on the fluid temperature.

Fig. 11(b) shows the network heat losses in all distribution pipes where a negative sign indicates heat gains. To obtain more clarity about the network losses/gains, the reader is advised to refer to the soil temperature presented earlier in Fig. 10(a) as it forms the boundary condition of the distribution pipes. Looking at the heat losses in cold pipes, one can see that the cold pipes are gaining heat most of the year even in winter months when the soil temperature is lower than the cold fluid temperature. This is primarily attributed to the anti-symmetrical component of the heat losses, i.e., the interaction between the two pipes due to the close distance between the warm and cold pipes at just 20 cm. From an annual perspective, the warm pipes have total heat losses to the ground of about 399 MWh, which corresponds to about 11% of the carried heat in all warm pipes. As for the cold pipes, the annual heat gains of 137 MWh constitute to about 7% of the carried heat in all cold pipes.

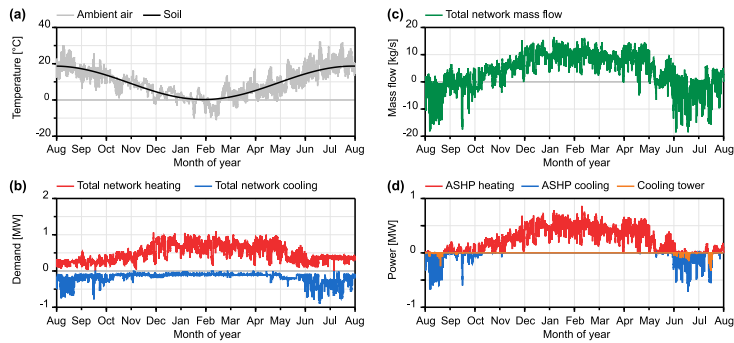


Fig. 10. Annual hourly simulation results of site climate conditions (a), total network heating and cooling demands (b), total network mass flow (c), and power provided by the balancing unit (d).

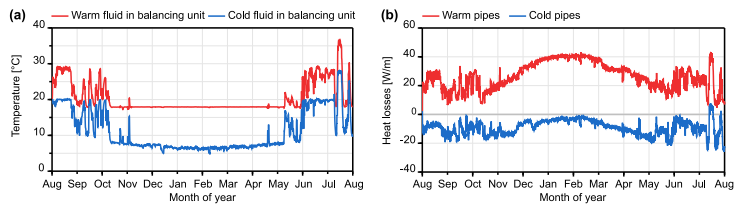


Fig. 11. Annual hourly network temperature (a) and network heat losses/gains (b) based on prescribed boundary conditions and network control setpoints. Negative heat flow rates indicate heat gains.

3.4. System energy balance and annual performance

To better understand the interactions between the buildings and the system components, Fig. 12 shows a Sankey diagram of the district system annual energy balance at different nodes. On the right-hand side, building heating and cooling demands are quantified according to measured data. Building demands are delivered by heat pumps and chillers located in each DSS. The amount of cooling provided by the free-cooling heat exchangers is not represented by an exclusive node in the diagram since it corresponds to only 0.3% of the annual delivered cooling. The total annual heating demands for all buildings are about 4.2 GWh, while the demands for cooling account for 1.2 GWh.

The interface between the DSS and the district supply side is realised at the cold side of each heat pump (HP) and alternatively at the warm side of each chiller (CH). The amount of energy extracted by the HP from the warm pipes is presented in the bars connecting the warm pipes and the HP. Likewise, CH extract energy from the cold pipes and reject waste heat to the warm pipes in an amount equivalent to the width of the connecting bars between the cold pipes and the CH. The annual network losses/gains are presented on the right-hand side of each pipe node. In this context, heat gains in the cold pipes may

also be considered as losses since the desired temperature quality is not maintained. On that account, the total network losses in all distribution pipes constitute 10% of the annual carried heat. Compared to the latest statistics about the Swedish district heating system reported in 2020 [50], the modelled district network with uninsulated pipes can have 28% lower distribution losses than traditional networks with insulated pipes. Network heat losses/gains have an impact on the network temperature and, consequently, on the system's seasonal performance factor (SPF). The annual SPF at each DSS can be visually estimated from the Sankey diagram since the corresponding amount of electric energy is also provided.

The left-hand side of the warm and cold pipes represents the energy flows in the network as well as the balancing unit. Shared energy occurs both locally inside the DSS and globally between the connected buildings, it is represented in the Sankey diagram as a total amount for the whole year. Shared energy constitutes about 40% of the total carried heat in all distribution pipes and it can take one of two forms depending on the network demand type. The first form takes place when heating dominates and when the energy at the cold side of the heat pumps is utilised as a cold source for the chillers. Conversely, the second form of sharing energy happens when cooling dominates and when excess

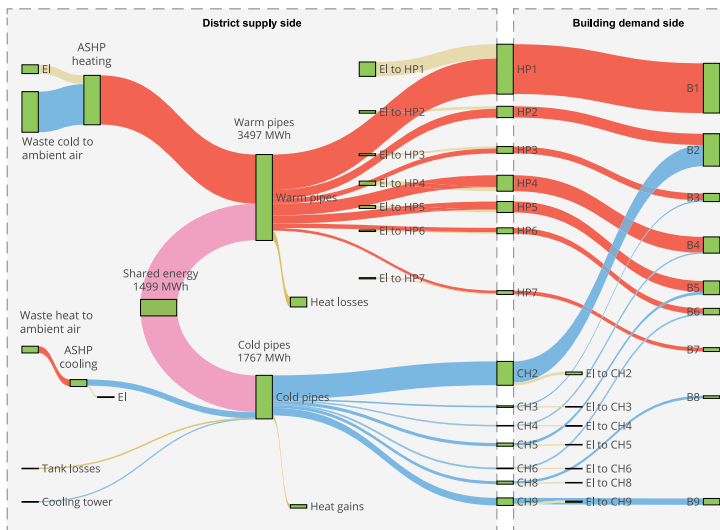


Fig. 12. Sankey diagram of the district system annual energy balance. The width of connecting bars is proportional to the amount of energy in unit MWh. Decentralised heat pumps (HP) and chillers (CH) represent the interface between the district supply and the building demand sides. The amount of shared energy is estimated to complement the system energy balance and it implies bidirectional energy flows between warm and cold pipes.

waste heat is rejected to the warm pipes. The excess waste heat acts as a hot source for the heat pumps and it is rejected outside the network when the temperature of the cold pipe reaches the cooling setpoint.

The mechanism for rejecting excess heat outside the network is achieved by the cooling tower and the reversible ASHP. About 2% of the rejected heat is handled by the cooling tower, while the rest is handled by the ASHP. The connection between tank losses and the cold pipes is established to represent the energy direction that flows out of the network. In the second mode of operation of the reversible ASHP, heat is injected into the network to maintain the temperature of the warm pipes according to the heating setpoint. Waste heat and waste cold from the ASHP to the ambient air are equivalent to 274 and 1651 MWh, respectively. These figures depend mainly on the performance of the ASHP.

Fig. 13 shows the annual heating and cooling SPF at different system levels. Overall, the system yielded good performance at all analysed levels. The highest performance was found in the BU due to the low temperature lifts required by the ASHP.

4. Discussion

The study presented a simulation model for the design and analysis of 5GDHC systems with two-pipe network topology and bidirectional energy flows. Lessons learned during the design, operation, modelling, and simulation of the system are shared in this section. The main discussion points encompass the applicability of the simulation

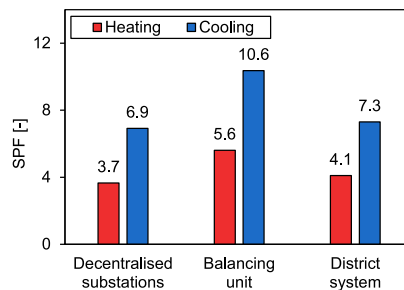


Fig. 13. Heating and cooling seasonal performance factors at different system levels.

model in addition to a few practical recommendations for future wider implementation.

The findings in this study confirm the benefits of integrating district and heat pump technologies. To mention a few, district thermal networks are transformed into electricity-driven networks. Simulation

results showed that an electricity-driven 5GDHC system could reduce the purchased energy by 69% compared to a traditional four-pipe district heating and cooling system. Moreover, coupling the electricity and heat sectors adds more flexibility to the power grid by alleviating the problem of intermittent electricity production. As more electricity will be generated from renewable sources with intermittent production such as wind and solar [51], heat pumps can operate at full capacity when the electricity production is high to store the additional heat in the accumulator tank for later use.

The developed simulation model has several practical implications where it can be used at different implementation stages. In the planning stage of a new 5GDHC system, the model can be used to find promising building clusters that increase the potential for sharing energy between interconnected buildings. When such a cluster has been identified, several system design options can be evaluated, and an optimal design option can be selected. Defining appropriate parameter values and sizing system components are carried out during the design stage. In the final stage when the system is realised, the model can be used by the system owner for real-time system monitoring and operation to optimise daily to weekly system operation based on network temperature levels, electricity spot price, and amount of shared energy.

Possible practical recommendations for improving the system performance are listed herein. The results showed that extremely little cooling was provided by the free-cooling heat exchangers. We found two aspects that directly influenced this. Firstly, many of the connected buildings integrate room systems with low cooling return temperature than the temperature at the primary district side of the heat exchanger. This violates the condition for operating the free-cooling heating exchanger. Secondly, the network temperature setpoints are not primarily defined to maximise the utility of the free-cooling heat exchanger. It might be useful for future work to investigate the role of ground thermal storage and network setpoints on the potential to supply free cooling.

Wider implementation of 5GDHC systems should not be seen as replaceable of existing traditional DHC systems. Rather, a synergy can be established where 5GDHC systems can be built in newly built areas in the urban environment such that traditional DHC systems function as balancing units. In such configuration, the return pipe of the traditional DHC system is connected as a source for the 5GDHC system, which may also increase the capacity of existing traditional systems without increasing the flow. In addition, small-scale 5GDHC systems can increase the market share of district systems by connecting households in villages and small communities where access to traditional DHC systems is limited. In all cases, new business transactions need to be developed to support the sharing of energy between prosumers without neglecting non-technical factors such as alternative financing schemes, social acceptance, and national legislations.

5. Conclusions and future work

This study presented a simulation model for the design and analysis of district systems with simultaneous heating and cooling demands. The model enables simulating any number of buildings connected to a two-pipe network topology with bidirectional energy flows. Annual simulations performed on an existing Swedish district system with similar characteristics enabled gaining a deeper understanding of the mechanisms in which new advanced district systems may operate. Additionally, the simulations provided an in-depth analysis of important operational aspects related to shared energy flows between interconnected buildings, network heat losses (or gains), and system energy balance.

The model can be utilised in different use cases, including design optimisation of new systems, or for performance optimisation of existing systems. In the former use case, the model is used to evaluate the feasibility of different design options and system configurations. While in the latter the model can be used for real-time system monitoring

and performance optimisation. For improved system performance, it is recommended to maximise the utility of free cooling by controlling the temperature of the cold pipeline to make it suitable for direct supply without local conditioning.

Extending the current model to include economic analysis would pave the way towards more research on flexibility by coupling thermal and power sectors. The economic analysis enables optimising the system heat production according to electricity spot price where additional heat can be produced and stored at times of low electricity price. Moreover, future research should focus on developing new business models for the prosumer concept considering alternative financing schemes, social acceptance, and national legislations.

CRedit authorship contribution statement

Marwan Abugabbara: Conceptualization (lead), Data curation, Investigation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft (lead), Writing – review & editing (supporting). **Saqib Javed:** Conceptualization (supporting), Project administration (supporting), Funding acquisition (equal), Supervision (lead), Writing – original draft (supporting), Writing – review & editing (lead). **Dennis Johansson:** Resources, Project administration (lead), Funding acquisition (equal), Supervision (supporting), Writing – original draft (supporting).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Design parameters

This appendix provides values for design parameters used in the DSS model (see Table A.1), pipe model (see Tables A.2 and A.3), and the balancing unit model (see Table A.4).

Pipe dimensions shown in Table A.3 are according to Standard SS-ISO 4427-2 [52] and provided for a standard dimension ratio equal to 17.

Table A.1
Design parameters used in the DSS model.

Parameter description	Symbol	Value	Unit
Temperature difference of heat pump/chiller condenser (outlet-inlet)	$\Delta T_{HP,cond}$	4 ^a	K
Temperature difference of heat pump/chiller evaporator (outlet-inlet)	$\Delta T_{HP,evap}$	-4 ^a	K
Temperature difference of district loop (warm-cold)	ΔT_{dis}	10 ^a	K
Pressure difference over heat pump/chiller condenser and evaporator at nominal flow	$\Delta P_{cond/evap}$	30 000 ^b	Pa
Carnot efficiency	η_{Carnot}	50 ^b	%
Pump combined hydraulic and motor efficiencies	η_{pump}	49 ^b	%

^aValue based on system design and/or measurements.

^bValue based on engineering experience.

Table A.2
Design parameters used in the distribution pipes model.

Parameter description	Symbol	Value	Unit
Burial depth to pipe upper surface	B	0.8 ^a	m
Horizontal distance between pipe walls	A	0.2 ^a	m
Thermal conductivity of soil	λ_{soil}	1.6 ^b	W/m K
Thermal conductivity of pipe	λ_{pipe}	0.17 ^b	W/m K

^aValue based on system design and/or measurements.

^bValue based on engineering experience.

Table A.3
Design parameters of different pipe sections.

Pipe section ^c	Nominal size	Wall thickness (mm)	Roughness [m] ¹	Length [m] ²
Pipe 1	DN250	14.8	2.5×10^{-5}	150
Pipe 2	DN225	13.4	2.5×10^{-5}	200
Pipe 3	DN200	11.9	2.5×10^{-5}	500
Pipe 4	DN250	14.8	2.5×10^{-5}	210
Pipe 5	DN225	13.4	2.5×10^{-5}	150
Pipe 6	DN225	13.4	2.5×10^{-5}	500

^aValue based on engineering experience.

^bValue based on system design and/or measurements.

^cThe reader is advised to refer to Fig. 8 to locate each pipe section on the model diagram.

Table A.4
Design parameters used in the BU model.

Parameter description	Symbol	Value	Unit
Temperature difference at the water side of the reversible ASHP	ΔT_1	10 ³	K
Temperature difference at the air side of ASHP	ΔT_2	2 ^a	K
Pressure difference over water side of ASHP at nominal flow	Δp_1	30 000 ^a	Pa
Pressure difference over air side of ASHP at nominal flow	Δp_2	6000 ^a	Pa
Carnot efficiency	η_{Carnot}	50 ^a	%
Tank volume	V_{tank}	150 ^b	m ³
Tank height	H_{tank}	15.6 ^b	m
Tank insulation thickness	t_{ins}	40 ^b	mm
Thermal conductivity of tank insulation material	λ_{ins}	0.036 ^b	W/m K
Cooling tower approach temperature	ΔT_{ATPP}	2 ^a	K

^aValue based on engineering experience.

^bValue based on system design and/or measurements.

Table B.1
Characteristics of thermal energy meters, flow sensors, and temperature sensors.

Connection size	Nominal flow rate q_n [m ³ /h]	Minimum flow rate q_i [m ³ /h]	Maximum flow rate q_m [m ³ /h]	Temperature range [°C]	Minimum temperature difference ΔT_{min} [K]
DN65	25	0.25	50	5–130	3
DN80	40	0.40	80	5–130	3
DN100	60	0.60	120	5–130	3
DN150	150	1.50	300	5–130	3

Appendix B. Characteristics of thermal energy meters

See Table B.1

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Paper IV





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Research paper

How to develop fifth-generation district heating and cooling in Sweden? Application review and best practices proposed by middle agents



Marwan Abugabbara^{a,*}, Signhild Gehlin^b, Jonas Lindhe^{a,c}, Monica Axell^d, Daniel Holm^e, Hans Johansson^f, Martin Larsson^d, Annika Mattsson^g, Ulf Näslund^e, Anjan Rao Puttige^h, Klas Berglöfⁱ, Johan Claesson^j, Morten Hofmeister^k, Ulla Janson^a, Aksel Wedel Bang Jensen^{l,m}, Jens Terménⁿ, Saqib Javed^a

^a Department of Building and Environmental Technology, Division of Building Services, Lund University, 221 00 Lund, Sweden

^b The Swedish Geoenergy Center, Box 1127, 221 04 Lund, Sweden

^c Alfa Laval Corporate AB, Box 73, 221 00 Lund, Sweden

^d RISE Research Institute of Sweden, Sven Hultins Plats 5, 412 58 Gothenburg, Sweden

^e Vasakronan AB, Box 30074, 104 25, Stockholm, Sweden

^f Umeå ProjektEnergi AB, Granvägen 24, 907 38 Umeå, Sweden

^g Granitor Properties, Jungmansgatan 12, 211 11 Malmö, Sweden

^h Department of Applied Physics and Electronics, Umeå University, 901 87 Umeå, Sweden

ⁱ Climacool, Sweden AB, Box 46, 131 06 Nacka, Sweden

^j Department of Building and Environmental Technology, Division of Building Physics, Lund University, 221 00 Lund, Sweden

^k Research Center for Built Environment, Energy, Water and Climate, VIA University College, 8700 Horsens, Denmark

^l Region Midtjylland, Vestergade 48 H, 3. sal, 8000 Aarhus, Denmark

^m Department of Planning, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark

ⁿ Energy Machines, Norra Skeppsbron 15A, 803 10 Gävle, Sweden

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ABSTRACT

Sweden has an ambitious plan to fully decarbonise district heating by 2030 and to contribute with negative emissions of greenhouse gases in 2050. The vagaries of the energy market associated with climate, political, and social changes entail cross-sectoral integration that can fulfil these national targets. Fifth-generation district heating and cooling (5GDHC) is a relatively new concept of district energy systems that features a simultaneous supply of heating and cooling using power-to-heat technologies. This paper presents best practices for developing 5GDHC systems in Sweden to reach a consensus view on these systems among all stakeholders. A mixed-method combining best practice and roadmapping workshops has been used to disseminate mixed knowledge and experience from middle agents representing industry professionals and practitioners. Four successful implementations of 5GDHC systems are demonstrated and the important learned lessons are shared. The best practices are outlined for system planning, system modeling and simulation, prevailing business models for energy communities, and system monitoring. A roadmap from the middle agents' point of view is composed and can be utilised to establish industry standards and common regulatory frameworks.

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1. Introduction

Heating and cooling of buildings are the largest energy-consuming sector in Europe and are responsible for 40% of the total final energy consumption and about 36% of related greenhouse gas (GHG) emissions (European Commission, 2020). The

EU adopted in 2019 the *Clean energy for all Europeans* package which sets ambitious targets to reach climate neutrality by 2050. In the short-term, the package has a binding target of at least 32% renewables in the EU energy mix by 2030 and to improve energy efficiency by almost one-third (European Commission, 2019). Sweden is an early mover on sustainable clean energy as it adopted in 2017 the national climate policy framework which aims at reaching zero net emission of GHG by 2045 (Government Offices of Sweden, 2018). The country has also an energy policy with a promising target to achieve 100% renewable electricity

* Correspondence to: Faculty of Engineering, Lund University, Box 118, 221 00 Lund, Sweden.

E-mail address: marwan.abugabbara@hvac.lth.se (M. Abugabbara).

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Nomenclature

5GDHC	Fifth-Generation District Heating and Cooling
BHE	Borehole Heat Exchanger
BM	Business Model
BMC	Business Model Canvas
CHP	Combined Heat and Power
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
DSS	Decentralised Substation
ESCO	Energy Services Companies
GHG	Green House Gases
HCF	Heat Carrying Fluid
HP	Heat Pump
TPA	Third-Party Access

production by 2040 (Government Offices of Sweden, 2016). One way to attain the national and European targets could be the development of innovative solutions, especially with cross-sectoral integration between the heat and power sectors.

District heating and cooling (DHC) systems are regarded by the EU Strategy on Heating and Cooling as effective solutions to decarbonise the building sector (European Commission, 2016). Globally, district heating (DH) has high implementation rates around 50% in Iceland, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Russia, and northern China — while district cooling (DC) is more common in the Middle East and the USA (Werner, 2017b). The systems can integrate renewable energy sources such as geothermal and solar while offering flexibility in the energy system by coupling the heat and power sectors to cheaply produce and store thermal energy. DHC have been developed through different generations that are mainly characterised based on the temperature levels of the heat carrying fluid (Lund et al., 2014). For DH, steam was used in the 1st generation and was replaced in the 2nd generation by high-temperature water above 100 °C (Werner, 2017b). The water temperature was reduced to about 80 and 60 °C in the 3rd and 4th generations, respectively (Pellegriani and Bianchini, 2018; Lund et al., 2018). On the other hand, DC was introduced in the 1st generation as a pipeline refrigeration system to supply cooling to the food industry and in the 2nd generation as a supplier of comfort cooling to buildings (Østergaard et al., 2022). Refrigerants were replaced by water in the 3rd generation and as renewable energy sources became possible to integrate into the system, the 4th generation was realised.

Prompted by increasing cooling demands due to climate change and urbanisation, a new generation referred to as 5th generation district heating and cooling (5GDHC) has emerged to supply simultaneous heating and cooling to connected prosumers who are producers and/or consumers of thermal energy (Buffa et al., 2019; Revesz et al., 2020; Calise et al., 2022). The network in this generation operates at temperature levels typically below 40 °C whereby decentralised heat pumps (HPs) and/or mechanical chillers adjust the network temperature to the desired building supply temperatures. Such a new and advanced district energy system transforms thermal grids into electricity-dominated grids, which in turn supports the uptake of renewables and offers flexibility in power grids (Paiho et al., 2018). Like any emerging technology, DHC need to undergo a sociotechnical change in order to provide political and public acceptance in

addition to technical solutions for wider implementations of 5GDHC systems.

A sociotechnical change within the energy sector with the aim of decarbonising buildings can be induced by either the common *top-down* or *bottom-up* approaches (van Vuuren et al., 2009). In the *top-down* approach, governmental agencies with legislative power enact policies and frameworks to lower carbon emissions. These policies are employed by the means of codes, standards, and regulations¹ which are communicated between different stakeholders and further down to citizens. The *bottom-up* approach stems instead from the efforts exerted by individuals and small to medium organisations to create a change. A complementary *middle-out* approach adds a new perspective that can further assist the process of reducing carbon emissions (Janda and Parag, 2013). The *middle-out* approach encompasses industry professionals and practitioners who are referred to in the remainder of the paper as ‘middle agents’ representing architects, engineers, district heating companies, property owners, and builders who can all be drivers of change towards greener DHC systems (Horsbøl and Andersen, 2021).

Since middle agents interact with all agents involved in the transition towards greener DHC systems, they can influence a change in three distinctive but compatible directions: (i) *upstream* towards policymakers by providing expertise and feedback to governmental bodies, (ii) *downstream* towards citizens by offering advice on techno-economically feasible solutions, and (iii) *side-ways* towards peer professionals by promoting and improving the industry (Horsbøl and Andersen, 2021). Accordingly, middle agents can have three indicative modes of influence: (i) by *enabling* (or *disabling*) the implementation of new technology, (ii) by *mediating* to modify or adapt the technology to suit specific situations, and (iii) by *aggregating* the gained experience from several projects (Janda and Parag, 2013). Perspectives from middle agents on a certain technology can be elaborated through organised participatory discussions.

An established way of organising participatory discussions in the energy sector is through workshops (Horsbøl and Andersen, 2021; Thomas and Rosenow, 2020). A best practice workshop is tailored to collect, collate, and disseminate mixed knowledge with experience and examples of effective technical solutions. A group of middle agents participate in a series of presentations and discussions on a certain topic to share lessons from other implementations, explore existing challenges, and refine best practice methods. In the course of a best practice workshop, a roadmapping workshop intended for business strategy and innovation can also be carried out. Robert Galvin, who was the CEO of Motorola at the time roadmapping was established, defines the method as: “A ‘roadmap’ is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field” (Galvin, 1998). Several tools can be exploited to conceptually align the gained technological and functional perspectives during a best practice workshop, with visual roadmapping templates being the most common (Phaal et al., 2015). In the context of developing 5GDHC in Sweden, a roadmapping exercise engages middle agents in a collaborative work to analyze the underlying key drivers and sociotechnical challenges with the aim of establishing a route towards effective implementation.

This paper targets to answer the question of *how to develop 5GDHC systems in Sweden* and uses a mixed-method approach

¹ We distinguish between the three expressions on the basis that codes provide guidelines with or without mandatory compliance, whereas standards elaborate the industry requirements and create a common language to meet the codes, and that regulations incorporate both codes and standards and require industry compliance by law.

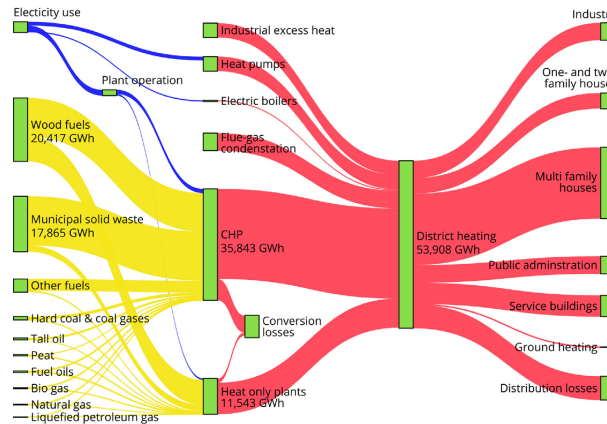


Fig. 1. Sankey diagram for the Swedish district heating energy balance in 2020. The width of connecting bars is proportional to the quantity of heat flow measured in GWh. Different nodes in the energy balance are illustrated in green rectangles. Yellow and blue bars correspond to fuel and electricity input, while red bars denote heat flows from heat sources to final deliveries. Conversion losses are derived from actual plant efficiency. Data source: Statistics Sweden and the Swedish Energy Agency (Energimyndigheten, 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

combining a best practice workshop and a roadmapping workshop for business innovation. The best practices are proposed by middle agents who are participating in the Interreg project COOLGEOHEAT (www.coolgeoheat.eu) titled *Shallow geothermal energy – the green and effective heating and cooling grids of the future*. The project aims to increase the production of renewable shallow geothermal energy in 5GDHC systems by (i) developing a thermo-hydraulic model to support the dimensioning of 5GDHC systems, (ii) analyzing operational data from existing 5GDHC systems in Sweden and Denmark, (iii) describing economic models based on certain forms of ownership and business transactions, and (iv) disseminating best practices for effective implementation of 5GDHC systems in Sweden and Denmark. This paper focuses on the Swedish market by aligning the workshop outcomes with the latest findings in the literature.

After the introduction section, the paper takes its point of departure in a review of DHC in Sweden concerning the current situation of the heating and cooling market, existing business models (BMs) and pricing mechanisms, types of system ownership, and the combination between DHC and HP technologies. Section 3 describes the methods used for designing the best practice and roadmapping workshops. Section 4 presents the findings of the workshops mainly in the form of proposed best practices from system planning to implementation and monitoring. Conclusions and outlook are finally outlined in Section 5.

2. Review of district heating and cooling in Sweden

2.1. Heating and cooling markets

Swedish DH has a long success story that started in Karlstad in 1948 aiming first to develop central heating systems for emerging industries and later in the 1970s to heat homes in the so-called The Million Homes Programme² (Werner, 2017a; Magnusson,

² The Million Homes Programme achieved its goal of building modern and affordable one million new housing dwellings between the period 1965 to 1974. More details about the project can be found in Ref. Hall and Viden (2005).

2016). To this day, about 500 DH systems exist in 283 municipalities with over 23000 km of pipe length delivering about 60% of all heating to buildings. Fig. 1 shows a Sankey diagram for the Swedish district heating energy balance in 2020. On the left side, yellow bars represent different fuel inputs showing the predominant biomass and municipal solid waste with respective 45 and 39% of the total fuel input. Electricity is also used to generate heat through large-scale HPs and boilers as denoted by the blue bars. Red bars indicate heat flows that are mainly produced by Combined Heat and Power (CHP) and heat-only plants. The red bars on the right show the deliveries to end-consumers with multi-family houses, service buildings, and public administration being the three largest consumer groups. The diagram also shows the latest reported national statistics of network distribution losses which amount to about 14% (Energimyndigheten, 2020).

By contrast, Swedish DC was introduced in the 1990s and currently exists in 42 cities with a total network length of 660 km (Energiföretagen Sverige, 2022). A total delivery of 1 TWh was reported in 2020 to provide comfort cooling in malls and buildings as well as process cooling for data centers and freezing equipment (Energimyndigheten, 2020). The two largest DC systems exist in Stockholm and Gothenburg. The Stockholm system is one of the largest in Europe with an installed capacity in 2020 of 270 MW and total delivery of 335 GWh and a pipe length of 250 km (Jangsten, 2020). The system has three sources of cold production with different shares: waste cold from HPs used in DH (55%), compression and absorption chillers (27%), and seawater free-cooling (18%) with accounted distribution losses of 8% (Stockholm Exergie, 2020). The Gothenburg system has a capacity of 70 MW with a pipe length of 30 km and mainly operates with absorption chillers that utilise available waste heat from incineration plants. Free cooling from the river is also available in winter.

The long-established DHC in Sweden has led to a well-developed and efficient system. Compared to other European countries, Sweden has an ambitious plan to fully decarbonise district heating by 2030 and to contribute with negative emissions

equivalent to -115.6 g/kWh of GHG emission in 2050 (Euroheat & Power, 2022). The transition towards negative emissions is expected to take place by producing heat mainly from bioenergy with carbon capture and storage (BECCS) and waste incineration technologies.

2.2. Business and price models

The majority of existing DH systems in Sweden are 3rd generation technology relying on conventional BMs with a clear distinction between the customer and the utility company (Lygnerud, 2019). In such a workflow, the utility company is responsible for heat production and distribution in addition to system maintenance. The utility company partners with fuel providers to operate the production plant(s) that it owns. The value created for the customer is realised in the delivered heat and hot water and the communication between the customer and the utility company is established through invoices.

The pricing mechanism in existing DH systems often uses the marginal cost method which is utilised in deregulated heating markets to determine the price of DH (Energiforsk, 2017). The marginal cost reflects the cost of generating one more unit of heat through DH. Since the DH price depends on the supplier's marginal cost, suppliers are motivated to reduce costs by: (i) maintaining good infrastructure conditions, (ii) investing in better equipment, and (iii) implementing energy-efficiency measures. A survey was conducted to investigate 237 different price models used by 80 DH companies in Sweden (Song et al., 2017). Generally, the survey findings showed that DH price typically includes the following four components:

1. *Fixed cost* that the user pays each month for being connected to DH. The fixed cost is proportional to the customer's peak load and is therefore divided into different incremental levels.
2. *Capacity cost* that is charged to cover the cost of maintaining a certain level of capacity for peak load and investment in new facilities. A price for a unit of load demand (SEK/kW) is usually set by the DH company and the cost is determined based on the customer's actual or estimated peak load.
3. *Energy cost* that includes all costs for heat production covering fuel cost, labor and operation cost, energy, and carbon emission taxes.
4. *Flow cost* that reflects the cost of delivering a volume of hot water to the customer. This price component motivates customers to improve energy efficiency in their buildings to reduce the required volume of water and consequently the pumping cost.

Findings from the previously mentioned survey showed that energy and capacity costs constitute more than 95% of the total cost. Fixed and flow costs on the other hand are usually added to reduce financial risks taken by the DH company due to the high investment and, therefore, are seen as less transparent. Prices for heating and hot water in each Swedish municipality have been reported annually since 1996 by the 'Nils Holgersson' group (Holgersson, 2022). The latest published report shows that the average DH price in 2021 was 887.9 SEK/MWh including VAT with a 1.2% annual increase compared to the previous year. Since the current BM used in many of the existing DH systems already generates profit for utility companies, there is a resistance to shift to BMs that adopt the prosumer concept (Lygnerud, 2019).

2.3. Forms of ownership

Before the Swedish DH market was deregulated on 1 January 1996, DH systems were owned and operated by municipalities

that were not allowed to make profits. After market internationalisation and liberalisation, DH systems were sold to either private or municipality- or state-owned companies. Figures from 2014 show that DH existed in 283 out of the 290 Swedish municipalities where 51% of these systems were municipality-owned, 20% had private owners, 4% were state-owned, and the rest of the systems were jointly owned (Magnusson, 2016). The period between 1996 and 2005 experienced the largest redistribution of Swedish DH ownership. The three big market players (E.ON, Fortum, and Vattenfall) benefited from internationalisation and expanded in the market through acquisitions. For instance, the Finnish Fortum bought Stockholm Energi around the year 2000 while the German E.ON bought Sydskraft in 2002.

There was some risk of oligopoly in the early 2000s when prices increased rapidly after Fortum bought Stockholm Energi and Vattenfall bought Uppsala Energi, which led to subsequent protests and requests for competition through third-party access (TPA) (Magnusson, 2016). After national investigations, the government proposed the bill commonly known as 'Fjärrvärmelagen' obliging owners of DH systems to permit access to the DH network to entrants who want to sell heat (Riksdag, 2022). The proposed bill was issued in 2008 but was only passed in 2014 (Magnusson, 2016; Lygnerud, 2018).

2.4. Combining district and HP technologies

Power-to-heat solutions such as HPs were promoted in Sweden in the 1980s after the oil crisis and due to the resulting surplus of electricity from 12 new commissioned nuclear reactors (Averfalk et al., 2017). HPs started to play an economic role in contrast to CHP plants that are typically expensive to run on winter days when electricity is mainly produced from wind. Large-scale HPs³ produced about 10% of the total heat production in the Swedish DH system in 2020. Meanwhile, small HPs exist in more than half of all Swedish single-family houses and have an overall share of about 25% of the heating market (Johansson, 2017). HPs are therefore considered the main competitor for DH in Sweden. Lygnerud et al. (2021) argue that there is a trend for customers in private and multi-family houses "converting from DH to individual HPs, triggered by cost savings and increased autonomy". These customers maintain the connection to DH to cover peak loads only while running the HP to provide the base load. This situation induces DH operators to change their business from selling a product, i.e., heat to selling services. Moreover, a window of opportunity is opened with combined DHC and HP technologies instead of viewing them as competing technologies. Such a combination is optimally realised in 5GDHC systems where the network temperature is reduced without deteriorating the system performance and whereby decentralised HPs adjust the network temperature to the desired supply levels. Moreover, the combination of DHC and HPs is estimated to cover up to 85% of the heating market and thus DH suppliers can gain more profits by setting a price lower than the market price.

The above discussion from the review provided in this section can be summarised in four main points. First, Swedish DHC is regarded as one of the most efficient systems in the world and has a key role in decarbonising the building sector. Second, the internationalisation of the Swedish energy market has created a good atmosphere for negotiation between different suppliers and possible joint ownership of DHC systems. Third, several arguments have been identified to motivate DHC suppliers to change their BMs and pricing mechanisms to adopt the prosumer concept dedicated to energy communities. Fourth, the combination of DHC and HP technologies reduces production costs, increases energy efficiency, and contributes to sustainable cities.

³ We adopt the definition provided by Averfalk et al. (2017) that a heat pump is classified 'large' when it has an installed capacity larger than or equal to 1 MW.



Fig. 2. Used template for the roadmap workshop which incorporates self-explanatory process steps. Source: Adopted from Ref. Cambridge Roadmapping (2022).

3. Method and materials

A mixed-method approach combining best practice and roadmapping workshops is used in this study to envisage the development of 5GDHC systems in Sweden. The workshops were carried out by inviting middle agents involved in the COOL-GEOHEAT project to form a ubiquitous understanding of 5GDHC systems and to share learned lessons from existing implementations. The workshops took place during a full working day at the Faculty of Engineering at Lund University in Sweden and were divided into two main parts: (i) presentations of existing 5GDHC systems in Sweden and (ii) roadmapping for business innovation. The first part aimed to exchange gained knowledge and experience and to identify key challenges and industry requirements. In the second part, a roadmapping template was used to visually align the key drivers behind 5GDHC systems and technology requirements with future outlooks.

3.1. Design of best practice and roadmapping workshops

A total of 19 professionals and other stakeholders participated in the workshops. The workshops were divided into two main parts. The first part consisted of a series of seven presentations where each speaker was given 20 min for presentation followed by a 10-min of Q&A session. A moderator was responsible for documenting the workshop minutes and to facilitate the Q&A session. The second part was intended to perform a roadmapping workshop after the participants were divided into three distinct groups based on their background experience. The groups covered (i) *System planners*, (ii) *District heating companies*, and (iii) *Heat pump experts*. The moderator first explained the instructions for performing the roadmapping workshop using the digital roadmapping wall chart shown in Fig. 2 and obtained from Ref. Cambridge Roadmapping (2022).

In general, all roadmapping templates share a common structure to address different questions related to the discussed topic. Processes one and two in Fig. 2 aim to respectively answer the *why* and the *what*. The current situation is described in process three to address the *who* and the *where*. In processes four and five,

the *how* is addressed by mapping the route forward and by listing the required capabilities and resources. Finally, learned lessons from different milestones are aggregated as shown in process six. Each group used a separate digital template and was asked to join its respective break-out room for about 30 min. Digital post-it notes were utilised to document the respective group's main discussion themes related to the development of 5GDHC systems according to the group's expertise. A group leader was assigned to document the discussion notes and present the group's roadmap after the workshop was finished.

3.2. Data collection and interpretation

The presentations from middle agents including the Q&A sessions in addition to the roadmapping workshop were audio and screen recorded and later on transcribed. Throughout the roadmap workshop, each group used a separate digital roadmap wall chart which was synchronised to a cloud for subsequent thematic analysis of the group discussions. Thematic analysis is particularly useful to identify discussion points that follow specific patterns. The main themes discussed in each group were then juxtaposed with themes discussed in the other groups to elicit common patterns across all middle agents.

4. Findings from the best practice and roadmapping workshops

This section presents the findings of the workshops with respect to suggested technical solutions, thematic analyses and proposed best practices.

4.1. Multiple technical solutions for 5GDHC systems

The middle agents presented and discussed four different case studies across Sweden that are summarised in Table 1 together with project key challenges. Each case has a unique technical solution for the shared energy concept that is presented in the following four subsections.

Table 1
Summary of four case studies of 5GDHC in Sweden sorted by project starting year.

Case study	Location	Project starting year	Total heated space area ^a [m ²]	Space use	Actual or estimated heating demand ^b [MW, GWh/year]	Actual or estimated cooling demand ^b [MW, GWh/year]	Energy source	Range of HCF temperature [°C]	Key challenges
Embassy of Sharing	Malmö	2022	61,901	52% office, 46% residential, 2% retail	2.0 MW, 2.2 GWh	1.1 MW, 0.4 GWh	111 borehole heat exchangers with 30,525 m of active depth	5–20	<ul style="list-style-type: none"> • coordination between consultants • capacity for peak load • deviation between estimated and actual amount of shared energy • adequate size of BHE • control strategies for the three-way valve • requirements for connecting new buildings
ectogrid™	Lund	2018	105,755	43% office, 11% lab, 4% sport center, 4% restaurant, 38% other	1.5 MW, 4.2 GWh	1.0 MW, 1.2 GWh	Reversible air-source HP and a 150 m ³ accumulator tank	5–40	<ul style="list-style-type: none"> • capacity for peak load • real-time system monitoring • data collection and management • HP failures • complexity of system design, commission, and operation
Hästskon	Stockholm	2017	56,799	68% office, 16% retail, 6% restaurant, 3% residential, 7% other	1.5 MW	3.0 MW	Aquifer consisting of two cold wells and four hot wells	2–17	<ul style="list-style-type: none"> • low competence • many sources of error due to multiple subsystems • adaptation of building distribution systems • development of beneficial BMS
NUS	Umeå	2014	330,000	Hospital	1.1 MW, 7.0 GWh	0.9 MW, 5.0 GWh	202 borehole heat exchangers with 42,250 m of active depth	9–17	<ul style="list-style-type: none"> • capacity for peak load • low competence • business risks • development of beneficial BMS

^aHeated spaces are defined according to the Swedish National Board of Housing, Building and Planning Regulations (BBR) as the area of temperature-controlled spaces intended to be heated more than 10 °C (Boverket, 2020).

^bPresented figures indicate deliveries from the 5GDHC system excluding deliveries from auxiliary systems such as connection to conventional DHC networks.

^cHCF = Heat Carrying Fluid at the district source loop.

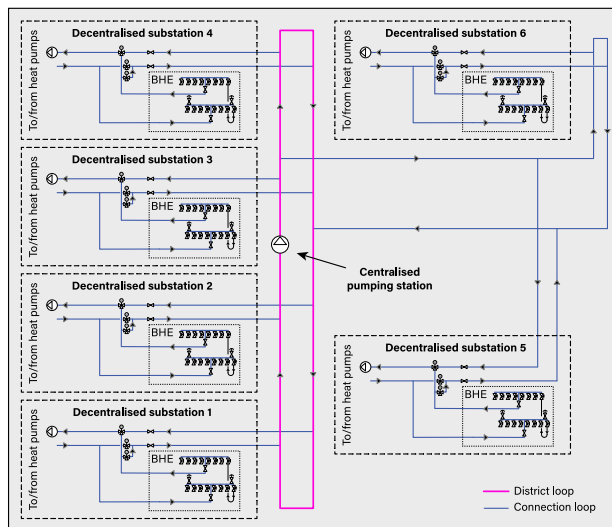


Fig. 3. Schematic diagram of a 5GDHC solution with one-pipe network topology, unidirectional mass flow, and DSS connected in series. The energy source is borehole heat exchangers.

4.1.1. Case study 1: The Embassy of sharing in Malmö

The new neighborhood in the Hyllie district consists of 6 decentralised substations (DSS) that supply both heating and cooling to 7 buildings with different space use. The system layout illustrated in Fig. 3 presents the mechanism for sharing energy

flows between DSS through a geothermal energy sharing system. Here, each DSS is equipped with several borehole heat exchangers (BHE) that provide heating and cooling throughout the year, whereby HPs adjust the temperature of the heat carrying fluid (HCF) to the desired supply temperatures. The three-way

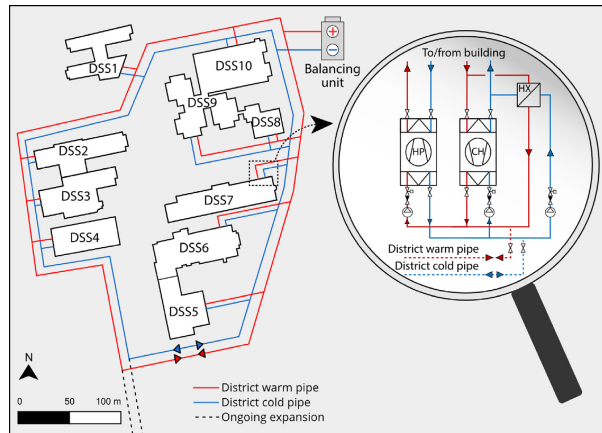


Fig. 4. Schematic diagram of a 5GDHC solution with two-pipe network topology, bidirectional mass flow, and DSS connected in parallel. The balancing unit incorporates a reversible air-source HP and a large accumulator tank.

valve is controlled such that it injects/extracts energy into/from a one-pipe loop (commonly referred to as the reservoir network (Sommer et al., 2020)) to balance the system demands.

4.1.2. Case study 2: ectogrid™ in Lund

The system is patented by E.ON Sverige AB (Rosén and Resoenvist, 2018) and is regarded as the first Swedish district network with simultaneous heating and cooling demands and bidirectional energy flows (Abugabbara et al., 2022). Currently, the system connects 10 buildings whereby energy is shared at three stages. In the first intra-balancing stage, each DSS is equipped with a HP, a chiller, and a free-cooling heat exchanger that share energy flows with each other as shown in the magnified part in Fig. 4. In the second inter-balancing stage, the excess heat or cold from each DSS is shared with other connected buildings through a bidirectional two-pipe network. To balance the demands across the entire network, a balancing unit finally injects/extracts heat into/from the network. The balancing unit incorporates a large reversible air-source HP (ASHP) and a 150 m³ accumulator tank for short-term storage. The sophisticated thermal interactions between buildings are controlled and monitored by ectocloud™, which is a control system based on Microsoft Azure cloud platform (Lindhe et al., 2022). The system is controlled based on several key performance indicators to improve system performance, minimise energy cost, and reduce peak demand.

4.1.3. Case study 3: Hästskon in Stockholm

The two blocks Hästskon 9 and Hästskon 12 located in the centre of Stockholm are typical examples of integrating several subsystems for increased synergy. The main energy source consists of an aquifer thermal energy storage with 2 cold wells and 4 warm wells as shown in Fig. 5. Cooling is mainly provided by the 2 water chillers and the refrigerant coolers in addition to conventional DC. Heating sources are realised in the available waste heat from server rooms, waste heat from chillers, and conventional DH. After its operation in 2016, cooling was provided solely by the aquifer and the purchased energy from conventional DH was reduced by about 68%. Ongoing system expansion includes connecting the adjacent property Jakob Större 18.

4.1.4. Case study 4: The Norrlands Universitetssjukhus (NUS) in Umeå

The geothermal system installed at the university hospital in Umeå covers about 90 and 30% of the respective annual cooling and heating demands while the rest is provided by conventional DHC (Granmar, 2017; Puttigg et al., 2022). The system illustrated in Fig. 6 consists mainly of three HPs with one being used for domestic hot water production and is connected in series with the other two HPs (Walfridson, 2022). Overall, the system has two chillers, three connection points to conventional DC, and four borehole thermal energy storages that have been expanded since 2014 to reach a total of 202 boreholes. In summer, heat from the space cooling loop and the available heat from HPs are injected into the BHE, while in winter the BHE act as a heat source. The components of the 5GDHC network operate in an economic sequence for simultaneous production of heating and cooling by optimising the buildings' power demands and power supply from DC.

4.2. Thematic analyses

The main discussed themes during the best practice and roadmapping workshops are presented herein for each corresponding group. An overview of the themes superimposed on the roadmapping wall chart is presented in Fig. 7 with more details deliberated below.

Group 1 – System planners: the group oriented their discussion towards the description of the current situation and on elaborating the key drivers. What was initially highlighted is the current lack of enough players on the market for the shared energy concept that is essential to gain momentum. The group also pointed out the current challenges in coordinating projects with the shared energy concept while knowledge still needs to be increased. From the group's viewpoint, focusing on improving knowledge would create common parlance between project partners which would ultimately facilitate coordination. Additionally, the group raised the challenge related to system control, especially controlling the valves for thermal energy exchange between

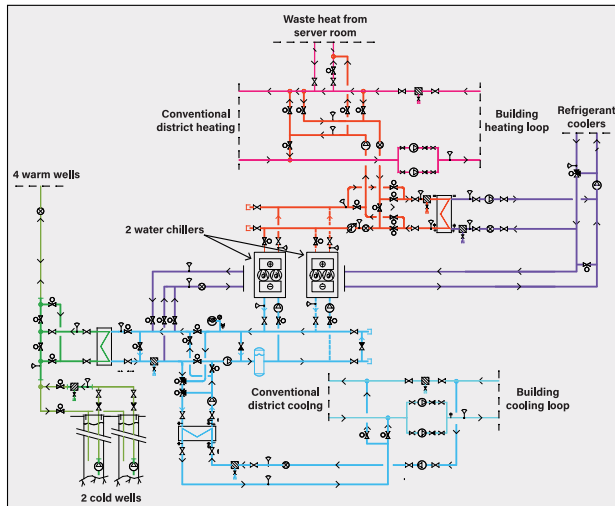


Fig. 5. Schematic diagram of a 5GDHC solution with aquifer thermal energy storage, waste heat recovery, and established synergy with existing conventional DHC systems.

Source: Adapted from Sweco, see Ref. Revholm (2013).

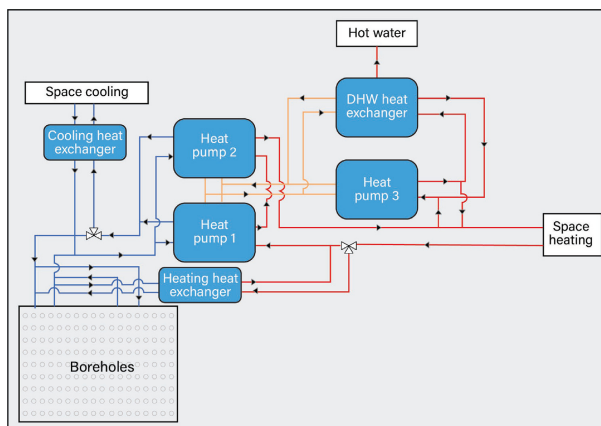


Fig. 6. Illustration of the 5GDHC system at NUS.

Source: Adapted from Ref. Puttige et al. (2020).

the DSS and the district network as depicted in the schematic shown in Fig. 3.

While mapping the route forward for business innovation, the group anticipated the challenge of connecting new buildings to

the district network since many questions related to this point remain unanswered. For instance, the already existing challenge of balancing the demands between prosumers is aggravated when a new building is connected to the network. The difficulties in

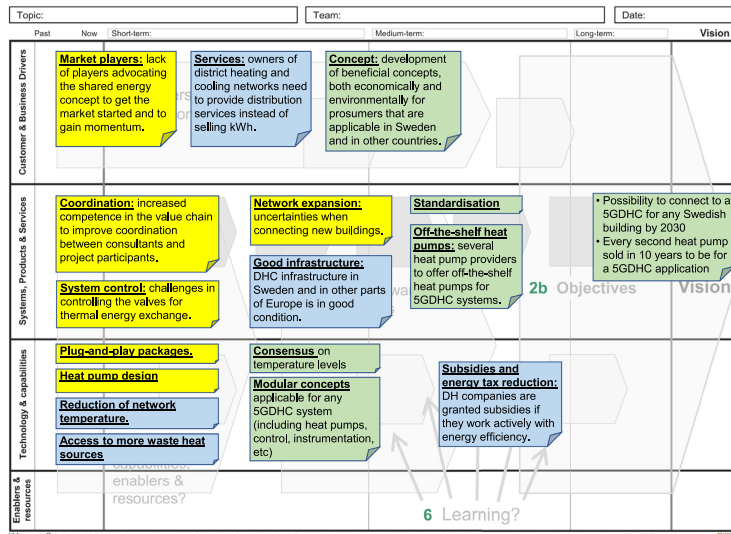


Fig. 7. Summary of the main discussed themes in the roadmapping workshop. Different colors denote themes discussed by each of the three groups: yellow = system planners, blue = district heating companies, and green = heat pump experts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

estimating the demand profiles for new buildings with high certainty add a new layer of complexity for ensuring reliable system operation.

When discussing technology and capabilities, system planners put forth the need for developing plug-and-play packages for 5GDHC systems that can be easily assembled on-site. The group accentuated this point as it would improve trustworthiness and reduce uncertainties during system commissioning and operation. To achieve this, the group recommended developing better HPs customised for 5GDHC systems that have low-temperature lifts.

Group 2 – District heating companies: the participants in this group decided to not focus their discussion on defining a vision that only relates to 5GDHC systems. Rather, the group discussed three important points that could be interesting for the development of DHC networks and the development of societies in general. These points encompass TPA, network temperature reduction, and energy subsidies.

First, the group looked at the fact that DH companies are used to running their business based on selling units of energy, i.e., kWh. However, the participants believe that this would soon change as aspects of sustainability are integrated into the industry. This implies that DH companies need to shift their business towards providing services, particularly through TPA to existing networks. This would benefit all players on the market after DH companies begin to offer such services given that the infrastructure in Sweden and other European countries is already in good condition.

Second, in order to make TPA more practical, the group pointed out the existing issue of operating DH networks at high-tempe-

perature levels. This would naturally limit the possibility for low-grade waste heat sources to gain access to the network. For instance, sewage networks are the closest waste heat source available to DH networks since both coexist in urban areas and are probably located in the vicinity of each other (Pelda and Holler, 2019). However, available temperatures from sewage networks are typically around 35 °C which would require DH operators to lower the network temperature for better utilisation of similar waste heat sources.

Third, the group underlined the slow rate of change in DH businesses due to the dilemma between low motivation to increase efficiency and existing governmental subsidies that make the energy cost relatively cheap for DH companies. This is currently changing as sustainability is integrated into the industry which necessitates business transformation. The group suggested that “DH companies can be granted subsidies if they work actively with energy efficiency”. Another suggestion was to inaugurate a new governmental agency that would be responsible for making controls and random checks for sustainable heat production and distribution. As such, the industry is motivated to improve energy efficiency by the tacitly increased subsidies.

Group 3 – Heat pump experts: the participants in this group exerted more effort in defining a vision since HPs are an intrinsic component of 5GDHC systems. The formulated vision constitutes two parts: (i) offering the possibility for any Swedish building to be connected to a 5GDHC system, and (ii) increasing sales such that every second HP sold in 10 years is for a 5GDHC application. This ambitious vision necessitates the development of economically and environmentally beneficial concepts for prosumers during the short- and medium-term. It was noted that

these concepts should also be applicable in other countries since Sweden has a relatively small market. The participants emphasised providing clear key performance indicators that are easy to understand by end-customers and not only technicians.

To realise the vision, the group highlighted the need for offering off-the-shelf HPs suitable for 5GDHC applications since the performance of traditional HPs deteriorates when operated with low-temperature lifts due to issues in the expansion valve. Moreover, developing industry standards is an essential part that would benefit all involved in the daily practices of 5GDHC systems. The standards also allow reaching a consensus on the expected range of network temperature to design HPs more adequately.

Heat pump experts talked about the manufacturers who would need to develop modular HPs using a Lego-like approach including HP controls, instrumentation, and data management. The main advantage of such an approach is that the product is always available and can be customised for a specific application by only changing one or a few components. For example, it was revealed from the previously presented case studies that HPs in 5GDHC systems generally have issues in the expansion valve that deteriorate the HP performance. This issue is related to the higher source temperature which increases the capacity at the same size of the evaporator and condenser leading to incorrect refrigerant charge. Therefore, it would be more relevant to change the swept volume or to have two smaller compressors to better match the design of heat exchangers and the capacity of the expansion valve.

4.3. Proposed best practices

This section puts forward proposed best practices by the middle agents obtained from the workshop findings for developing 5GDHC systems starting from the planning stage up to system monitoring during operation.

4.3.1. Best practice for system planning

The technology behind 5GDHC is considered relatively new and findings from existing literature point to the lack of clear design guidelines for system planners (Gjoka et al., 2023; Volkova et al., 2022). The integration of social and political acceptance with possible technical solutions is required during the planning stage where several design options might be considered. The *ex-ante* and *ex-post* approaches are useful for considering the social, political, and technical barriers of these elements during the planning stage (Schubert et al., 2015). The *ex-ante* approach considers all the previous barriers at the same stage and only feasible options with regard to the three elements remain. It may be the case that successful design options arising from this stage are not technically or commercially viable. For example, a social acceptance of 5GDHC could be reached if the system guarantees full autonomy from other energy systems such as conventional DHC. This situation can lead to an oversized system that is difficult to finance. Therefore, the *ex-post* approach is recommended since only technically feasible options are assessed for their social and political desirability.

The communication tool between scientists, citizens, and policymakers to integrate social and political acceptance with feasible technical solutions can take the form of science cafés. In these cordial events, participants who are not experts in the technology are engaged in discussions and are on equal terms with scientists (Dallas, 1999). A colloquial language to encourage citizens to be part of an energy community based on the shared energy concept can evolve in science cafés designated for 5GDHC systems. Furthermore, they can be an ideal platform for establishing industry standards and designing training courses for certified installers of 5GDHC systems.

4.3.2. Best practice for system modeling and simulation

The feasibility of technical solutions during the design stage is evaluated with the aid of modeling and simulation. The middle agents recommend the use of Modelica language for modeling 5GDHC systems since it offers features, including, but not limited to (i) multi-domain modeling covering thermal, fluid, control, and economic domains, (ii) hierarchical modeling from small components up to the assembly of large district systems, (iii) ability to model bidirectional mass flows, (iv) ability to reuse and/or edit existing component models (object-orientation), (v) acausal modeling where no strict definition of input/output relationships is required, (vi) easy adoption of design changes since the system architecture is retained. Such recommended use of Modelica as a physics-based modeling and dynamic simulation approach for 5GDHC systems confirms the latest findings in the literature (Abugabbara et al., 2020, 2021; Abugabbara, 2021; Abugabbara and Lindhe, 2021; Mans et al., 2022).

Different use cases can be applied to the developed Modelica model during the project lifecycle. In the early design stage where no detailed representation of the system is required, the user may be interested in evaluating the system performance for a varying number of connected buildings. This poses a scalability challenge since Modelica models are connected through visual connection lines that can make the model prone to errors when the model becomes large. One way to circumvent this issue is to utilise array declaration which Modelica supports. Here, the model for DSS is vectorised and only one model for the distribution pipe is used with connection to each array element, i.e., the number of DSS. Thus, the model for the 5GDHC system consists of only three subsystem models: DSS, distribution pipe, and a balancing unit for heat injection and/or extraction. The interested reader can refer to Ref. Lawrence Berkeley National Laboratory (2022) for practical examples of this solution.

To use the model for real-time system monitoring and operation, it is recommended to first identify the required measured quantities needed for evaluating the system performance. These can be, e.g., heat flow rate, temperature, and volume flow rate at different spatial locations in the district system. Afterwards, it is necessary to standardise the method for data collection and pre-processing techniques to handle missing and unrepresentative data. Finally, Modelica runs in the continuous time domain and it is therefore important to pay attention to the selected method for data interpolation (between the measurement sampling frequency) and extrapolation (outside the measurement period). Data interpolation is crucial for validating variables that represent a time derivative such as heat flow rate, but of less importance for variables with conserved quantities such as energy.

4.3.3. Best practice for business models and ownership structure

The maturity of the Swedish DHC market along with market liberalisation has created an atmosphere with flourishing potential. Although market deregulation permits internationalisation and obliges DH companies to allow TPA, the middle agents confirmed the findings by Bürger et al. (2019) that a regulator is still needed, especially for 5GDHC applications, to minimise the cost for prosumers and to increase the share of renewable energy production. Because of the current minimal state intervention, the regulator plays a key role in overseeing the negotiations for TPA between owners of 5GDHC systems, which would otherwise be a voluntary and tedious process. Thus, it is important to design BMs that are likely to emerge in 5GDHC systems to identify the required regulatory frameworks.

To support the design of BMs for 5GDHC systems, the business model canvas (BMC) can be utilised. The BMC was developed by Osterwalder and Pigneur (2010) as a visual tool in which an organisation can design its BMs on nine building blocks for

KEY PARTNERS <ul style="list-style-type: none"> • Community members • Technology manufacturers • Technical know-how providers (engineers, lawyers, accountants, etc.) • External investors • Network operators • Municipalities and public entities 	KEY ACTIVITIES <ul style="list-style-type: none"> • Local heat generation and supply • Services provision • System operation • New members recruitment 	VALUE PROPOSITION <ul style="list-style-type: none"> • Economic value • Environmental value • Social value • Energy self-sufficiency • Distribution of costs and responsibilities 	CUSTOMER RELATIONSHIPS <ul style="list-style-type: none"> • Personal and direct contact 	CUSTOMER SEGMENTS <ul style="list-style-type: none"> • Households • Small- and medium-sized enterprises • Public entities
	KEY RESOURCES <ul style="list-style-type: none"> • Members • Physical conditions • Available funding • Regulatory frameworks • Public incentives 		CHANNELS <ul style="list-style-type: none"> • Face-to-face meetings 	
COST STRUCTURE <ul style="list-style-type: none"> • Technical and economic feasibility studies • Planning and licensing costs • Capital costs for building and installing assets • Conventional DHC network usage costs • Reinvestment costs to maintain, improve and increase the existing infrastructure • Procurement costs • Outsourcing costs 			REVENUE STREAM(S) <ul style="list-style-type: none"> • Sale of community members' shares • Sale of energy to other consumers • Sale of energy surplus • Subsidies or long-term contracts between the government and renewable energy producers 	

Fig. 8. Energy community business model canvas. Source: Adapted from Ref. Reis et al. (2021).

different business dimensions. The BMC is vertically divided into two main parts, as shown in the BMC for the energy community presented in Fig. 8. The four blocks on the left including key partners, key activities, key resources, and cost structure show how value is created. The middle block, i.e., value proposition identifies the created values from the customers' perspective. The last four blocks on the right aim to address how value can be delivered and captured. Below we discuss three BMs for energy communities that are adapted from Reis et al. (2021) for 5GDHC applications.

Local energy markets: this BM would establish energy communities with peer-to-peer energy exchange between community members who would like to increase autonomy and reduce trading with external energy providers. Thus, pricing can be directly negotiated between community members and revenues would be equally distributed among them. All members shall be decision-makers whereby heat producers choose which consumer they sell their available energy to, and vice versa. A practical example of this application is seen in the case study Embassy of Sharing in which the seven connected buildings freely trade with each other in a fully decentralised way. However, challenges such as demand balancing, system control, and the requirement for an advanced trading platform to keep a record of energy and money transactions may limit the applicability of this BM.

Third-party-sponsored communities: this BM would enable community members to find sponsors who would become responsible for financing energy community projects. Available financing schemes for community members can be, e.g., grants and subsidies, private or public loans, leasing, and crowdfunding (Leoni et al., 2020). While representatives from the energy community can be involved in the decision-making process, the financing entity would be the main decision-maker in these projects since all financing risks are put on its side. The financing entity would hold assets of system ownership and would generate revenue through a long-term Public Purchase Agreement (PPA) with community members who benefit from cheaper and renewable energy.

Community ESCO: this BM would be realised when external energy services companies (ESCO) partner with energy communities to provide heat-as-service or comfort-as-service. ESCO are slightly different from ordinary energy companies or consultants in the sense that they can finance energy community projects. ESCO BM can take a variety of customised forms, out of which a practical example is presented in ectogrid™. In this case study, the energy company, i.e., ESCO selected a community of interest to implement a 5GDHC system and offered complete retrofit of all DSS by installing heat pumps, chillers, heat exchangers for free-cooling, pumps, valves, etc. The ESCO financed the project and owned the new infrastructure. In doing so, remuneration for ESCO existed in the guaranteed energy savings which were estimated in the ectogrid™ case to be around 60%. By the end of the binding contract period between ESCO and community members, the latter may choose between buying the entire system to run the business as local energy markets or continuing the community ESCO BM. The three discussed BMs need to be further investigated in their respective real cases at different heat tariffs and carbon taxes to assess the economic as well as environmental benefits of 5GDHC implementation (Pakere et al., 2023).

4.3.4. Best practice for system monitoring

Best practices for system measurement and verification are discussed herein based on lessons learned from the presented case studies. Firstly, in situations where multiple HPs are installed in one DSS, measurements from the thermal energy meter installed directly after the connection to the DSS should be used for model verification, energy audits and billing, and system performance evaluation. This is mainly because flow and temperature sensors in individual HPs do not necessarily represent the actual flow and temperatures entering and leaving the DSS since mixing between different streams usually occurs. Secondly, a best practice for correcting synchronisation errors between measurements is to shift or resample the measurements. Shifting is recommended when two time series are out of phase, while resampling to a common time frame is suitable when

different intervals are used. These approaches would circumvent the practical issues arising when the controllers recording the timestamp are not connected to the internet and/or unable to use internet clock time. Finally, significant improvements in the system performance can be attained by employing heat pump control strategies that allow stable refrigerant charge through the expansion valve. To ensure correct control and operation of the heat pump, it is recommended to follow the latest guidelines for instrumentation and data management published by the International Energy Agency IEA HPT Annex 52 in Ref. [Davis et al. \(2021\)](#).

5. Conclusions and outlook

The paper presented proposed best practices by middle agents for developing 5GDHC systems in Sweden based on findings from workshops. Four different case studies were demonstrated to highlight the variety of technical solutions that 5GDHC systems can incorporate, including, e.g., one- and two-pipe network topology, uni- and bi-directional mass flows, and several energy sources. The main key challenges found in all presented case studies are the sophisticated control of energy exchange between connected buildings, the system capacity to cover peak load demand, the undefined requirement for connecting new buildings, and the need for well-established and beneficial BMS.

A roadmap was composed by the workshop participants who were divided into three groups consisting of system planners, district heating companies, and heat pump experts to analyze the current market situation and to provide an extended look at the future. It was found that wider implementation of 5GDHC systems entails technological development in HPs as well as in providing purchased packages, which would consequently create more jobs, boost the economy, and contribute to low-carbon cities.

The best practice for planning 5GDHC systems requires first identifying a set of technically feasible solutions which could then be evaluated for their political and social desirability. It is essential to include policymakers and citizens together with systems experts in this process to promote energy communities. Based on the demonstrated case studies, three BMS for energy communities are presented for cases of full autonomy (local energy markets), with a sponsoring agent (third-party-sponsored), or when a company provides services (community ESCO). The Modelica language is recommended for the modeling and simulation of 5GDHC systems due to its capabilities in modeling such systems including thermohydraulic, control, and economic aspects. Approaches for correcting synchronisation errors between measurements may involve shifting when two time series are out of phase, or resampling when different intervals are used.

Although the study focused on the Swedish DHC market, the best practices can be explored and adapted to suit specific market needs. The study findings are novel in the sense that they provide fresh insights into the current and future situation of the Swedish DHC. It is recommended that the main development efforts of 5GDHC systems should be focused on the following four major topics: (1) standardisation to elaborate industry requirements, (2) legislation and training courses for certified installers, (3) provision of purchase packages, and (4) promotion of joint ownership and TPA.

CRedit authorship contribution statement

Marwan Abugabbara: Conceptualization, Literature review, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Signhild Gehlin:** Methodology, Project administration, Review and editing. **Jonas Lindhe:** Review

and editing. **Monica Axell:** Review and editing. **Daniel Holm:** Review and editing. **Hans Johansson:** Review and editing. **Martin Larsson:** Review and editing. **Annikka Mattsson:** Review and editing. **Ulf Näslund:** Review and editing. **Anjan Rao Puttige:** Review and editing. **Klas Berglöf:** Review and editing. **Johan Claesson:** Review and editing. **Morten Hofmeister:** Review and editing. **Ulla Janson:** Review and editing. **Aksel Wedel Bang Jensen:** Review and editing. **Jens Termén:** Review and editing. **Saqib Javed:** Project administration, Resources, Supervision, Review and editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

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Paper V



Manuscript submitted to *Science and Technology for the Built Environment*.

Paper VI



Manuscript submitted to *Energy*.

Paper VII



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