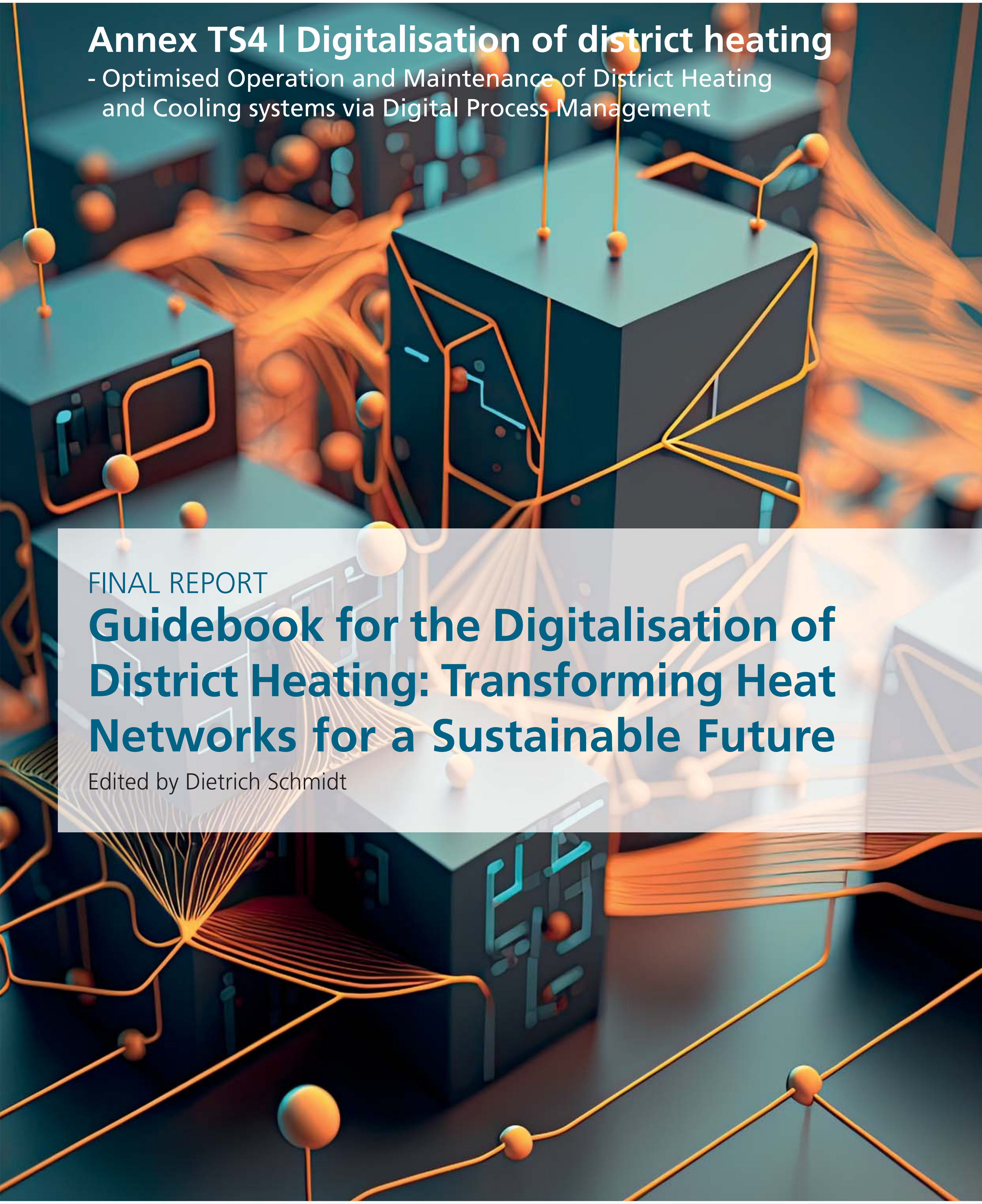
INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON
DISTRICT HEATING AND COOLING



Annex TS4 | Digitalisation of district heating

- Optimised Operation and Maintenance of District Heating and Cooling systems via Digital Process Management

FINAL REPORT

Guidebook for the Digitalisation of District Heating: Transforming Heat Networks for a Sustainable Future

Edited by Dietrich Schmidt

Technology Collaboration Programme
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1 Executive Summary

The district heating and cooling sector, which accounts for more than half of total energy consumption in many industrialised countries, is experiencing new challenges with the current transformation of the energy systems. The required decarbonisation will result in a more complex energy system, as a few large plants which utilise fossil fuels will be replaced by many small production plants distributed around the system, that use renewable or waste energy sources. Many of these sources are volatile; their output is affected by weather and other factors. Furthermore, district heating and cooling systems must be operated more efficiently and flexibly to ensure a consistent and cost-effective thermal energy supply, as well as effective participation power system balancing market. Because of the necessary changes in the energy system, district heating becomes increasingly beneficial to both end users as well as other energy sectors, and the number of connections is increasing in many countries in conjunction with the phase-out of fossil fuels such as oil and gas for space heating and hot water supplies. In this changed environment, increased adoption of digital technology in the district heating and cooling sector provides a chance to make systems smarter, more flexible, efficient and reliable, hence accelerating the necessary integration of additional renewable and waste energy sources into supply systems. This change affects the entire district heating energy chain, from generation to end user usage, and supports the transformation of the overall energy system.

The digitalisation of district heating systems represents a paradigm shift in the production, distribution, and consumption of heat. Sensor technology, IoT connectivity, and AI algorithms advancements provide prospects for higher energy efficiency, system stability, and increased integration of renewable energy sources. However, for successful deployment, issues such as data privacy and system integration must be addressed. The future of district heating is to embrace digitalisation and capitalise on its promise for creating sustainable, smart, integrated and resilient energy systems.

The IEA DHC Annex TS4 is a three-year international research project aimed at promoting the opportunities for integrating digital processes into district heating and cooling systems and clarifying the role of digitalisation for different parts of the operation and maintenance of these supply systems. The report provides background material and current knowledge on the digitalisation of district heating systems for the target groups of decision makers in utilities, district heating operators, system suppliers, the district heating and energy supply industries, as well as the scientific community. It has been demonstrated how digital technology can improve the entire energy system, along with increasing efficiency and the integration of more renewables into the system. Digital applications will assist district energy system operators fully optimise their plants and, network operations, as well as their participation in the wider energy market in the future, while additionally empowering the end user.

Buildings and how end users utilise thermal energy provide a framework for potential improvements, such as system temperature decrease in district heating systems. The demand side optimisation is viewed as a critical part of the project, as the operation of the end-user sets a limit on the optimisation of the supply system. Furthermore, the recent implementation of new rules that promote the digitalization of the demand side have opened up novel possibilities for monitoring and managing heating and cooling systems in buildings, paving the way for the district heating industry's sustainable transformation. As a result, the current state of digitalisation in buildings is benchmarked and documented with case studies, as well as experience demonstrating how low temperatures, improved operation, and fault detection in substations and thermal distribution systems can be achieved.

The investigation of the role that digitalisation can play in the district heating and cooling system as a whole, as well as in the rest of the energy system, offers several key insights. At the system level, digitalisation can be divided into two categories. The first is operational optimisation, which means that digital assets directly intervene in network or component control. In contrast to the rule-based control loops that are commonly used to control network components, digital tools can be utilised to optimise system operation. The second is analytics-based optimisation strategies that are being researched in addition to operational optimisation. Analytics refers to the analysis of (huge amounts of) measurement data to ensure the network's failsafe and optimal operation. Analytics digital tools provide information on system behaviour, often in an offline mode.

Based on this data, actions can be done to improve the behaviour. The analyses offered provide an accurate overview of how digitalisation is implemented in various elements of a district heating and cooling system. Of course, the current state of adoption of various digital technologies in the sector is not uniform.

The concept of Digital Twins in particular, facilitates the development of digital services that support district heating and cooling infrastructure operators in their everyday operations. As a result, concrete application areas for Digital Twins in DHC operation and maintenance are highlighted. A selection of best practise examples of using Digital Twins for the deployment of digital technologies for DHC infrastructure are additionally provided to demonstrate the practical value of this strategy.

Digitalisation of district heating networks requires not only technological implementation in existing infrastructures, but also rethinking of current operational strategies. Simultaneously, processes for monetising innovative technology must be initiated. Following that, how digitalisation can lead to the creation of new and innovative economic opportunities in the operation of current district heating networks is explained. Representative business models for the various stages of district heating generation, distribution, and consumption are additionally offered, as well as an outlook on business models of other digitalised sectors and markets.

As demonstrated throughout the report, data processing will continue to play an increasing role in district heating supply. However, this necessitates a greater focus on the legal requirements and obligations pertaining to data protection and data security. The legal requirements are complex and differ in the various countries and regions of the world. An overview of the relevant European legal framework is provided, as well as an excursus on the South Korean circumstance.

The material gathered and summarised in this guidebook demonstrates that digitalisation is an essential enabling technology for increasing the flexibility and efficiency of district heating and cooling systems and facilitating the wider integration of renewable and waste energy for the decarbonisation of our energy supply. More research and development is required to evaluate the practical and widespread application of digital technology in various situations and environments: It is very important to identify ways to overcome the impediments. This encourages additional discussions to ensure that more digitalisation solutions are implemented and operational in district heating and cooling systems.

Digitalisation of district heating and cooling systems is an essential technology for decarbonising the thermal energy system, and with growing complexity or the demand for system flexibility and a green/renewable heat supply, it is just vital!

2 Preface

2.1 International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the thirty one IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

2.2 Technology Collaboration Programme on District Heating & Cooling (DHC)

Established in 1983, the IEA Technology Collaboration Programme on District Heating & Cooling including Combined Heat and Power (IEA-DHC) brings countries together to research, innovate and grow district heating and cooling including CHP.

The IEA-DHC research programme addresses technical as well as policy issues aimed at low environmental impact. We select, manage and publish collaborative co-funded projects, collating and exchanging information on R&D projects between participating countries.

IEA-DHC programme control is vested in its Executive Committee, which comprises on official representatives from each participating country. The Executive committee maintains close links with Euroheat & Power and the International District Energy Association.

The Executive Committee closely cooperates with other IEA programmes. In particular the IEA-DHC is a member of the IEA's Building Coordination Group, resulting in more knowledge sharing and planning of joint activities. The world may be challenged by climate change, but countries can make district heating and cooling including CHP part of an integrated energy and environmental solution.

The IEA's Technology Collaboration Programme on District Heating & Cooling has played a significant role in the DHC/CHP industry's history and will play a vital role in its even brighter future!
Participating countries in IEA DHC: Austria, Belgium, Canada, China, Denmark, Estonia, Germany, Finland, France, Italy, Ireland, Korea, Norway, Sweden, the Netherlands and the United Kingdom. Furthermore, the International District Energy Association (IDEA) is a sponsor of the programme.

More information can be found at:
www.iea-dhc.org

Section 13.2 of the appendix contains a list of the other IEA DHC initiatives.

2.3 The IEA DHC Annex TS4

DHC Annex TS4 was a three-year international research project.

Annex TS4 is a project aiming at promoting the opportunities of the integration of digital processes into DHC schemes and to clarify the role of digitalisation for different parts within the operation and maintenance of the district heating and cooling system. Furthermore, the implementation of these technologies is going to be demonstrated. Digital technologies are believed to make the whole energy system smarter, more efficient, and reliable and to boost the efficiency and the integration of more renewables into the system. In the future, digital applications might enable district energy systems to fully optimise their plant and network operation while empowering the end consumer. On the other hand challenges need to be tackled, such as data security and privacy as well as questions about data ownership.

TS4 is a task-shared annex which means that there will be no individual, separate research projects started within the Annex. It also means that there is not one financing organization. Instead, the participants bring own funding. Annex TS4 provides a framework for the exchange of research results from international initiatives and national research projects and allows gathering, compiling and presenting of information concerning on the digitalisation of district heating and cooling systems.

Further information about the project can be found on the internet under:
https://www.iea-dhc.org/the-research/annexes/2018-2024-annex-ts4

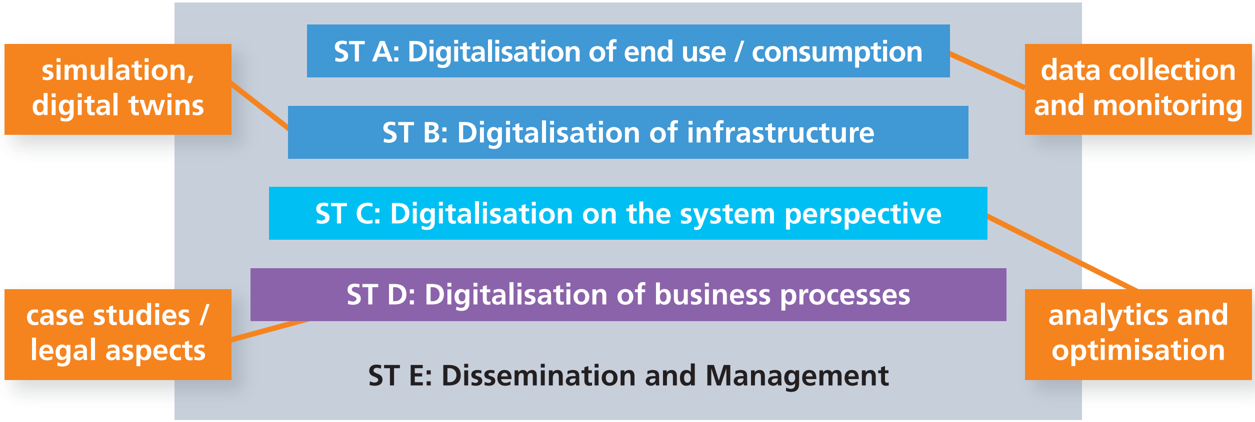

Figure 2.1: Structure of the IEA DHC Annex TS4

2.4 Task manager

This international cooperation project has been coordinated by the task manager

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2.5 This guidebook

This Guidebook of DHC Annex TS4 is the result of a joint effort of many experts from various countries. We would like to gratefully acknowledge all those who have contributed to the project by taking part in the writing process and the numerous discussions. This cooperative research work is funded by various national sources and from industry partner. The authors would like to thank for the given financial support.

A list of the participants within Annex TS4 and their corresponding countries can be found in the appendix in section 13.1. All participants from all countries involved have contributed to the guidebook. However, the following annex participants have taken over the responsibility of writing the chapters (in alphabetic order):

Oliver Antoni	especially chapter 9
Roland Baviere	especially chapter 7.3.1
Markus Blesl	Subtask D coordinator, especially chapter 8
Martin Brüssau	especially chapter 6.6
Christian Holm Christiansen	especially chapter 5
Jakob Fester	especially chapter 5
Carsten von Gneisenau	especially chapter 9
Markus Gölles	especially chapter 6.2
Oddgeir Gudmundsson	Contributed to almost all chapters, especially 5, 7.3.6, 7.3.7, 6.2.3.2, 6.2.3.3, 6.4, 11
Théau Le Guern	especially chapter 6.3
Steen Schelle Jensen	Contributed to almost all chapters, especially 7.3.2, 7.3.4, 11
Valentin Kaisermayer	especially chapter 6.2
Nicola Kleppmann	especially chapter 6.5, 6.6
Pakdad Pourbozorgi Langroudi	Subtask B co-coordinator, especially chapter 7
Jae Yong Lee	especially chapter 5, 8.5.3
Dennis Lottis	especially chapter 5
Grace Zheng Ma	especially chapter 8.4.1
Daniel Muschick	especially chapter 6.2
Bernd Rüger	especially chapter 7.3.8, 6.5.3.1

Étienne Saloux	especially chapter 6.7, 11
Dietrich Schmidt	Editor, task manager and Subtask D coordinator contributed to almost all chapters, especially chapter 1, 2, 3, 4, 8, 11,12, 13
Ralf-Roman Schmidt	especially chapter 8.4.3
Jonas Theiss	especially chapter 6.6
Michele Tunzi	Subtask A coordinator, especially chapter 5, 8.4.4
Mathieu Vallee	Subtask C coordinator, especially chapter6, 6.3, 6.5, 6.6, 10, 11
Dirk Vanhoudt	Subtask C coordinator, especially chapter 6, 6.4, 6.7
Nicolas Vasset	especially chapter 6.3, 7.3.1
Frank Wendel	especially chapter 8.4.5
Edmund Widl	Subtask B coordinator, especially chapter 7
Veronika Wik	especially chapter 8.4.2
Yinchen Xu	especially chapter 8.4.5
Xiaochen Yang	especially chapter 5

This publication also includes contributions from the following guests, in addition to the participants:

Stefano Coss (Arteria, Austria)	chapter 7.3.3
Mirko Morini (University of Parma, Italy)	chapter 7.3.9
Filippa Sandgren (Utilifeed, Sweden)	chapter 7.3.5
Kai Vahldiek (Ostfalia University of Applied Sciences, Germany)	chapter 7.3.8, 6.5.3.1

This report is a summary of the conducted work of DHC Annex TS4. More detailed information of the various activities are freely available on the internet (www.iea-dhc.org).

3 Introduction

3.1 Background and motivation

District heating contributes to climate preservation and CO_2 reduction initiatives through effective heat production via the integration of renewable energy and waste heat sources, as well as the utilization of combined heat and power generation. These heat sources, as well as industrial waste heat, contribute significantly to resource and climate protection within the heating sector as well as in the industry sector. As a result, district heating is a necessary component of an effective and sustainable energy supply. Furthermore, it holds an essential interface position within an increasingly dynamic and networked energy system, e.g. through sector coupling, whose overall systemic relevance will grow even more throughout the energy transition (AGFW 2019 and DHC+ 2019).

To underline the importance of measures, it should be noted that the building segment accounts for more than one-third of total energy consumption in societies and creates the greatest amount of greenhouse gas emissions (GHG) of any sector. This is due to the use of combustion processes, primarily of fossil fuels, to meet the heating and cooling demands of the building stock (the cooling need is normally met using electricity generated by combustion processes). District heating (DH) can significantly contribute to more efficient use of energy resources as well as better integration of renewable energy (e.g. geothermal heat, solar heat, heat from biomass combustion or waste incineration) and surplus heat (e.g. industrial waste heat, waste heat from electrofuels manufacturing or power generation) into the heating sector. The more efficient use of all energy resources, as well as the use of renewable energy, are steps that contribute to a reduction in the use of fossil energy, and hence a reduction in GHG emissions (Schmidt Kallert 2017, State of Green 2023). In this regard, digitisation supports the realisation of more efficient and sustainable district heating systems.

Information must be digitally available and automatically utilised in order to boost the effectiveness of district heating systems and make them more adaptable. Furthermore, greater integration of renewable energy sources increases system complexity, which must be managed. This complexity results from the decentral and varying nature of these energy sources. Many tasks will become manageable only with digital process management. Increased digitalisation is clearly required as part of the transition to a sustainable energy and resource system. Different technologies must function together very flexibly in such a system, there are various obstacles to overcome (technical, legal,...), and there is very limited time and manpower resources available. Digitalisation enables more automation and the adoption of standardised (more efficient) processes as well as more sophisticated methods. However, many systems still lack a high level of digitalisation. With more complexity, flexibility, and so forth, more powerful tools and approaches (and hence increased digitalisation) will simply be required. Aside from technology, the integration of new digital business processes will make deployment easier. On the other side, new concerns, such as data security and privacy, as well as questions concerning data ownership, must be addressed.

District heating and cooling (DHC) networks are traditionally operated with a limited number of controls (as the control of the supply temperatures or the network pressure) to secure the required supply task and to optimise economics and ecologic performance. Detailed information on the supply and utilisation structures (e.g. heat plant characteristics, power demand or time profiles) is not provided in classical network operation. On the other hand, an optimised heat generation and overall network operation is possible with more information on the demand and flexibility options (as thermal energy storages, the building mass and the incentivised end-users) and resulting in e.g. peak shaving and the reduction of expensive peak boiler use, as well as integration of fluctuation heat sources, such as solar thermal energy and power-to-heat applications operating on the electricity markets as shown by already realised projects. A wider implementation of information and communication technologies, as in many other industries, provides room for up for better network management based on real time measurement data.

There is a strong need for increased digitalisation for the transition to a sustainable energy system:

- Sustainable energy supply
  - different technologies need to work together in a very flexible way
  - many hurdles still must be overcome on this path (technical, legal, …)
  - only very limited time and personnel resources are available for the transition

- Digitalisation
    - allows a significant increase in the degree of automation and therefore a more efficient operation
    - standardised and more efficient processes, as well as more sophisticated methods can be utilised

Many systems still lack a high level of digitisation nowadays. However, as complexity increases, the requirement for flexibility, more sophisticated tools and procedures (and hence more digitalisation) simply becomes essential.

3.2 Scope and objectives

The intention of Annex TS4 is to provide information and solutions for the digitalisation of both new and existing district heating systems. It is primarily concerned with the deployment of digitalisation technologies as well as the economic, environmental, and legal constraints on this field of technology. The introduction of digitalisation measures at the district heating system level is the application under consideration. This includes taking into account all stages of the value chain, from the digitalisation of heat generating facilities and plants to end-user heat utilisation. This provides for an overall improvement in the performance of district heating systems.

Annex TS4 focuses on digitalisation measures in district heating systems. District cooling systems are under consideration, although the project's application cases are limited to the district heating sector. Today, heating is by far the major energy user in the Annex countries, but cooling energy demand is likely to increase in the future. As a result, the primary focus of this paper is on the provision of heat for space heating (SH) and the preparation of domestic hot water (DHW).

The main objective of Annex TS4 is to enhance the opportunities for integrating digital processes into DHC systems and to clarify the role of digitalisation for different sections of the district heating and cooling system operation (and maintenance). Additionally, the application of these technologies is illustrated. Digital technologies are thought to make the entire energy system smarter, more efficient, and reliable, as well as to increase efficiency and the integration of more renewables into the system. In the future, digital technologies may enable district energy systems and system operators to fully optimise plant and network functioning while also empowering end users. On the other hand, new concerns, such as data security and privacy, as well as data ownership questions, must be addressed.

The aim of Annex TS4 is to provide insights into how digitalisation impacts the district heating sector, system providers, displays current state of the art, identifies barriers, and presents objectives, targets, and recommendations.

In this regard, the following are the project's primary goals;

- Raise awareness among all stakeholders and users about the benefits of implementing digital procedures.
- Provide a current overview of the digitalization of district heating schemes in terms of R&D projects, demonstrators, and case studies; and
- Evaluate non-technical barriers and enablers for digitalization processes in district heating and cooling schemes such as business models, legal aspects, and policy instruments.

To meet the outlined objectives and goals, challenges for various components of the heat supply are acknowledged. The development of appropriate solutions, as detailed in this report, supports in the widespread application of digitalisation initiatives. Improvement areas include innovative methodologies, digitalisation, and business concepts for more efficient operation in the district heating application industry.

The focus of Annex TS4 can be said to be based on the need to reduce resource consumption and GHG emissions through overall system optimisation via digitalisation measures in collecting the most recent knowledge in the district heating and digitalisation sector in this report to maximise the future implementation rates of the regarded measures.

3.3 The Role of Digitalisation in District Heating

What exactly is digitalisation? Digitalisation can be described as the increasing use of information and communication technology (ICT) throughout the economy, including energy systems including district heating (Forbes 2023). Digitalisation can be characterised as the growing connection and convergence of the digital and physical worlds. There are three key aspects within the digital world:

- Data: digital information
- Analytics: the utilisation of data to generate relevant knowledge and insights
- Connectivity: data exchange between humans, devices and machines

In general, the trend towards greater digitalisation is enabled by advances in all three of these areas: increased data volumes resulting from lower sensor and data storage costs, rapid progress in advanced analytics and computing capabilities, and greater connectivity with faster and cheaper data transmission (IEA 2017).

Digitalisation is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business.
(Gartner Glossary 2023)

District Heating and Cooling (DHC) systems are increasingly transforming due to the increasing complexity of designing and managing modern supply systems. The traditional approach of single, programmable, large heat or CHP plants is being replaced by distributed, renewable, or waste heat sources. Smart heat meters enable the automatic collection of extensive consumption data sets with high granularity, evolving the role of the customer in the end-to-end system but also forcing us into GDPR-related considerations. The integration of multiple energy sectors is transforming DHC systems into key balancing players in the decarbonisation path of a multi-energy system, yet at the cost of reacting to increasingly volatile energy and capacity prices.

The increasing significance of digitalisation can be attributed to the necessity of managing vast quantities of data and multiple objectives, such as operating margin optimization vs reduction of CO_2 emissions, flexibility vs operational reliability. This encompasses the infrastructure required to measure and collect data across the entire value chain, and the capability to transform this data into information, insights, actionable decisions, and potentially, automation.

A survey conducted online on how the industry is coping with the digital innovation issue reflects the relevance of digitalisation for actors on the district heating market. The study was created with the intention of reaching out to digital solution providers, DHC utilities, and heat/energy planners who use digital solutions to develop, operate, and monitor DHC systems. The findings revealed that, while there are a greater number of mature digital solutions on the market, real adoption of such solutions remains a largely untapped potential, particularly on the design and end-user side of the value chain (Euroheat & power 2023).

Although just a small number of pioneers is actively engaging in digital innovation, a substantial portion of operators see this opportunity as a side-line to their core business and allocate limited time and resources to it. This report provides insights into how digitalisation measures can be effective in resolving operational issues and improving overall efficiency and long-term sustainability of heat supply in increasingly complex scenarios, while also generating returns on capital and operational investments.

3.4 Main objective and layout of the report

This report is a summary of the results acquired during the Annex TS4 research. It is aimed at utilities, district heating operators, system suppliers, decision makers in the district heating and energy supply industries, as well as the scientific community. The purpose of the handbook is to familiarise the target audiences with the benefits, advantages, and problems of digitalisation methods. The main principles, functions, and system layouts are presented and explained in a straightforward and practical manner. Several case studies and examples are used to address practical applicability. As a result, the major aspects of district heating digitisation clearly demonstrate the advantages of this approach. More information can be obtained in extended publications or in the material indicated in the appendix in section 13.3, which is publicly accessible via the website www.iea-dhc.org. This material is intended in part for scientists and researchers working on new district heating systems and the digital transformation of our energy system.

The major goal of the IEA DHC Annex TS4 in this respect is to demonstrate and validate the potentials of a further integration of digitalisation measures within the district heating sector as a key solution to achieving 100% renewable and GHG emission-free heating energy supply. In turn, the following chapters cover the themes indicated above: Following a broad description of the International Energy Agency's (IEA) Annex TS4 activities in chapter 2 and an introduction to this report in chapter 3, chapter 4 provides a quick review of the fundamental notion of district heating digitalization. There are several features and major benefits described there. Digitalisation measures on the demand and end user side are outlined. In chapter 5 the relevance of demand side systems in lowering return temperatures and so ensuring the effective functioning of the whole district heating network is emphasised. Chapter 6 provides insights and summarizes the possibilities for digitalisation measures at the system level. Several instances of operation optimisation are shown.

The potential for using analytics in the field of fault detection, predictive maintenance, and system optimisation, as well as forecasting methodologies, are described in the second half. The Digital Twin concept is introduced thoroughly in chapter 7. This concept's application areas within the district heating sector are given, as are various actual examples. By doing so, the true benefits of using Digital Twins are emphasiszed. Chapter 8 presents an overview of the economic aspects of district heating system digitalisation. Case studies provide insight into how the proposed techniques are put into practice. The thorough analysis of the legal implications of digitalisation presented in chapter 9. The current challenges and future directions in chapter 10 as well as the conclusions in chapter 11 complete the report.

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4 Digitalisation of District Heating

In recent years, the world has witnessed a rapid transformation in the energy sector, driven by the increasing need for sustainable and efficient solutions. Among these solutions, district heating has gained significant attention as an effective means of supplying heat to residential and commercial buildings. With the advent of digitalisation, district heating systems are undergoing a paradigm shift, ushering in a new era of smart and interconnected networks. This report explores the digitalisation of district heating, focusing on the advancements, challenges, and opportunities associated with this emerging field (IEA 2017, Euroheat & Power 2023).

4.1 Background for digitalisation measures

4.1.1 District Heating: An Overview

District heating is a centralised heating system that supplies heat to multiple buildings through a network of pipes. It offers numerous advantages, including improved energy efficiency, reduced greenhouse gas emissions, and increased flexibility in energy sources. Traditionally, district heating systems have been characterised by centralised control and limited monitoring capabilities. However, the rise of digital technologies is revolutionising the way these systems are operated and optimised.

4.1.2 Digitalisation in Energy Systems

Digitalisation refers to the integration of digital technologies into various aspects of energy systems, enabling enhanced monitoring, control, and optimisation. The application of digitalisation in energy systems has the potential to improve energy efficiency, enable demand-response mechanisms, and facilitate the integration of renewable energy sources. In the context of district heating, digitalisation offers opportunities to optimise heat production, distribution, and consumption, leading to more efficient and sustainable energy systems.

4.2 Advancements in Digitalisation of District Heating

4.2.1 Sensor Technology and Data Collection

Digitalisation enables the deployment of (new and existing) sensors throughout the district heating infrastructure and in secondary side systems (e.g. substations), allowing real-time monitoring of key parameters such as temperature, flow rates, and pressure. These sensors collect vast amounts of data, providing valuable insights into system performance and enabling predictive maintenance strategies. Furthermore, advanced data analytics techniques can be applied to optimise heat production and distribution, ensuring the most efficient use of resources. Smart metres must also be mentioned here. With smart metres (sensors in every building), it is possible to obtain information about the entire network's state and base operations on that.

4.2.2 Internet of Things (IoT) and Connectivity

The Internet of Things (IoT) plays a crucial role for a higher degree within the digitalisation of district heating systems. By connecting various devices and sensors, IoT enables the seamless exchange of data, facilitating efficient communication and control. IoT-based solutions can monitor and regulate individual building energy consumption, enable demand-response mechanisms, and enhance the overall flexibility and reliability of the district heating network. Large efforts are required to archive such a high level of connectivity.

4.2.3 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) algorithms have the potential to revolutionise the operation and optimisation of district heating systems. These technologies can analyse large datasets, identify patterns, and make intelligent predictions. AI and ML algorithms can optimise heat production schedules, predict energy demand, and dynamically adjust heat distribution based on real-time conditions. This leads to improved energy efficiency, reduced operational costs, and enhanced system reliability.

4.3 Challenges in the Digitalisation of District Heating

4.3.1 Data Privacy and Security

As district heating systems become more interconnected and reliant on data exchange, ensuring data privacy and security becomes paramount. The large volume of data collected by sensors and devices poses risks if not properly protected. Measures must be taken to safeguard sensitive information and prevent unauthorised access, ensuring the integrity and reliability of the system.

4.3.2 Integration and Interoperability

The integration of digital technologies in district heating systems often requires the collaboration of multiple stakeholders, including energy providers, technology vendors, and regulatory bodies. Achieving seamless integration and interoperability among different components and systems can be challenging, requiring standardised protocols and interfaces. Cooperation and coordination among stakeholders are essential to overcome these challenges and realise the full potential of digitalisation.

4.4 Opportunities for the Digitalisation of District Heating

4.4.1 Demand-Side Management

Digitalisation enables the implementation of demand-side management strategies in district heating systems. By providing real-time information and feedback to consumers, it encourages energy-efficient behaviour and allows for dynamic pricing mechanisms. This empowers consumers to actively participate in energy conservation and load balancing, leading to a more sustainable and resilient energy system.

4.4.2 Renewable Energy Integration

The digitalisation of district heating systems provides for new possibilities for the integration of renewable energy sources. By leveraging advanced forecasting techniques and real-time data, renewable energy generation can be optimised and synchronised with heat demand. This promotes the utilisation of clean energy and reduces reliance on fossil fuels, contributing to the decarbonisation of the heating sector and generally increases energy supply security.

4.4.3 Big Data Analytics and Predictive Maintenance

The abundance of data generated by digitalised district heating systems presents opportunities for advanced analytics and predictive maintenance. By analysing historical and real-time data, patterns and anomalies can be identified, enabling proactive maintenance and minimising downtime. Predictive maintenance strategies improve system reliability, reduce maintenance costs, and prolong the lifespan of assets.

In general, the digitalisation of district heating systems represents a transformative shift in the way heat is produced, distributed, and consumed. Advancements in sensor technology, IoT connectivity, and AI algorithms offer opportunities for enhanced energy efficiency, improved system reliability, and increased integration of renewable energy sources. However, challenges such as data privacy and system integration need to be addressed for successful implementation. The future of district heating lies in embracing digitalisation and leveraging its potential to create sustainable, smart, and resilient energy systems.

4.5 Literature references in Chapter 4

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IEA (2017).
Digitalization & Energy. International Energy Agency. Paris

5 Digitalisation of demand side

The energy consumption for heating and cooling in industry, residential, commercial and service buildings accounts for 50% of the total final energy demand (European Commission, 2016). Fossil fuels still have the highest share in the fuel mix (78%), where natural gas dominates with 43% (Kranzl et al., 2022). Moreover, the current high volatility of fossil fuel prices is increasing pressure for the green transition to tackle climate change by decarbonizing heating and cooling in buildings and to secure a fair energy price for end-users.

With regard to district heating (DH), the technical and economic challenges of phasing out fossil-fuel energy generation require a reduction in DH operating supply and return temperatures to 55/25 °C, which accords with the definition of 4th Generation District Heating (4GDH) given by Lund et al. (2014). With regard to district cooling (DC), 4th Generation District Cooling (4GDC) has recently been introduced by Alberg Østergaard et al. (2022). Considering typical design supply temperatures of 4–7 °C and a delta-T of 9–12 °C (which is smaller than in DH networks), 4GDC aims to empower cross-sectorial integration in the energy system where cooling will play an important role. Jangsten et al. (2020) increased the focus on higher-temperature cooling to enable the utilization of free cooling sources and maximize the efficiency of heat pumps. This will ensure the full exploitation of the potential of renewable energy sources and excess heat recovery without compromising the economic competitiveness of district energy systems.

District energy (DE) systems can be ideally divided into three main parts: heat and cooling generation plants, distribution networks, and substations/end-users. DE operators have been working extensively on improving the efficiency of heat and cooling generation and distribution. They have the ability to monitor and control the heating/cooling supply plants and networks, which they can use to optimize the supply temperature and the pressure in the networks. They have also developed reliable protocols and strategies for identifying suboptimal operations and making fast interventions in the case of faults that may prevent the fulfilment of the end-users' energy requirements.

In contrast, substations and thermal distribution systems to supply space heating (SH), space cooling (SC), and domestic hot water (DHW) demands have typically been overlooked (as these are not under the control of DE operators) despite the fact that the return temperature in the networks is exclusively the result of how these systems are controlled and operated. Historically, buildings had a low level of monitoring and control, and building owners and building service personnel tended to perceive them as "black boxes". This led to the situation in many buildings where detecting faults is typically only carried out in response to customers' discomfort and complaints. This situation affects the overall system efficiency and inevitably results in unnecessarily high operating temperatures in the heating system (Gadd & Werner, 2015; Werner, 2017) and unnecessarily cold operating temperatures in cooling systems. Systems like these in the existing building stock therefore represent one of the challenges in the transition towards 4GDH and 4GDC.

The recent introduction of new policies to stimulate the digitalization of the demand side has opened new opportunities for monitoring and controlling heating and cooling systems in buildings, paving the way for the sustainable transition of the DE industry. This section of the report aims to benchmark the current status of digitalization in buildings across several countries and in various settings and to document with case studies and experience how low temperatures, improved operation, and fault detection in substations and thermal distribution systems can be achieved even with the current level of digitalization in buildings.

5.1 Future role of demand-side digitalization

The flexibility and capabilities of district heating and cooling networks make them essential for supporting the decarbonization of the energy system in Europe and globally. According to Averfalk et al. (2021), transitioning from high to low-temperature district heating could reduce costs by 14 billion EUR/year in Europe. However, one of the major challenges is ensuring that existing buildings can be comfortably heated with lower operating temperatures.

There is a common misconception that existing buildings cannot operate with temperatures lower than their "design" temperatures without undergoing significant retrofitting to their heating systems or building envelopes. This is not so. A recent comprehensive review has shown that it is possible to achieve low-temperature heating without building renovation (Skaarup Østergaard et al., 2022). Heating systems are typically designed to ensure indoor comfort in extreme outdoor temperatures without any heat gains. However, normal operations rarely exceed 80% of the design heat demand (Lund et al., 2018). Moreover, system components come in discrete sizes, and the heating elements and heat exchangers selected are usually designed to handle the most extreme conditions and are therefore oversized for most of the year (Lauenburg, 2016). The result is that existing buildings from different periods in Denmark, such as those from the 1930s (Skaarup Østergaard & Svendsen, 2016b), the 1950s (Skaarup Østergaard & Svendsen, 2016a), and the 1980s (Skaarup Østergaard & Svendsen, 2017), have all been documented as able to meet their heat demand with low operating temperatures. Similarly, Jangsten et al. (2020) found that 87% of the radiator systems in 109 multi-family buildings in Gothenburg were capable of operating at supply temperatures below 55 °C with an outdoor temperature of 5 °C.

According to a recent survey conducted in Denmark, return temperatures of 25–30 °C and 30–35 °C can be maintained in single-family and multistorey buildings respectively with well-controlled and well-operated heating systems (Skaarup Østergaard et al., 2021; Rämä et al., 2019). Despite attempts to reduce operating temperatures, large DH networks are unable to maintain an annual average return temperature below 30 °C due to poorly performing substations and heating systems (Averfalk & Werner, 2018). Nearly two-thirds of errors and faults are associated with incorrect temperature regulation and control on the demand side of the substations (Averfalk et al., 2021). Such high unintended return temperatures can reduce the hydraulic capacity of DH networks, leading DH operators to compensate during periods of high heating demand by raising the supply temperature or increasing the differential pressure. Neither solution tackles the real cause of the high return temperatures and both inevitably have the impact of increasing overall operating costs. These increased costs delay investments in renewable energy sources and may lead to negative environmental impacts when high-cost heat from peak boilers is used.

The "Digital Roadmap for District Heating & Cooling" (Euroheat & Power, 2019) provides an overview of the current state, impact, goals, and difficulties of digitalizing the DE industry. It emphasizes the potential advantages of automated monitoring and advanced analytics for the control and operation of heating/cooling systems in buildings. The shift from labour-intensive manual readings to cost-effective automatic data collection provides new opportunities to gain more precise insights into heating system control and operation. Volt et al. (2022) highlight the technical and economic robustness of smart meters, thermostats, and sensors, which have a technology readiness level (TRL) of 9. This means that the current level of digitalization can already lead to improved operation of heating and cooling installations, paving the way for future software development with artificial intelligence (TRL 3–6) and digital twins (TRL 3–7).

5.1.1 The European Digitalization Roadmap

Digitalization of the demand side was stimulated in Europe by the EU Directive 2012/27/EU on energy efficiency (EED) – updated in 2018 with the EU EED directive 2018/2002 – to convey precise information to end-users about their energy consumption and the effect of energy efficiency actions (European Commission, 2018a; European Commission, 2018b). The EED directive 2018/2002 bound EU member states to install only remotely readable devices after October 2020 and to have all existing meters remotely readable by January 2027.

The direct heating (or cooling) as highlighted in Figure 5.1, meters show the energy delivered to (or extracted from) a building or an apartment based on the energy balance calculated using the mass flow rate of the fluid measured through a closed circuit and the operating supply and return temperatures. In multi-apartment buildings with vertical riser systems and centralized heat supply, where direct metering is not feasible, the EED also requires the installation of remotely readable submeters (commonly known as heat cost allocators) to enable fair distribution of the space heating and DHW consumption between the apartments. In a review of heat accounting and cost allocation in residential buildings, Canale et al. (2019) describe how direct metering is not cost-effective in old buildings and heat cost allocation is typically the feasible solution. Figure 5.2

illustrates a typical heat cost allocator mounted on a radiator used to estimate the heat emitted from all heating elements and divide the building's heating supply between each apartment (Skaarup Østergaard et al., 2019). It has been reported that 16 out 27 EU member states already have a national regulation for heating and hot water cost allocation based on a variable share from metered energy. On average, this share amounts to 50–70% of the total building heating cost; the remaining cost is distributed as a fixed cost between the apartments (European Commission, Joint Research Centre, Castellazzi, 2017).

The EED philosophy is to ensure billing transparency and increase end-user awareness about energy consumption. This can lead to energy savings due to changes in occupant behaviour. Cholewa et al. (2022) report that heat consumption in a residential building with heat cost allocators was 24% less than in a comparable building without heat cost allocators.

Similarly, building automation and controls (BACS) – defined as all products and engineering services for automatic controls and management to achieve energy-efficient, economical, and safe operation of building services – have become an active, manageable part of the energy system, ensuring more flexible options and paving the way to energy savings in buildings due to smart operation. One of the main objectives of the new revised EU Energy Performance of Building Directive (EPBD) 2018/844 (European Commission, 2018b) was to achieve the EU's ambitious goal of a low-carbon economy by 2050, and EU member states are integrating this into their national goals. On the basis of the EPBD, Grözinger et al. (2017) have shown that the introduction of BACS to optimize building systems focusing on two possible scenarios defined as "Get the basics right" and "High-performance packages" could lead to energy savings in the range of 14–34% and 33–49% respectively, depending on the reference building considered.

Figure 5.1: Typical meters in buildings for heating/cooling, water and electricity

Figure 5.2: Heat cost allocator mounted on radiators

5.1.2 Regulation framework in South Korea

South Korea has a lot of large-scale apartments and commercial building complexes in cities and districts with high heating demand. The government has continued to support the DE business in its role of distributed power generation utilizing the various waste and unused heat near cities. To promote and sustain the DE industry, the government is implementing policies such as mandatory usage of district heating in urban districts with a certain minimum heat demand, switching to a more environmentally friendly power dispatch by expanding liquified natural gas (LNG) power generation and offering heat cost compensation for variable costs in fuel prices. As a result, district heating charges are generally lower than in other countries as depicted in Figure 5.3, which contributes to reducing carbon emissions. Moreover, the South Korean government is taking further steps to reduce carbon emissions from the building sector, which currently constitute 25% of the country's total emissions. One way it has done this is by implementing policies that improve energy efficiency and insulation in buildings, resulting in a 43% reduction in heat demand since 1985 as shown in Figure 4. To continue this trend, the government will require new buildings to meet

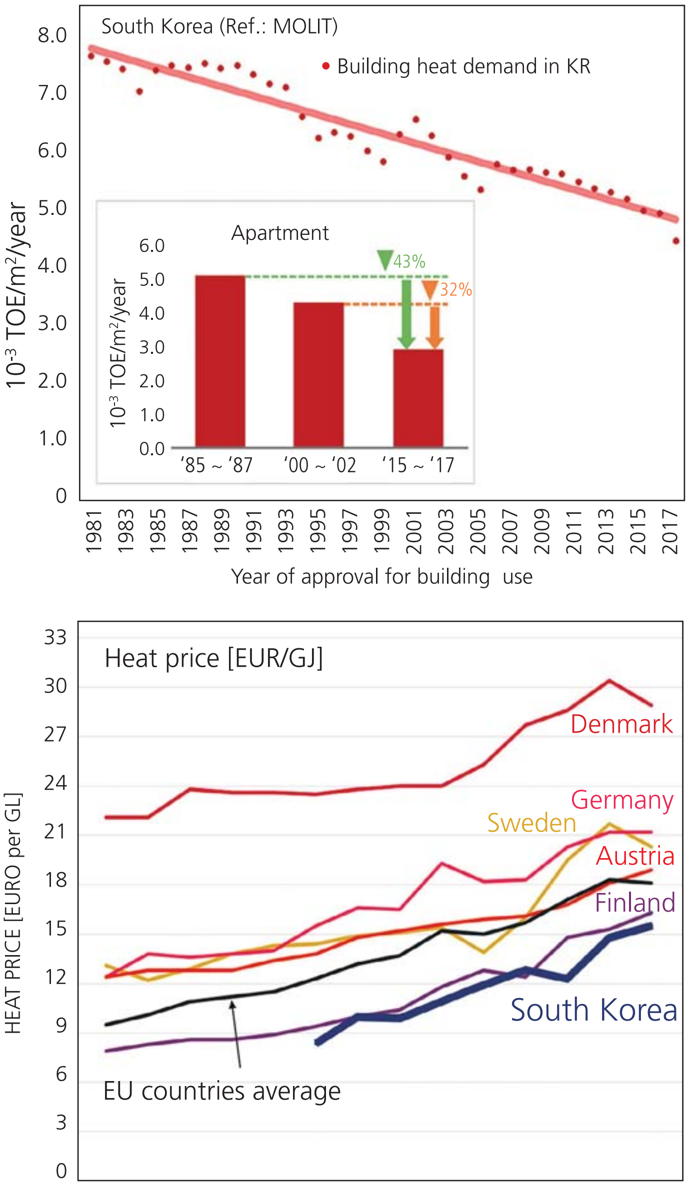


Figure 5.3: Domestic heat price comparison (BOTTOM), Building heat demand in South Korea (TOP)

zero-energy building (ZEB) standards starting in 2025. These standards mandate the use of Building Energy Management Systems (BEMS) or remote submetering systems and will apply to private buildings larger than 1,000 m² and apartments with more than 30 households, as well as all buildings over 500 m² by 2030. The government will also offer incentives for buildings that meet these standards, an initiative which is expected to increase demand for smart submeters and create new business opportunities in the energy demand management market.

Figure 5.4 illustrates the typical layout of a secondary side district heating system in South Korea, including the locations of heat meters in both heat suppliers and households. Most central substations serving 300–400 households have four pipelines for space heating and domestic hot water. Central substations built after 2010 have a two-stage domestic hot water system, which increases energy efficiency by using the return line from the primary side space heating system to preheat city water for domestic use. Recently, the Korea District Heating Company (KDHC) has offered subsidies for upgrading to two-stage domestic hot water systems in older central substations. All apartment buildings in South Korea use underfloor heating, so only one SH submeter is used to measure heat usage. By law, all central and district heating households must install an SH submeter. Prior to 2014, either a flow submeter or an energy submeter could be used, but since 2014, only SH energy submeters have been allowed and they must be replaced every 5 years. Many apartment buildings also use a central supply of domestic hot water (DHW), so every household must also have a DHW submeter installed. These DHW submeters only measure flow and must be replaced every 6 years.

Heat meters for district heating (DH) suppliers are installed in all central substations, and many of these have recently been upgraded to use 4G long-term evolution (LTE) communication for real-time usage monitoring every hour. On the end-user side, automatic meter reading (AMR) submeters have been installed in most apartments since the mid-2010s for the purpose of billing, and it will be mandatory for all apartments to have advanced metering infrastructure (AMI) by 2025, although there is no requirement to replace existing manual reading meters. The use of SH and DHW smart meters is currently being evaluated through small-scale pilot studies involving hundreds of households in order to determine their benefits and drawbacks and to develop related services.

Remote meter reading is not yet mandatory in South Korea, so about 40% of district heating households still manually check their usage once a month for billing purposes. When submeters are read manually, SH and DHW readings are collected once a month, while with remote reading, they are collected every hour or once a day. The heat meter for the district heating company is read every hour. The cost of heat used for the entire building, as measured by the district heating company, is distributed among households based

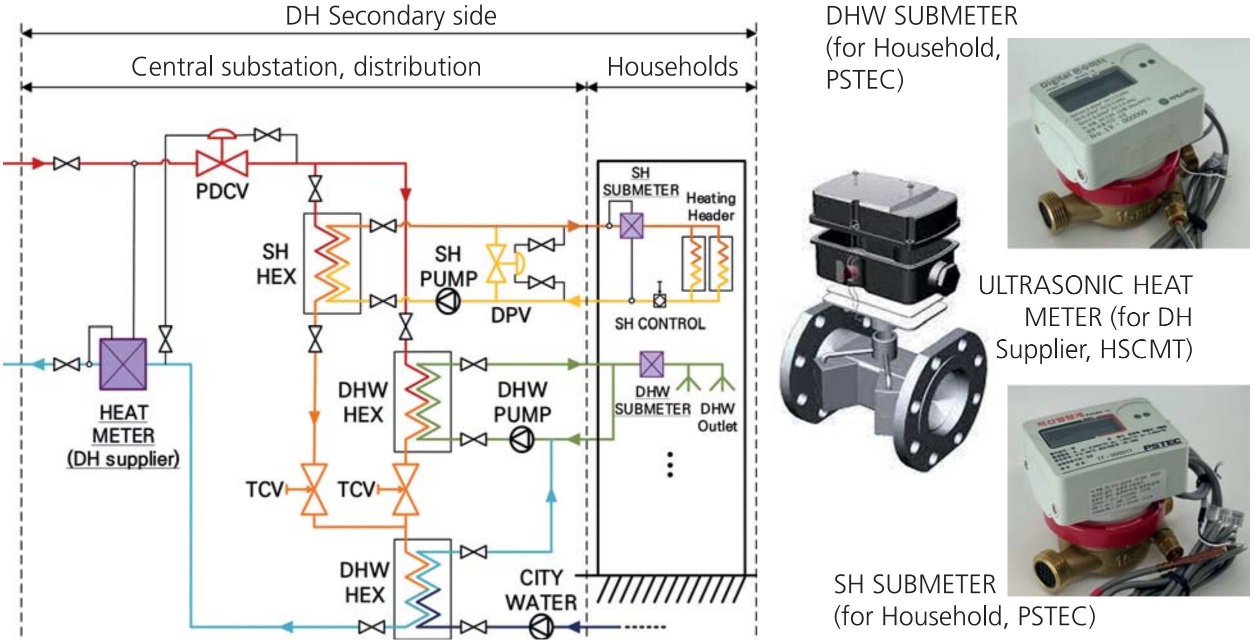


Figure 5.4: DH Secondary side schematics in Korea (LEFT), Heat meters for supplier and household (RIGHT)

on their submeter readings, with any remaining heat loss being accounted for as well. Households are usually billed monthly for space heating (during the November to April period) and for domestic hot water. The latter charges include fees for basic maintenance and heat losses.

The handling of energy data and privacy protection are ongoing issues. After the amendment to the "Personal Information Protection Act" in 2020, SH and DHW submeter data can be considered personal information that can identify individuals when combined with other data. As a result, South Korea is closely following the developments of the European Union's General Data Protection Regulation (GDPR). At present, as long as the current collection period and billing metrics are maintained, there is no need to obtain additional consent to use personal information for billing purposes because consent was already obtained when occupants moved into the building. However, if the collection period or metrics change, separate consent will be necessary to use the personal information. Pseudonymous or anonymized data can be provided to third parties for statistical processing, scientific research, and public record-keeping without consent.

5.1.3 Regulation framework in China

The DH industry in China is developing fast. Over the last 10 years, the average expansion rate of the area covered by DH has been about 9% per annum. In 2020, the DH area in the northern cities of China reached 15.6 billion m², with a total energy consumption of 214 million tonnes of standard coal equivalents (tce), where 1 tce = 29.3076 GJ (Building Energy Research Center, 2022). DH in China is currently undergoing the transition from fossil fuels to more sustainable energy sources, with the aim of achieving carbon neutrality in 2060 (Fu et al., 2021). The digitalization of the DH system also reflects the huge scale and the complex layout of the Chinese DH network.

The general layout of a typical Chinese DH system is shown in Figure 5.5. If there is a long distance between the heat generation site and the consumer, two or more substations can be established to compensate for losses in the flow and the pressure of the DH supply. The secondary substation located in the secondary network (the distribution line) is usually in charge of regulating the DH supply parameters to match the demand on the consumer side. The secondary substation often supplies a group of consumers with similar requirements for temperature, Flow rate or medium, and the scale of such groups of consumers can be tens or hundreds of thousands of m² of heating area.

The digitalization transformation therefore starts and focuses mostly on the secondary substations instead of directly on the heat consumer side. The schematics of DH control implementation in China are shown in Figure 5.6. The parameters

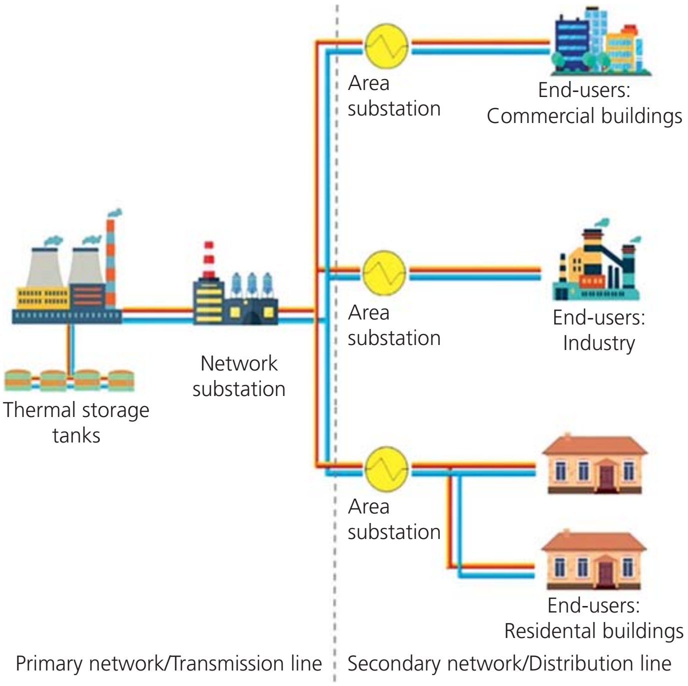


Figure 5.5: General layout of a Chinese DH system (Zhang et al., 2021)

measured and recorded are supply/return temperatures, pressure, flow rates, and heat consumption. To avoid the huge cost of labour and facility investment, temperature sensors are not usually installed in every household. Only critical users such as those at the corner of a building, or on the top or bottom floor have indoor temperature sensors. The temperature for feedback control is calculated by integrating typical indoor temperatures with certain weightings. The fundamental concept is to guarantee the critical users' indoor temperature above the lower boundary of the comfort requirement so that other users in the building have a higher temperature at least.

Along with the development of the DH industry in China, a large number of DH companies have applied the SCADA platform for data visualization and remote control. More cutting-edge technologies, such as cloud computing, machine learning, and IoT techniques are also spreading in the smart DH establishment. However, data acquisition and storage have not yet been standardized on a national scale.

Recently, some regions have formulated their own detailed directives on smart DH. For example, Heilongjiang Province published the "Technical regulation of smart district heating in cities" in 2020, which specifies that data should be collected from the heat source, the distribution network, the substations, and the demand side of a smart DH system. The time interval should be within 30 minutes for the collection of weather data, the thermal parameters on the building side, and the indoor temperatures, while other parameters should be measured and recorded at intervals of no longer than every 10 minutes (DB23/T 2475, 2020). The same year, Hebei province issued a regional smart district heating regulation which requires that the operational data of the heat source and substations should be collected at least every 30 seconds, while the indoor temperature should be measured every hour (DB13(J)T 8375, 2020). It should be noted that different regions share some commonalities in their DH data collection, while slight differences still exist. The essential DH parameters for smart control and the process of DH data collection need further national clarification to make the control more efficient and avoid extra investment due to unnecessary meter installation or data storage.

Most DH consumers pay for their heating bills based on the heating area in use, not the actual heat consumed. Although China has started to promote household heat metering since 2000, only a limited number of pilot sites are currently using it due to the complexity of the facility installation and maintenance. Heating bills only include the space heating expenses, and the DH companies charge once a year. In the various regions with different outdoor climates, the heating season varies from 4 months to 7 months.

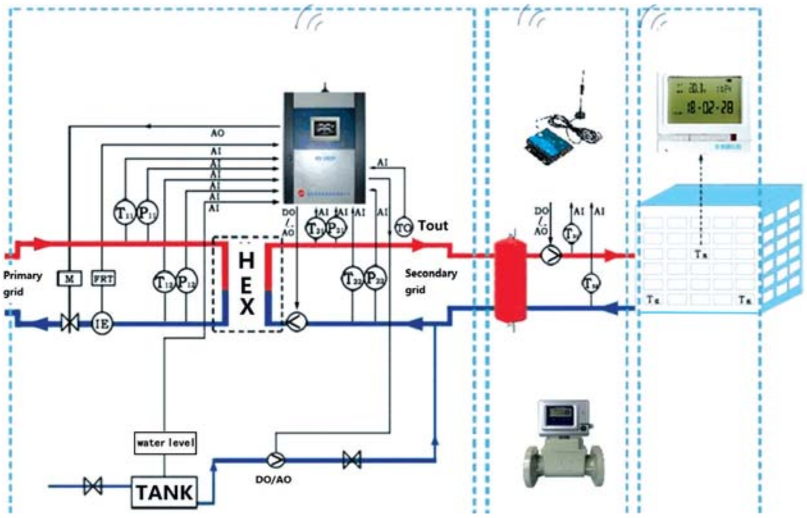


Figure 5.6: DH control schematics in China

5.2 Current status and experiences

The reduction of operating temperatures in buildings is critical for district heating operators, both technically and economically. The potential for improvements in heating systems and components continues to increase with the greater availability of high-resolution data and enhanced software developments. This section presents a collection of the main experiences and best practices for substations, SH, and DHW systems in various countries. The aim is to show that despite local differences the current level of digitalization and data available can be already used to assess the performance of systems and components and help ensure improved operation, without waiting for more advanced AI and software solutions to be implemented in all building stock in the future.

5.2.1 Heat cost allocators for low-temperatures in multi-apartment buildings

Heat cost allocators are a robust technology used in multi-family buildings to allocate and fairly distribute the total cost of building heating consumption among end-users. In Europe, they are regulated by the European standard EN 834, and as discussed in section 5.1.1, the European Energy Efficiency Directive (2018/2002) binds member states to replace and/or install remotely readable meters and submeters to ensure billing transparency in multi-apartment buildings connected to DH networks or with central heating systems. While ensuring fair energy bills was one of the principal objectives of the Directive, gathering and using this data cost-effectively provides new opportunities for building services. Benakopoulos et al. illustrate this by using data from heat cost allocators to estimate a new minimized supply temperature for residential buildings and to encourage end-users to keep all radiators in operation (Benakopoulos et al., 2022; Benakopoulos, Tunzi, et al., 2021).

An innovative stepwise methodology has documented how existing data from heat cost allocators, energy meters, and temperature sensors installed on the supply/return pipes of the secondary side of the space heating heat exchanger can be combined to improve the operation of residential multi-apartment buildings (Tunzi et al., 2023). The heat cost allocators are used first to estimate the distribution of the total energy consumption measured by the central energy meter and then to identify the apartment and radiators with the highest energy consumption. Measurements for December and January are used for the analysis to minimize the impact of solar gains in the buildings. Assuming a typical indoor temperature of 22 °C, and using a heating degree days distribution, it is possible to estimate the heat loss coefficient for the critical room to estimate the heat demand based on the outdoor temperature. The measurements from the temperature sensors define the actual operating temperature difference in the space heating systems; the lowest measurement is then used as the constraint to calculate the minimum required supply temperature for the critical radiator based on outdoor temperature using Equations 1 and 2.

$$\frac{Q(T)}{Q_0} = \left(\frac{LMTD(T)}{LMTD_0}\right)^n \tag{1}$$

$$LMTD(T) = \frac{T_{sup}(T) - T_{ret}(T)}{ln\left(\frac{T_{sup}(T) - T_{in}}{T_{ret}(T) - T_{in}}\right)} \tag{2}$$

where $Q(T_{out})$ is the specific radiator heating demand (kW) based on the outdoor temperature, LMTD (T_{out}) is the logarithmic mean temperature difference (°C) between the radiator surface and the indoor temperature at the specific outdoor temperature, Q0 is the heat capacity of the radiator (kW), LMTD0 is the logarithmic mean temperature difference (°C) at set reference design temperatures, n is the radiator exponent (in a typical radiator this is 1.3), and T_{sup}, T_{ret} and T_{in} are the supply, return and indoor temperatures (°C).

Figure 5.7 gives a general overview of the applicability of the proposed methodology, linking the low-temperature operation in a multi-apartment building in Viborg (Denmark) with the temperature control curve for the district heating network. The supply temperature required in the building is below 55 °C for outdoor temperatures equal to or higher than -1 °C – when almost 80% of the total space heating consumption occurred in 2021 (Tunzi & Svendsen, 2022). This highlights that the district heating operators can maintain a supply temperature in the range of 55 - 60 °C (depending on the DHW requirements) for the majority of the heating season and need to increase it only for limited periods of time.

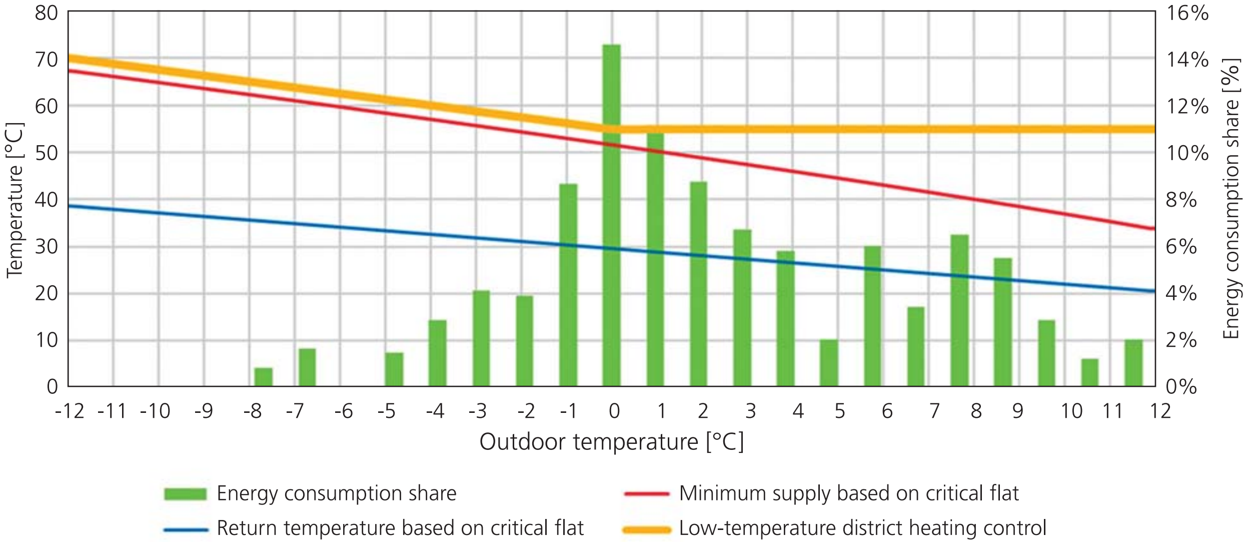


Figure 5.7: Minimized operating temperatures in a multi-family building and DH low-supply-temperature control curve (Tunzi & Svendsen, 2022).

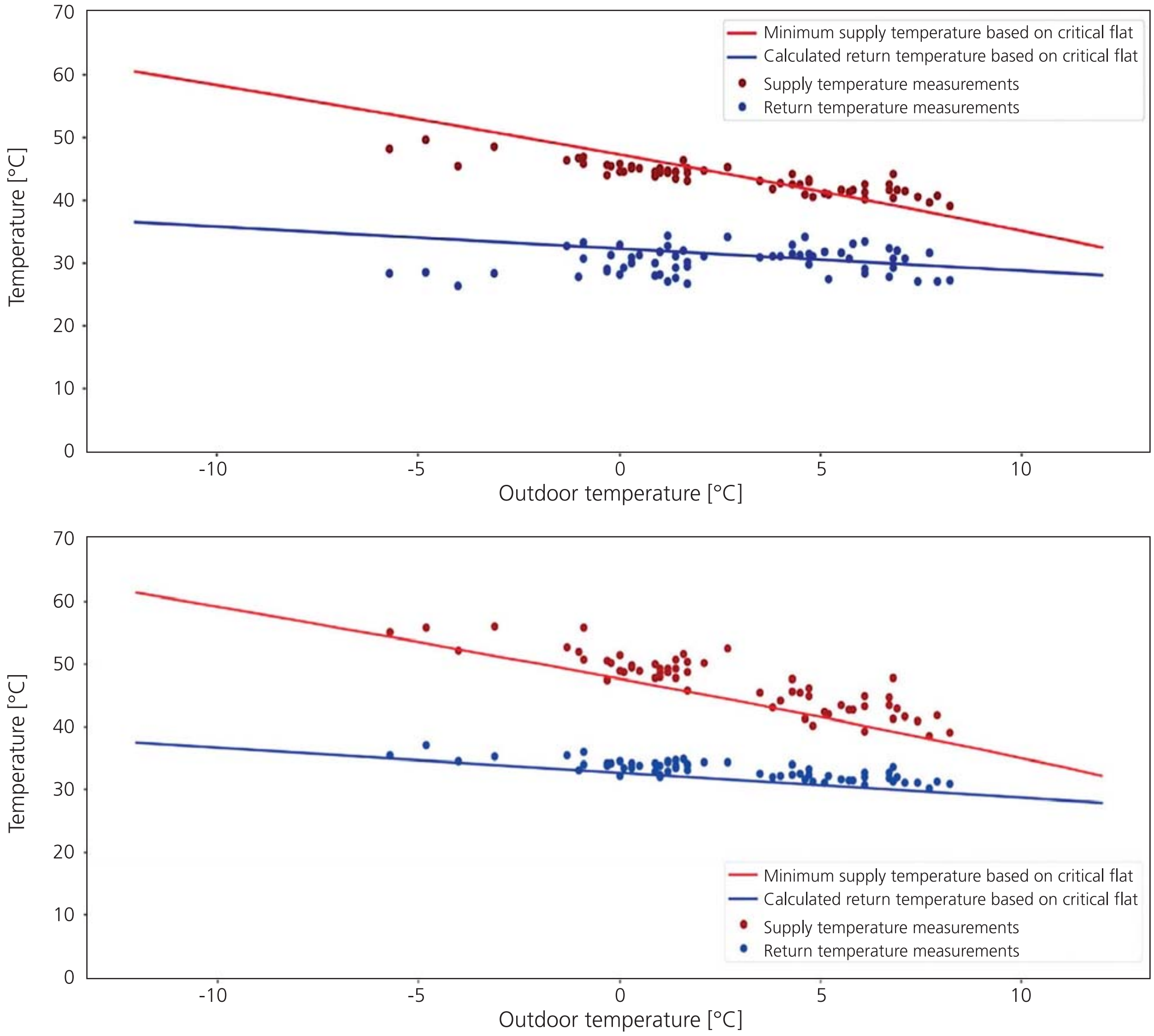


Figure 5.8: Minimum supply temperature based on the critical radiators in Building 1 (TOP) and Building 2 (BOTTOM) compared to the daily average measured supply temperature in December 2021 and January 2022 (Tunzi et al., 2023).

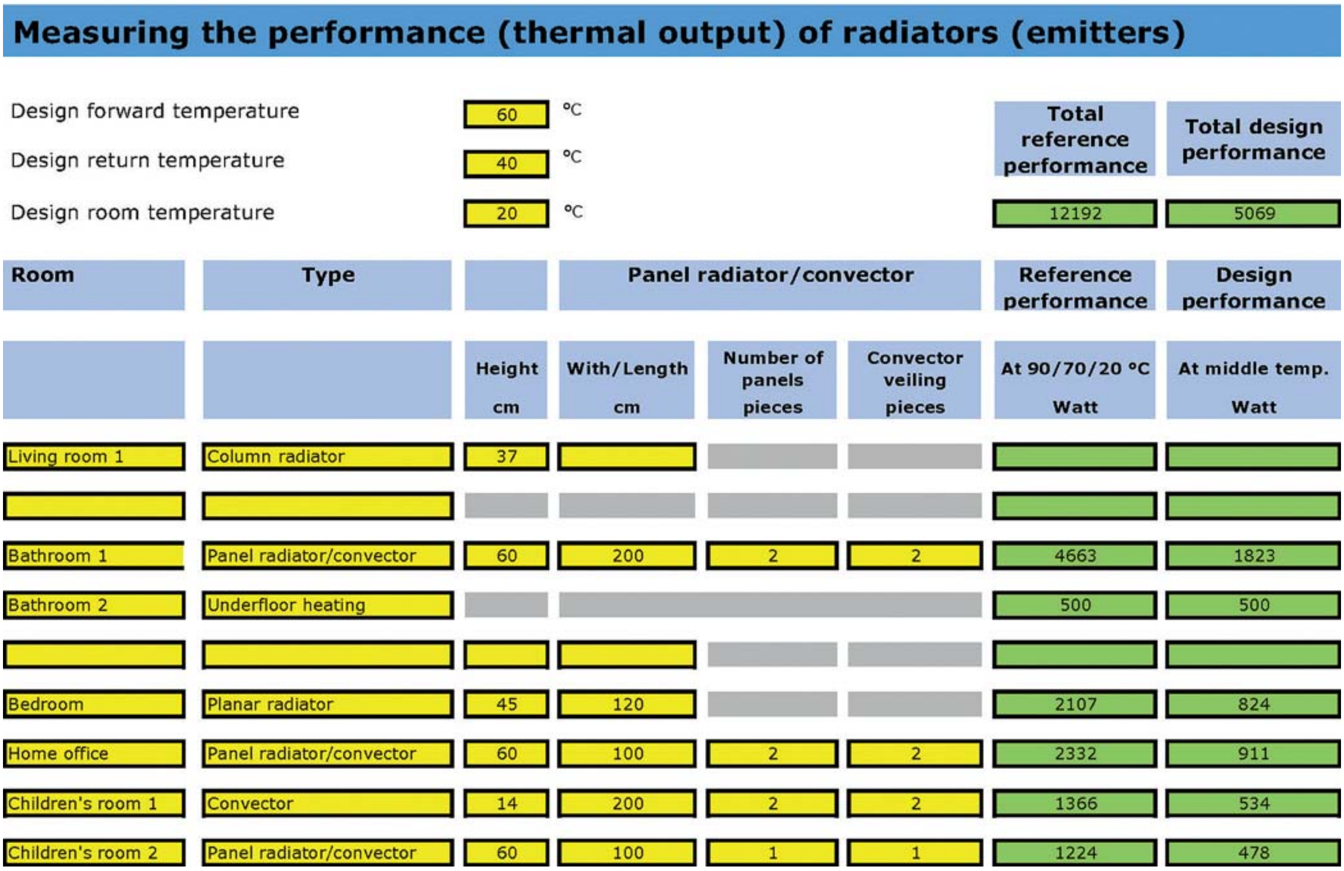
Figure 5.8, measurements from two Danish multi-family buildings connected to the local district heating network in Viborg were compared with the newly calculated control curves. Building 1 is from 1943 and Building 2 is from 1992. Respectively, they have 24 and 14 apartments, a total of 127 and 76 radiators with heat capacity of 192 and 102 kW at reference temperatures of 90/70 °C. Neither building had undergone any deep energy renovation.

The results show a good alignment between the calculated minimum supply temperature curves based on the critical radiators and the measured daily average supply temperature in the space heating systems in December 2021 and January 2022. Supply temperatures in the range of 47 - 50 °C were enough to ensure the expected comfort in both buildings at an outdoor temperature 0 °C (Tunzi et al., 2023).

The application of the proposed methodology is a pragmatic strategy for improving the current operation of the space heating systems in residential buildings. It underlines the idea that there is a non-uniform heat distribution among flats, with some flats stealing heat from adjacent ones. This is typically caused by end-users keeping some or all their radiators off, different apartment locations and set-points, and in some cases specific faults in the settings or components (Benakopoulos et al., 2022; Canale et al., 2019; Dell'Isola et al., 2018; Siggelsten, 2018). A uniform heat distribution between flats would enable a further reduction in the operating temperature. This will be one of the future steps in the building servicing, when the current data is integrated with indoor temperature sensors to ensure continuous monitoring of the systems and help building service personnel locate and fix faults and end-user misbehaviour whenever they occur.

5.2.2 Estimation of reference thermal output of heat elements

The methodology described in the previous section uses as one of its inputs the heat capacity of radiators at reference temperatures. However, the thermal output of radiators may not always be available for the entire building or even for a single flat. In this case, the thermal output can be



Measuring the performance (thermal output) of radiators (emitters)

Design forward temperature 60 °C
Design return temperature 40 °C
Design room temperature 20 °C

Total reference performance: 12192
Total design performance: 5069

Room	Type		Panel radiator/convector			Reference performance	Design performance
		Height cm	With/Length cm	Number of panels pieces	Convector veiling pieces	At 90/70/20 °C Watt	At middle temp. Watt
Living room 1	Column radiator	37					
Bathroom 1	Panel radiator/convector	60	200	2	2	4663	1823
Bathroom 2	Underfloor heating					500	500
Bedroom	Planar radiator	45	120			2107	824
Home office	Panel radiator/convector	60	100	2	2	2332	911
Children's room 1	Convector	14	200	2	2	1366	534
Children's room 2	Panel radiator/convector	60	100	1	1	1224	478

Figure 5.9: Overview of the tool interface

estimated by a simple tool (Excel) developed on the basis of on a large number of radiator catalogues and laboratory experience.

The tool provides a calculation procedure that uses the physical dimensions and characteristics of typical radiators as input. For a panel radiator, for example, we need the height, the length, the number of panels, and the amount of convector veiling to estimate the performance in the reference conditions, i.e., water temperatures of 90/70 °C and room temperature of 20 °C. The tool interface is presented in Figure 5.9 and can be freely accessed through this link:
https://www.teknologisk.dk/iea-dhc-annex-ts4-digitalisation-of-district-heating-and-cooling/45243

5.2.3 Electric radiators thermostats

Achieving low return temperatures from buildings is fundamental to increasing the hydraulic capacity of heating networks and giving district heating operators the flexibility to minimize the supply temperatures. An innovative electronic radiator thermostat has recently been developed and tested in two Danish multi-family buildings (Tunzi et al., 2022). The innovative part of the new electronic thermostat is an additional return temperature sensor and an algorithm to control the operation of the valves and maintain the maximum set point for the return temperature. Moreover, by controlling the flow through the radiator, the electronic thermostat provides automatic hydronic balancing. The thermostat prototype is presented in Figure 5.10.

In both buildings, the tests showed an improvement in the average return temperature that was maintained around the setpoint of 35 °C, increasing the overall temperature difference in the substation. The thermostats were also remotely readable, which made the monitoring easier. During the test in one of the buildings, just two radiators (out of 175) had uncontrolled high return temperatures (as shown in Figure 5.11), and they caused an increase in the overall return temperature in the building of 5 °C. In one, there was a manufacturing problem with the valve; in the other, the end-user had tampered with the thermostat. After locating and fixing these faults, the operation of the heating systems improved, and the return temperature in the building was restored to 35 °C (Tunzi et al., 2022).

Figure 5.10: Example of the prototype thermostat and return temperature sensor and how they were installed on the supply (left) and on the side of the radiator (right) in the test buildings.

5.2.4 Automatic fault detection and diagnosis

Faults on components and installations in the end-user substations in district heating are currently among barriers for achieving a system with optimal low-temperature operation. Faults and malfunctioning installations result in poor cooling of DH water, high return temperatures, and therefore unnecessary heat losses in the system. Moreover, they limit the potential for cost-effective integration of low-grade heat, such as excess industrial heat. With this background, efforts have been made for decades to utilize data from the heat meters associated with the individual installations for fault detection and diagnosis (FDD). Today, heat meter data can be resolved hourly and remotely read – two factors that strongly increase the potential impact of FDD in automated setups. There is currently a flourishing focus in the literature on the development of appropriate and implementable analysis techniques as well as interest among individual utilities.

The most important of fault types to be identified and corrected are those associated with the poor performance of the substations. These types of faults include fouling of heat exchangers, deteriorating valves, stuck valves, adjustment errors, and high setpoint values in the customer system. When such faults are corrected, installations improve their operation and reduce their return temperatures.

FDD in DH installations also includes the detection of broken, drifting, or misplaced sensors. For example, Yliniemi et al. (2005) presented a way of detecting faults in temperature sensors by

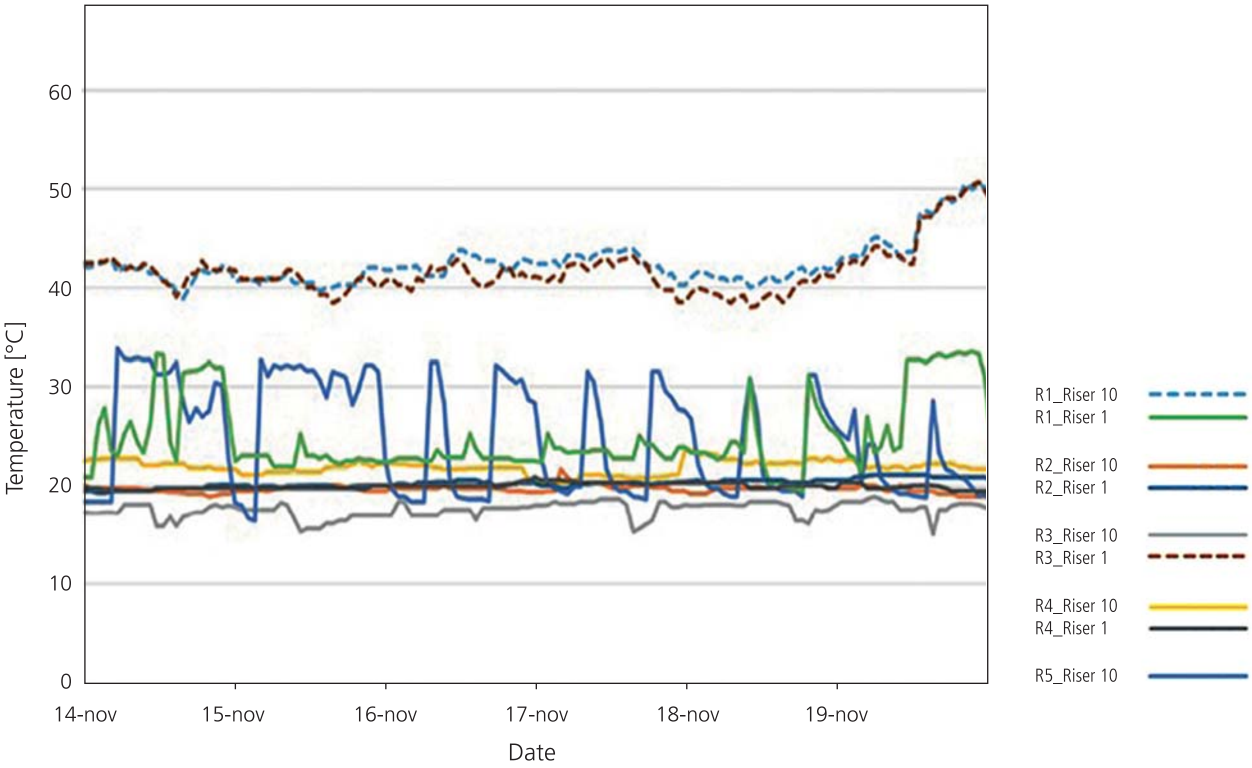


Figure 5.11: Return temperature measurements from some of the radiators in the multi-apartment building.

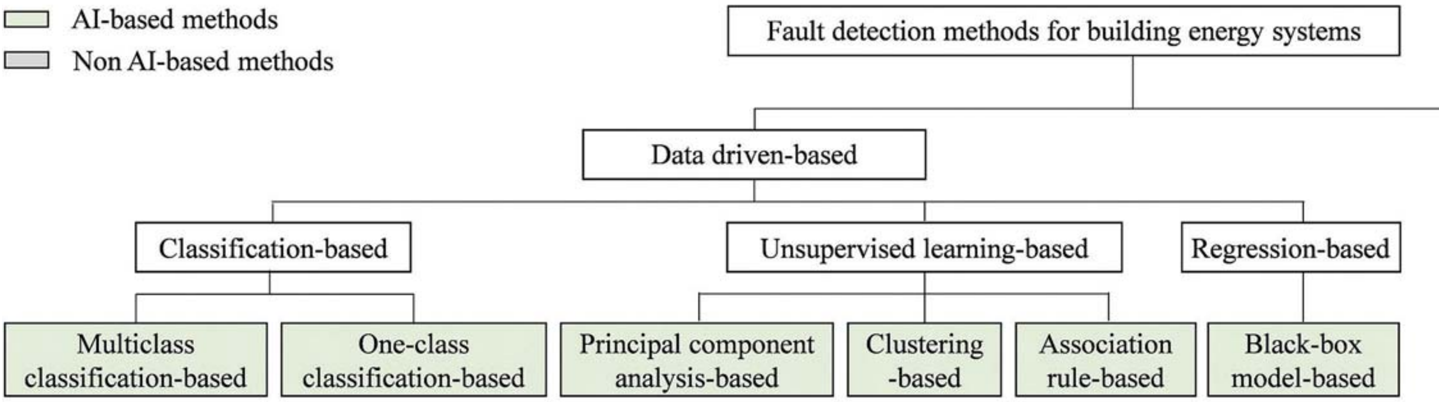
analysing the noise amplitude. Typical temperature sensor problems include drift, noise, and mechanical problems such as cut cables, short circuits, or faulty installation. However, increases in sensor noise associated with incorrect installation can be difficult to detect and, if the sensor is used for this purpose, it can result in controller problems, such as faulty billing or discomfort for the consumer. Sandin et al. (2013) also pointed out that there are several components of an energy meter that can change behaviour over time. This can affect not only flow and temperature sensors, but also electronic sensors (amplifiers and voltage reference sensors). Since there is no sudden, abrupt change associated with such drifting, these faults are difficult to detect using basic limit checking and outlier analysis. Nevertheless, Sandin et al. showed how drifting can be detected using cumulative sums. The cumulative sum of several substations can be qualitatively compared once a normalization constant has been calculated for each, which enables the ranking of installations and gives an indication of the sensors most likely to drift.

Furthermore, substations with oversized or misconfigured instrumentation can result in abnormal quantization of the data. This phenomenon, as well as issues of a lack of precision due to inappropriate rounding, can also be detected directly using the proposed analysis methods, e.g., the technique based on ranking with entropy described by Sandin et al. (2013).

5.2.4.1 Methods

The decrease in the price of sensors, together with the leaps in ICT infrastructure, computer power, and data analysis techniques in recent decades, has paved the way for the introduction of FDD in buildings connected to district heating. A number of methods are available for FDD in building installations, as summarized in the study by Zhao et al. (2019) in Figure 5.12.

Two different families of approaches can be distinguished, namely knowledge-driven-based approaches and data-driven-based approaches, as summarised in Figure 5.12. The oldest approaches are knowledge-based. In these, expert knowledge is needed to assess whether a building installation is performing optimally or not. The simplest ones are rule-based approaches by which measurements are evaluated against certain rules – e.g., if the return temperature of a building is higher than the supply temperature, something is obviously wrong.



Gadd and Werner (2014) introduced a new method using temperature difference signatures for fault detection. The signature consists of a diagram in which the daily average temperature difference is plotted against the outdoor temperature, approximating an inversely proportional relationship that forms the basis of statistical outlier detection. Gadd and Werner demonstrated that the method was effective for 140 substations with hourly data for one year. It worked as long as the outdoor temperatures did not exceed 10 °C and most of the substations in a data set performed well with a correct temperature difference. This established a fast way of continuous commissioning with the capability of detecting faults in customer secondary systems within one day. Furthermore, inspection of the temperature difference signature enables quality assurance of any repairs carried out.

In a subsequent study, Gadd and Werner (2015) used similar annual heat meter data to identify three types of faults: inappropriate load patterns, low annual temperature differences, and poor control of substations. The fault groups were identified by manual analysis, but the authors say the process could easily be automated. They found faults in 74% of the 135 substations analysed.

Other knowledge-based approaches make use of white-box or grey-box models of the building installation. The actual behaviour of the building (e.g., the return temperature) is then compared with the behaviour expected by the model. These approaches demand sufficiently accurate models of the buildings investigated, and it can be very challenging to build these models, because a lot of knowledge about the system might be required which is not always available. This often makes it hard to scale this kind of approach for general applicability.

More recent approaches are data-driven. These approaches require very little or no information about the buildings investigated. Machine-learning techniques are used to build models of building behaviour based on historical measurement data, and the actual behaviour of the building is then compared with that predicted by the model. The advantage of these approaches is that there is much less need of specific building information, but very large amounts of data with sufficient resolution and quality are needed for these data-driven approaches, which might also be a burden. A number of different methods, ranging from simple to more complex, were described and demonstrated by Sandin et al. (2013) using Swedish utility data. Limit checking is a basic method where constant thresholds are defined or based on historical variations of the data, and an alarm is generated when the test fails. An example could be that the primary supply temperature should never exceed the supply temperature of the network. While limit checking was already in use in the industry, outlier detection was further developed in the study. This is a useful complement to limit checking tests since it does not involve ad-hoc thresholds, which can be difficult to select in an implementation context. The next step was to describe and develop probabilistic models that consider several other variables, including analysis of the primary temperatures and the flow in addition to the power. Statistical tools were formulated to provide input models to the probabilistic outlier detection methods, in particular using linear regression, bimodality analysis, cluster analysis, and correlation analysis. This enabled a data-driven probabilistic methodology that can handle complex effects not easily handled by the dynamic equations of buildings and substations. These include intraweek and intraday cycles, human behaviour, weather conditions, and interactions with other systems such as ventilation. Such models can

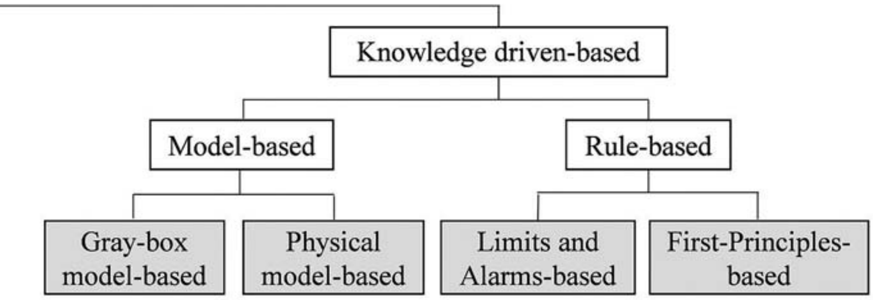


Figure 5.12: FDD techniques for building installations (based on Zhao et al., 2019)

also compare neighbours in the network by exploiting redundancy in the supply temperatures measured by different substations.

Johansson and Wernstedt (2012) took a different approach to fault detection by demonstrating that operational relationships can be visualized using parallel coordinates and scatter plot matrices, as in contour mapping. To allow the method to be used for large-scale operational analysis, performance metrics were formulated as an extension of the visualization techniques to remove subjective interpretation. Xue et al. (2017) proposed a data-mining-based method and applied it to data from two substations in the DH system in Changchun in China. Beside data cleaning and transformation steps, the method involved clustering to discover distinct operation patterns using k-means algorithms, partitioning around medoids and hierarchical clustering, and finally association rules to help understand the various substation regulation strategies. This led to the detection of a malfunctioning secondary valve and energy-inefficient operation that could then be modified.

All the studies mentioned above are examples of how progress and success has been achieved in developing appropriate fault detection methods, but the methods still rely on a certain amount of manual handling or interpretation, or even advanced understanding of computer science statistical analysis. An attempt to eliminate as much manual interaction as possible was made by Månsson et al. (2019) using linear regression and outlier detection. Hourly measurements from 3000 customer installations in Sweden for one year were analysed, and they revealed that 43% of the substations were poorly performing.

5.2.4.2 Implementation

Very few examples of FDD implementation in utility data infrastructure have been realized to date, apart from basic limit-checking applications. This is also the case for FDD implementation in commercial products, although heat meter data is starting to be integrated into software offered by heat meter manufacturers. The limited emergence of available solutions is partly due to the difficult data handling, which is compromised by the large amount of data to be transferred as well as the classification of the data as GDPR-sensitive, meaning that it must be handled in secure environments.

An example of FDD implementation was carried out in the Smart District Heating I & II projects led by the Danish Technological Institute in collaboration with several Danish DH utilities from 2018 to 2021 and supported by the Danish District Heating Association (Fester, 2019). Data made available from four different utilities and various heat meter manufacturers were compared, and it became clear that a scalable implementation for the broad target group utilities would have to be based on an aggregated data format due to widespread holes in exports of hourly data, rounding errors, and other issues. Nevertheless, an application was made available on the basis of daily resolved heat meter data, which almost every Danish utility was able to deliver at this point, and freely available weather data from an application programming interface supplied by the Danish Meteorological Institute (DMI). The program incorporated six levels of analysis ranging from limit checking and ranking by single parameters to outlier detection from long-term timeseries, inspection of temperature difference signatures, and the use of machine learning for predictive models for fault detection, as proposed by Månsson et al. (2018). In close collaboration with the utilities demonstrating the program, the user interface and selected FDD methods were adapted to their needs, e.g., for the incorporation of flow or power weighting of the outlier substations prioritized by the algorithms to maximize the energy savings achieved after inspection and repair activities. Even based on daily aggregated data, the analysis program was able to pinpoint faults in networks with as many as 16,000 substations. The compiled stand-alone version comprises a solution targeted at small and medium-sized utilities that do not have the internal capacity to develop and implement fault detection. It was made available to all Danish utilities in the prototype version and used by DH utilities external to the initial project group. However, future solutions with highly professional maintenance, solutions to data extraction set-up, and continuously updated advanced functionality, including the transition to hourly data when the time is ready, are eagerly awaited.

In another example of a knowledge-based approach, heat meter data were gathered from 3000 installations in the network of a DH utility in Sweden between April 2015 and March 2016 (Al Koussa & Månsson, 2022; Månsson et al., 2019). The data included accumulated energy consumption, accumulated flow volume, and primary supply and return temperatures. In this study, first the overflow method (Gadd & Werner, 2014) was used to determine a reference set of well-performing substations. The overflow method can quantify the excess of water volume needed by a building because the return temperature is too high. In this case, the 25 % of buildings with the lowest overflow were considered well-performing and taken as the reference set. Then, for this reference set, a regression model was built to describe the cooling of the DH water in the substations and the return temperature, both as a function of the outdoor temperature. The poorly-performing buildings were then detected as outliers compared to the regression model using the mean and the standard deviations of the reference case values. Values located at a distance greater than three standard deviations from the mean were considered outliers.

Figure 5.13 shows the results of these analyses. The grey dots are the data from the reference set on which the regression model was built. The blue dots represent well-performing substations, and the red dots poorly performing substations. This fault detection approach identified 1273 installations as poorly-performing, which corresponds to approximately 43% of the installations investigated.

For future work on FDD in DH substations, the potential availability of open data sets for researchers and developers has been identified as a critical means for further development (Sandin et al., 2013). In particular, labelled data sets with known and well-described faults and diagnoses would strongly help the common efforts towards diagnostical tools. Indeed, this can be viewed as the obvious next step, going beyond the outlier detection methods described, which primarily rank and pinpoint poorly-performing installations, but generally do not indicate the specific repair needed.

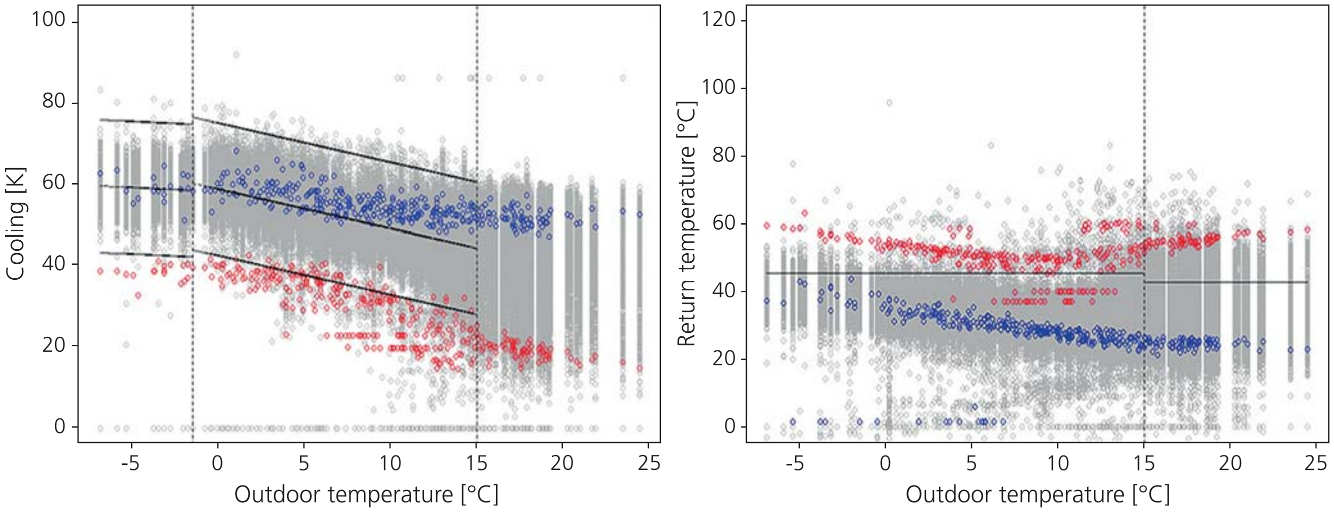


Figure 5.13: Results from the analysis of the building performance based on a regression model

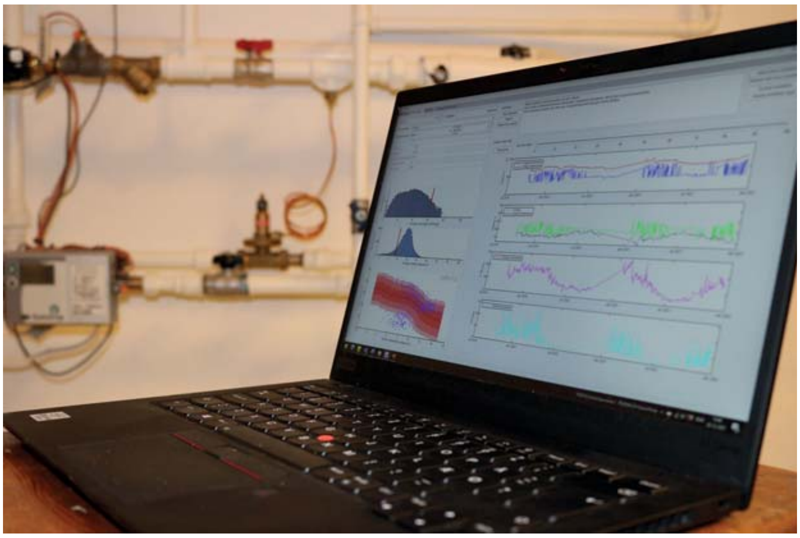


Figure 5.14: Example of a fault detection and diagnosis (FDD) implementation provided by the Danish Technological Institute and Danish District Heating (Dansk Fjernvarme) in the form of a MATLAB-compiled freely distributable stand-alone program.

5.2.4.3 Potential impact of return temperature reduction on network efficiency

The potential impact of reducing the return temperature of a network by fixing the faults detected in buildings was assessed in a case study of a DH network in the south of Sweden with 192 substations, where the effects of the improvements on the return temperature, total flow volume, and operational costs were estimated.

The heat demand for a heating season in this network is 127,000 MWh. The faulty substations were first identified from the data using clustering and domain knowledge. Then they were ranked by their effect on the total volume flow in the network. The substations with the highest impact were ranked the highest. Figure 5.15 shows the effect of fixing faults in a certain number of substations with regard to the network's total water flow over a heating season. The absolute reduction in water flow is shown on the primary y-axis, and the relative reduction in water flow is shown on the secondary y-axis. The figure shows that targeting the substations with the highest effect can contribute the largest gains. For instance, if the 20 substations with the highest impact are fixed, the volume of water that has to be circulated in the network during a heating season is reduced by about 17 %, whereas fixing 100 of the faulty substations only leads to a further reduction of 3 % in the total flow. Any reduction of water volume has a direct effect on the electricity consumed by the circulation pumps. So, in this case, the electricity consumption for pumping is also reduced by 17 %, if the 20 substations with the highest impact are fixed.

The effect of fixing faults in a certain number of substations with regard to the main return temperature in the network is shown in Figure 5.16. The same trend can be seen as for the water volume. Fixing the substations with the highest impact has the biggest effect on the network. For instance, fixing the 20 substations with the highest impact leads to a total reduction in the return temperature of 8 °C, whereas fixing 100 substations only leads to a further reduction of 2 °C. Any decrease in return temperature has a direct effect on the efficiency of the heat production depending on the technology used for the production of the heat. Typical financial gains of reduced return temperatures can be expressed in the form of cost reduction gradient (CRG, in EUR/MWh °C), and can be found for various heat production technologies in the IEA-DHC Annex TS2 report (Averfalk et al., 2021).

If we assume that heat production in the district heating in the network is provided by a gas boiler with flue gas condensation, and we use the proposed CRG range of 0.1-0.13 EUR/MWh °C in the IEA-DHC Annex TS2 report, the cost savings in the thermal production unit can be calculated. Figure 5.17 shows the range of savings as a function of the number of faulty substations fixed. Fixing the faults in the 20 substations with the highest impact can yield savings in the range of EUR 100,000 to 130,000 per heating season. However, if the heat production source is low-temperature geothermal heat, the savings can be as much as five times the savings for the gas condensing boiler (Averfalk et al., 2021) due to the higher CRG.

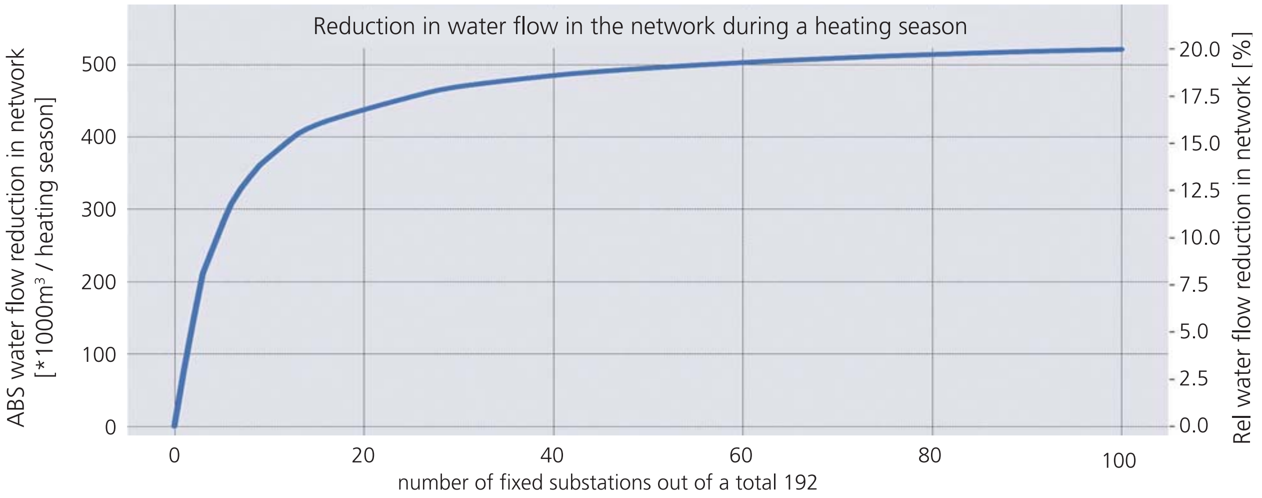


Figure 5.15: The absolute and relative reduction in water flow per heating season as a function of the number of faulty substations fixed.

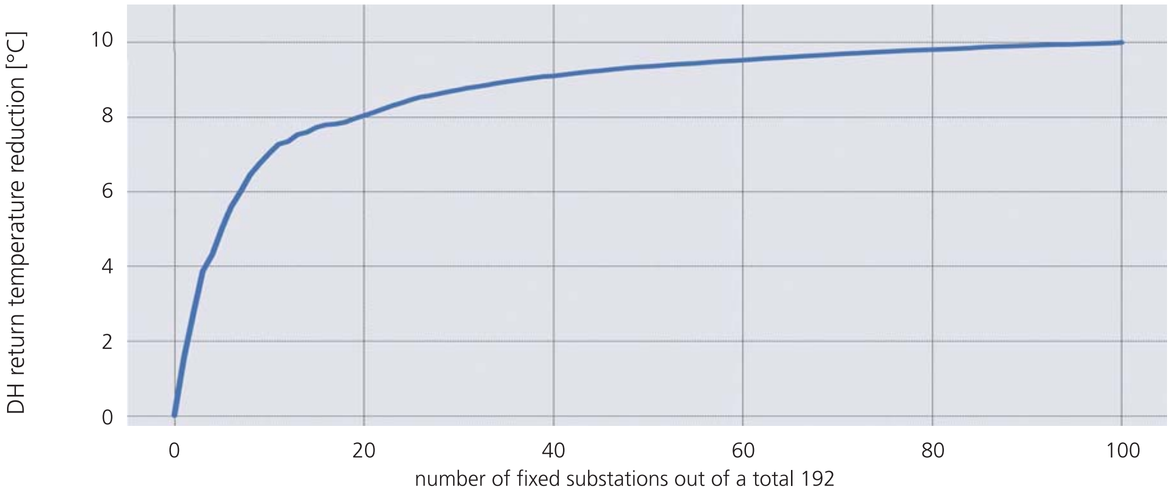


Figure 5.16: The reduction of the return temperature in the district heating system per heating season as a function of the number of faulty substations fixed.

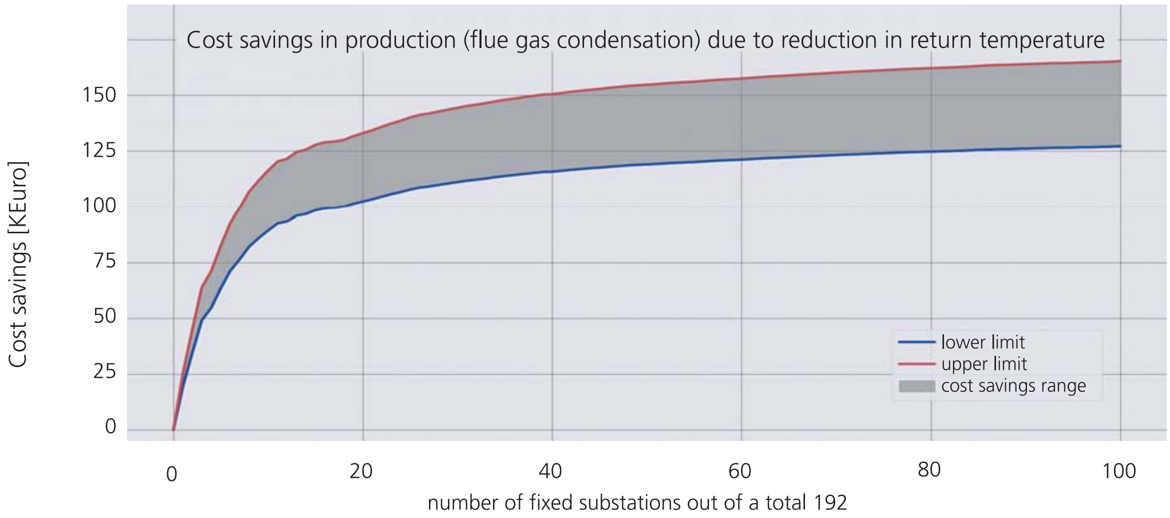
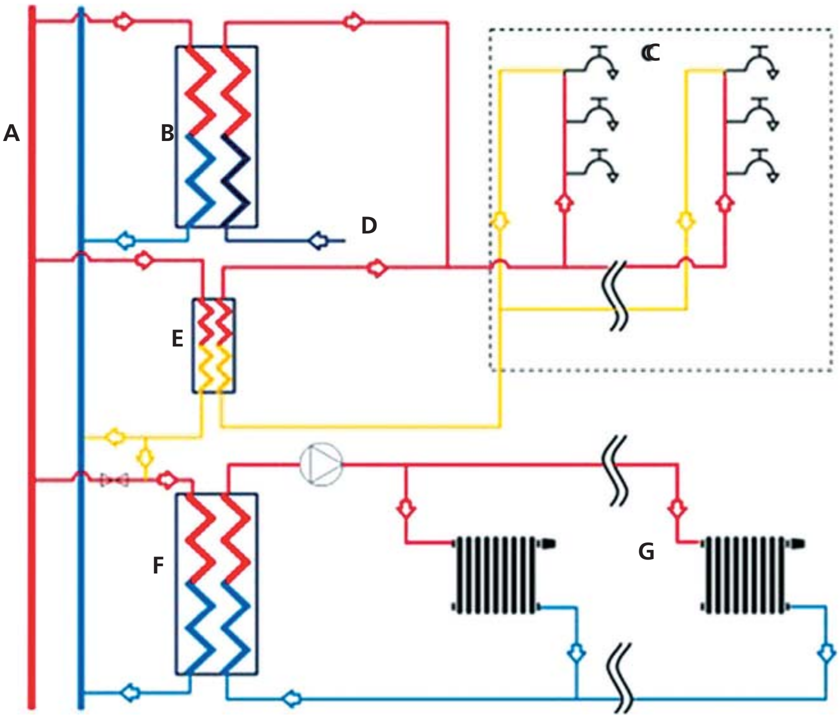


Figure 5.17: Cost savings in the production unit (assumed to be gas boiler with gas condensation) due to reductions in the return temperature as a function of the number of faulty substations fixed during a heating season. A range of cost savings is shown, based on the CRG from IEA ANNEX TS2 report (Averfalk et al., 2021).

5.2.5 Intelligent aftercooling of DHW circulation flow

To ensure hygiene and comfort in DHW preparation, national standards always require a high-temperature level. This may set a limit to the lowering of the DH operational temperatures, particularly in the future when the DHW demand in buildings is expected to be as high as the demand for space heating (Skaarup Østergaard et al., 2022). According to Danish Standard DS 439 (Danish Standards, 2009), the DHW system should be able to deliver hot water with a minimum temperature of 50 °C for hygiene and comfort requirements, but 45 °C can be accepted during peak situations. DHW systems with hot water tanks generally maintain a higher temperature in the tank, usually in the range of 55 - 65 °C, depending on the national legislation that applies in the particular country (Averfalk et al., 2021). DHW systems with circulation loops are the most common solutions for multistorey buildings, with either storage tanks or heat exchangers (Pomianowski et al., 2020). According to the regulations, every point of the circulation needs to be maintained at a minimum of 50 °C, which generally leads to a standby (not tapping) DH return temperature that is typically higher than 50 °C. While circulation heat losses are often perceived as a fraction of the total DHW consumption, they can represent a substantial share of the annual heat consumption for domestic hot water, as much as 65% and 80% in multifamily and commercial buildings respectively, as documented by Averfalk et al. (2021). Buildings with DHW circulation loops may therefore be one of the main bottlenecks for transitioning towards low return temperatures in DH networks.

A new DHW concept has been investigated as a technical solution to achieve low DH return temperatures with a supply temperature in the DH networks as low as 55 - 60 °C. The idea is to decouple the DHW preparation and the reheating of the DHW circulation flow in separate heat exchangers, as illustrated in Figure 5.18. This setup enables the high DH return temperature from the reheating of the circulation flow to be aftercooled in the heating circuit of the building, minimizing the overall DH return temperatures from the building. The investigation found that if the space heating systems are well controlled and operated, it is possible to achieve a return temperature from the DHW substation as low as 30 - 35 °C (Benakopoulos, Vergo, et al., 2021). Others have also shown that in well-operated substations in multifamily buildings, the expected average return temperature should be in the range of 30 - 35 °C (Skaarup Østergaard et al., 2021; Rämä et al., 2019). Theoretical analysis has shown that the building DH return temperature reduction potential could be 4 - 7 °C on an annual basis, which is significant considering the low investment costs of the aftercooling concept.



A District heating
B DHW heat exchanger
C Circulation loop
D Cold water
E DHW circulation heat exchanger
F SH substation
G SH system

Figure 5.18: Schematic overview of the aftercooling concept

Crucial for the aftercooling concept is the control of the systems. A number of operational conditions must be addressed:

1. In the situation of no DHW tapping, the control system must be able to close the primary valve of the DHW heat exchanger immediately. This means the temperature sensor at the outlet of the DHW side of the heat exchanger must be located in the heat exchanger, providing good thermal contact with the primary side, so it can detect when the temperature exceeds the set temperature and consequently close the primary valve. As the DH supply temperatures become lower, this change will not be adequate on its own. To ensure the closing of the primary valve, there should also be a flow switch on the DHW side that gives a direct signal to the primary valve to close when there is no DHW tapping.
2. For optimal cooling of the DH return from the DHW circulation heat exchanger, as much of this return flow as possible should be led into the heating circuit. The control system must be able to detect and handle situations where the heating circuit can only partly, or not at all, “absorb” the DHW circulation return flow, e.g., situations when the heating load is low or even zero. In these situations, the return flow from the DHW circulation heat exchanger that cannot be utilized by the space heating is led back to the DH return line.

The greatest DH return temperature reduction potential is in buildings with low space heating operational temperatures. The concept therefore works with buildings with floor heating as well as buildings with radiators. To achieve low return temperatures in buildings with radiators, it is important to ensure a balanced operation of all radiators. The aftercooling concept requires little installation and only minor adjustments to the DHW system.

Unlike a booster heat pump, the aftercooling concept does not require additional operating energy for the heat pump (Benakopoulos, Vergo, et al., 2021; Thorsen et al., 2020). On the other hand, the heat pump-based concept is not sensitive to the temperature profiles of the heating system, as presented and discussed in section 5.2.6.

5.2.6 EnergyLab Nordhavn / Denmark

EnergyLab Nordhavn was a Danish flagship project that ended in 2019. The project used the Nordhavn area in Copenhagen as a full-scale smart city energy lab. The main objective was to investigate and demonstrate the most cost-effective smart energy system in a real new urban area and develop innovative solutions to pave the way for the integration of renewable energy sources and increase energy system flexibility.

An interesting case study documented the use of a heat booster unit for a DHW substation in a multi-family building with 22 apartments in 2018 - 2019 (Thorsen et al., 2019). The concept schematic is presented in Figure 5.19. An electric heat pump used energy from district heating to increase the ultra-low supply temperature (in the range of 35 - 45 °C) to an acceptable temperature for safely delivering hot water from an instantaneous heat exchanger. In addition, a small booster heat pump covered the circulation heat losses and ensured that the circulation loop was kept above 50 °C at all times. The results showed a return temperature of 30 °C. The district heating storage tank was used to accumulate energy irrespective of the hot water tapping to test load shifting. The charging control of the tank was based on draw-off forecasts, heat loss minimization, and charging optimization based on energy prices, and it indicated a potential DHW load shift of 75 kWh/day. The proposed solution guarantees a high level of control and potential for achieving low-temperature operation and increased flexibility due to demand management. The system is suitable for Ultra-LTDH systems that supply energy-efficient buildings with floor heating installations. Although increased flexibility and demand management of buildings is becoming highly beneficial for district heating operators, particularly during peak load demand, the current price structure of district heating markets does not yet take this into account and requires some adjustments (Bosco & Honoré, 2019).

A common issue with multi-apartment blocks is that the requirement to maintain a DHW circulation temperature at 50 °C typically results in high average return temperatures, especially when the circulation heat loss share of the total DHW consumption is high (Benakopoulos, Vergo, et al., 2021). A circulation booster for DHW systems, as illustrated in Figure 5.20, was tested in a multifamily building comprising 15 apartments (Thorsen et al., 2021) to improve the control of the DHW substation and ensure a lower average return temperature. The supply temperature from district heating with a typical range of 70 - 90 °C was used to cover the hot water consumption; a small booster heat pump was used to pre-heat the circulation flow to 53 °C, which was then increased to 55 °C using a direct heat exchanger. The return flow from the direct heat exchanger was used as a heat source for the booster heat pump, which cooled it down to 23 °C before returning it to the district heating network. Despite an electricity share of about 19%, the reduced return temperature from the application unlocked end-user cost saving from the typical Danish motivation tariff structure, that enable an attractive payback period of 5.1 years (Thorsen et al., 2021).

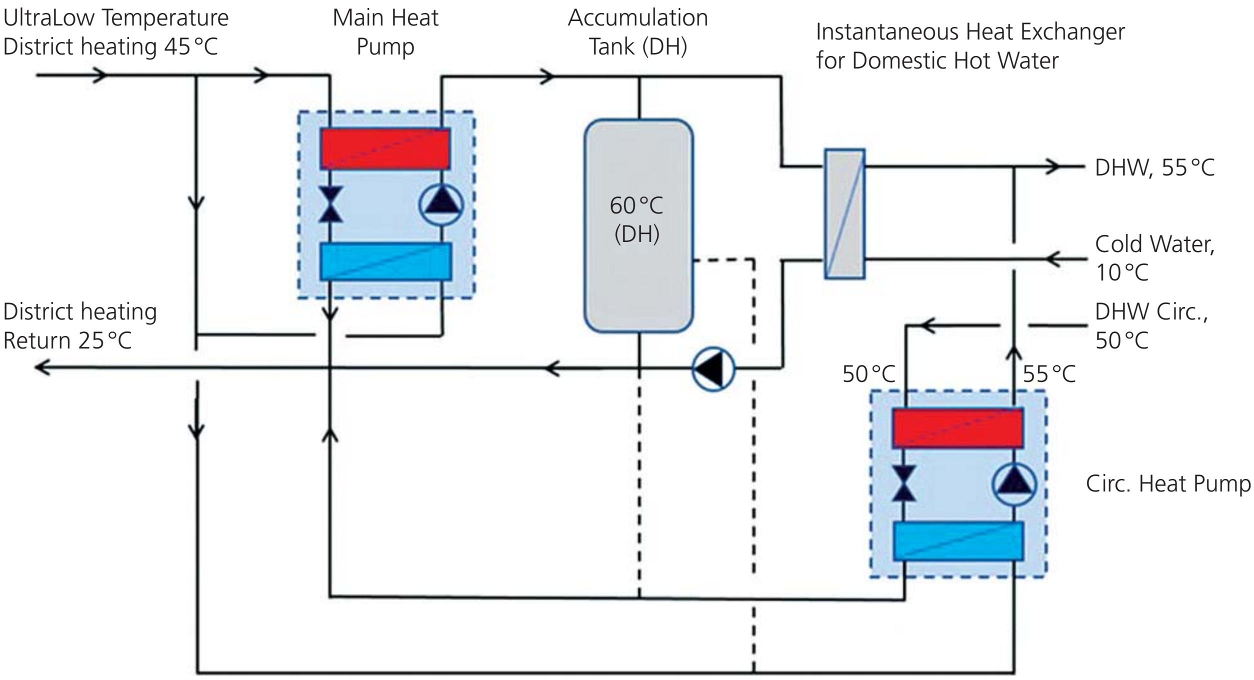


Figure 5.19: Heat booster system for the Nordhavn residential building (Thorsen et al., 2019)

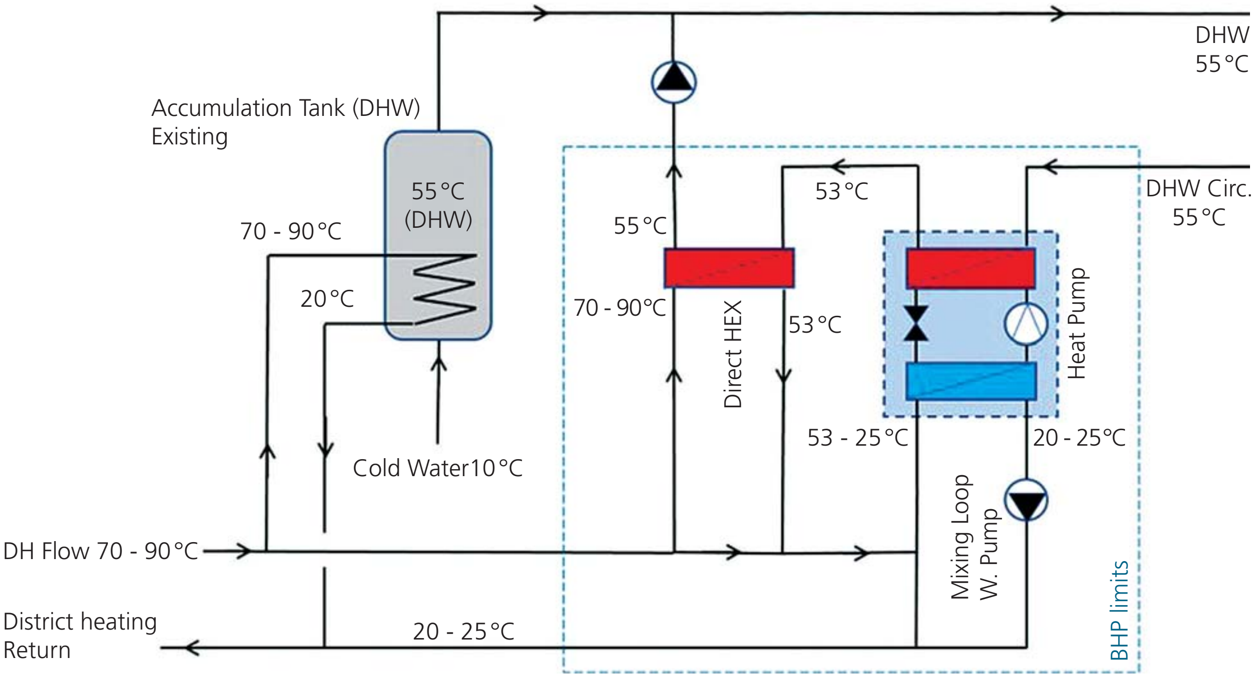


Figure 5.20: Circulation booster system for the Nordhavn residential building (Thorsen et al., 2019)

Another case study investigated and tested demand-side management for a multi-apartment building designed for 20 kWh/m² per year for heating, ventilation, and domestic hot water in accordance with the latest Danish building regulations. The study explored the potential for morning peak load shifting by remotely controlling 90 rooms with underfloor heating using a simple time-based penalty signal and overriding the temperature setpoints. Bathrooms were excluded from the test because the end-users wanted to decide their comfort freely. Performed in March 2019, the test compared the impact on the heat demand profiles of the proposed control with the reference end-users' control (Christensen et al., 2020). The test showed a reduction of 85% in the morning power demand of the underfloor heating systems, with a limited reduction in indoor temperatures that was not detrimental to the end-users' indoor comfort. However, beside the impact of the thermal mass of the buildings, the authors suggested further investigations into other factors that might affect the indoor temperatures, such as various solar and internal gains, outdoor temperatures, and mechanical ventilation and heating from adjacent flats.

In another low-energy apartment building in the Nordhavn urban area, the peak load shaving was investigated using the storage capacity of the thermal mass. The results showed that the preheating of the building ensured a load shifting and morning peak shaving. In particular, during morning peaks, a generally challenging period for the operation of district heating networks, it was found that the energy consumption was reduced by 40 % to 87 % depending on the different control strategies implemented (Foteinaki et al., 2020).

Using the measurements from one of the tested buildings from EnergyLab Nordhavn, Sarran et al. (2022) combined the data from room thermostats, heat meters, and circulation pumps to create a grey-box model of the space heating system of an apartment. The study investigated and tested an automatic solution for fault detection, which could locate the triggers for high return temperatures and poor hydraulic balancing in the underfloor heating system. The model was also used to assess the potential minimization of the operating temperatures without compromising comfort, and showed reduction potentials of 8.6 and 6.5 °C in the energy-weighted supply and return temperatures.

5.2.7 Substation digitalization and optimization: Case studies in Asia

5.2.7.1 Central substation control and operation in South Koreas

Currently, 30 - 40% of central substations that provide DH service in apartment buildings in South Korea still manually set the constant supply temperature. The remainder of the central substations generally use outdoor temperature reset control. Up until now, DH operation optimization has largely relied on the building manager's expertise, which makes it difficult to find temperature settings or reset control correlations that take into account the outdoor environment, resident preferences, and building conditions. As a result, pipe heat loss can increase if the SH setpoint is too high and does not match the outdoor environment, or households may feel uncomfortable if the SH setpoint is too low. With the aim of achieving central substation digitalization on the secondary side, the Korea Institute of Energy Research (KIER) and KDHC have developed a new DH-EMS system that includes intelligent supply temperature control. A pilot system for optimizing SH supply control for secondary central substations has been in operation since 2021.

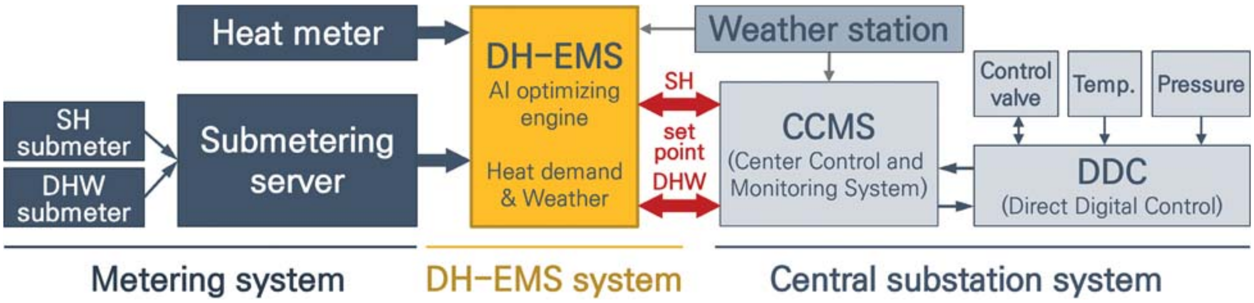
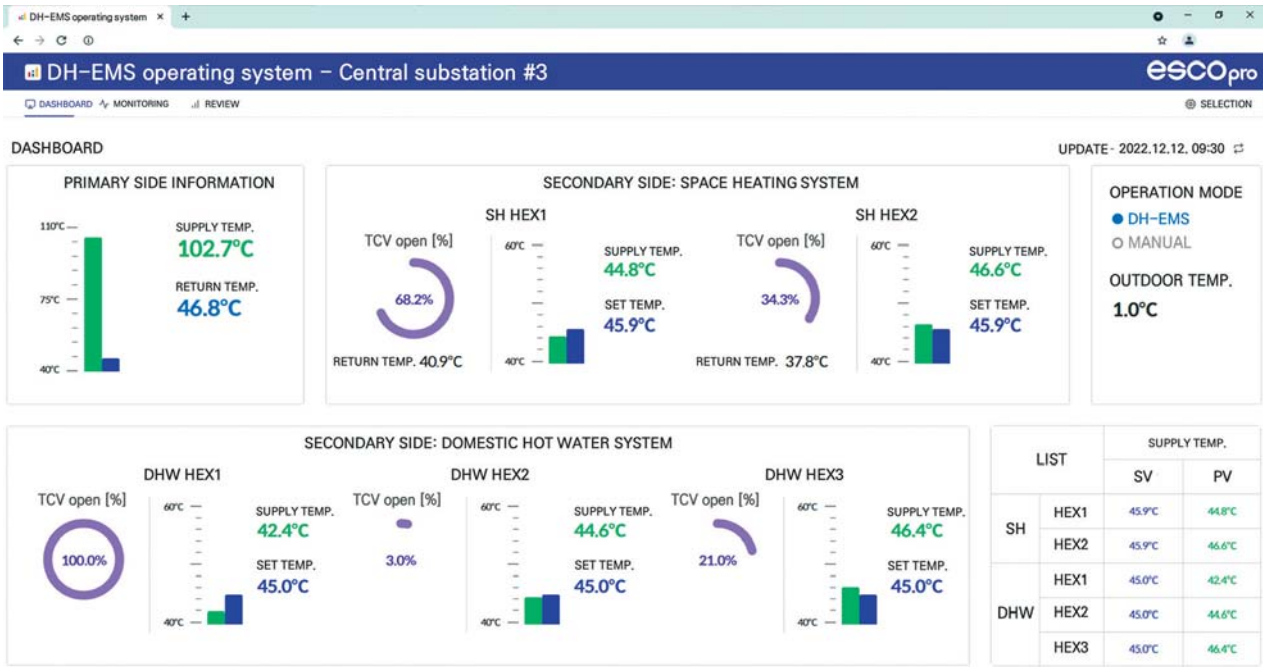


Figure 5.21: DH-EMS platform for optimizing SH and DHW supply conditions at the central substation



DASHBOARD

UPDATE - 2022.12.12. 09:30

PRIMARY SIDE INFORMATION
SUPPLY TEMP. 102.7°C
RETURN TEMP. 46.8°C

SECONDARY SIDE: SPACE HEATING SYSTEM

SH HEX1
TCV open [%] 68.2%
RETURN TEMP. 40.9°C
SUPPLY TEMP. 44.8°C
SET TEMP. 45.9°C

SH HEX2
TCV open [%] 34.3%
RETURN TEMP. 37.8°C
SUPPLY TEMP. 46.6°C
SET TEMP. 45.9°C

OPERATION MODE
● DH-EMS
○ MANUAL

OUTDOOR TEMP.
1.0°C

SECONDARY SIDE: DOMESTIC HOT WATER SYSTEM

DHW HEX1
TCV open [%] 100.0%
SUPPLY TEMP. 42.4°C
SET TEMP. 45.0°C

DHW HEX2
TCV open [%] 3.0%
SUPPLY TEMP. 44.6°C
SET TEMP. 45.0°C

DHW HEX3
TCV open [%] 21.0%
SUPPLY TEMP. 46.4°C
SET TEMP. 45.0°C

LIST		SUPPLY TEMP.	
		SV	PV
SH	HEX1	45.9°C	44.8°C
	HEX2	45.9°C	46.6°C
DHW	HEX1	45.0°C	42.4°C
	HEX2	45.0°C	44.6°C
	HEX3	45.0°C	46.4°C

Figure 5.22: DH-EMS operating system dashboard (Courtesy of ESCO Products)

Previously, the centre control and monitoring system (CCMS) determined SH and DHW setpoints on the basis of the primary and secondary side temperature, pressure and temperature control valve openness under direct digital control (DDC), and the outdoor weather. In contrast, as shown in Figure 5.21, the new DH-EMS system also makes use of heat meter data from DH suppliers and submeter data from households.

As shown in Figure 5.22, the DH-EMS system uses AI logic to automatically adjust the optimum SH and DHW setpoints based on supply, secondary side heat demand, and outdoor conditions, without the intervention of the building manager. When heat demand is high, the system raises the supply temperature to minimize customer inconvenience by ensuring an adequate supply of heat. When heat demand is low, the system lowers the supply temperature to reduce unnecessary pipe heat loss.

The DH-EMS system was implemented in a central substation serving 380 households for three winter months from December 2021 to February 2022 and achieved an average energy saving of 6.2% after correcting for heating degree days. As depicted in Figure 5.23 and Figure 5.24, the heat demand on the supply side decreased, but there was no significant change on the demand side. The energy savings can be primarily attributed to reduced pipe heat loss due to the reduced supply temperature.

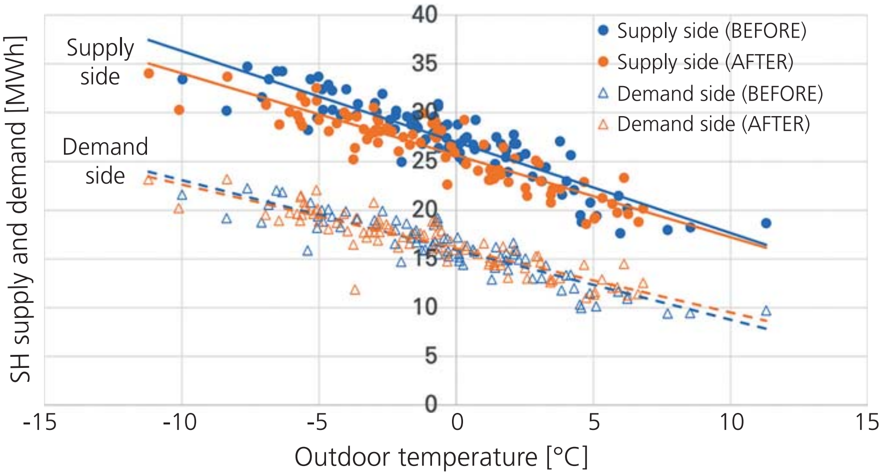


Figure 5.23: Variation of the supply temperatures on both supply and demand side during the DH-EMS test

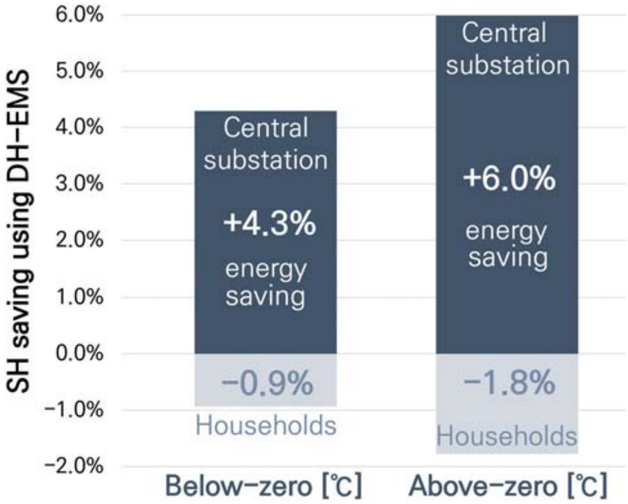


Figure 5.24: Comparison of energy saving on the supply and demand sides using DH-EMS

The SH flow rate increased by an average of 23.3% on the household side as the SH supply temperature decreased, but since the heat energy savings are greater than the increase in electrical energy due to the increased pumping, it is possible to save energy while maintaining the convenience of using heat.

5.2.7.2 Submetering digitalization and demand response in South Korea

About 40% of households still use manual reading of meters. The remaining 60% are at the stage of collecting SH and DHW data, but have not yet reached the full digitalization of being able to properly utilize the data. To help promote the digitalization of district heating end-users, KIER and KDHC have developed both wired and wireless SH and DHW smart submetering systems for households (see Figure 5.25). In 2017, wired systems were installed in 918 households in 16 buildings to begin verifying the effectiveness of smart submetering. In 2020, to evaluate the possibility of expanding the applicability of smart submetering, a second pilot demonstration, this time of a wireless (private LoRa) system, was conducted in 348 households in three buildings. In addition to collecting usage data for billing purposes, this smart submetering system integrates additional SH and DHW usage information providing both building managers and households with the results of abnormal detection and demand forecasting through mobile apps to help them check their usage and status in real-time.

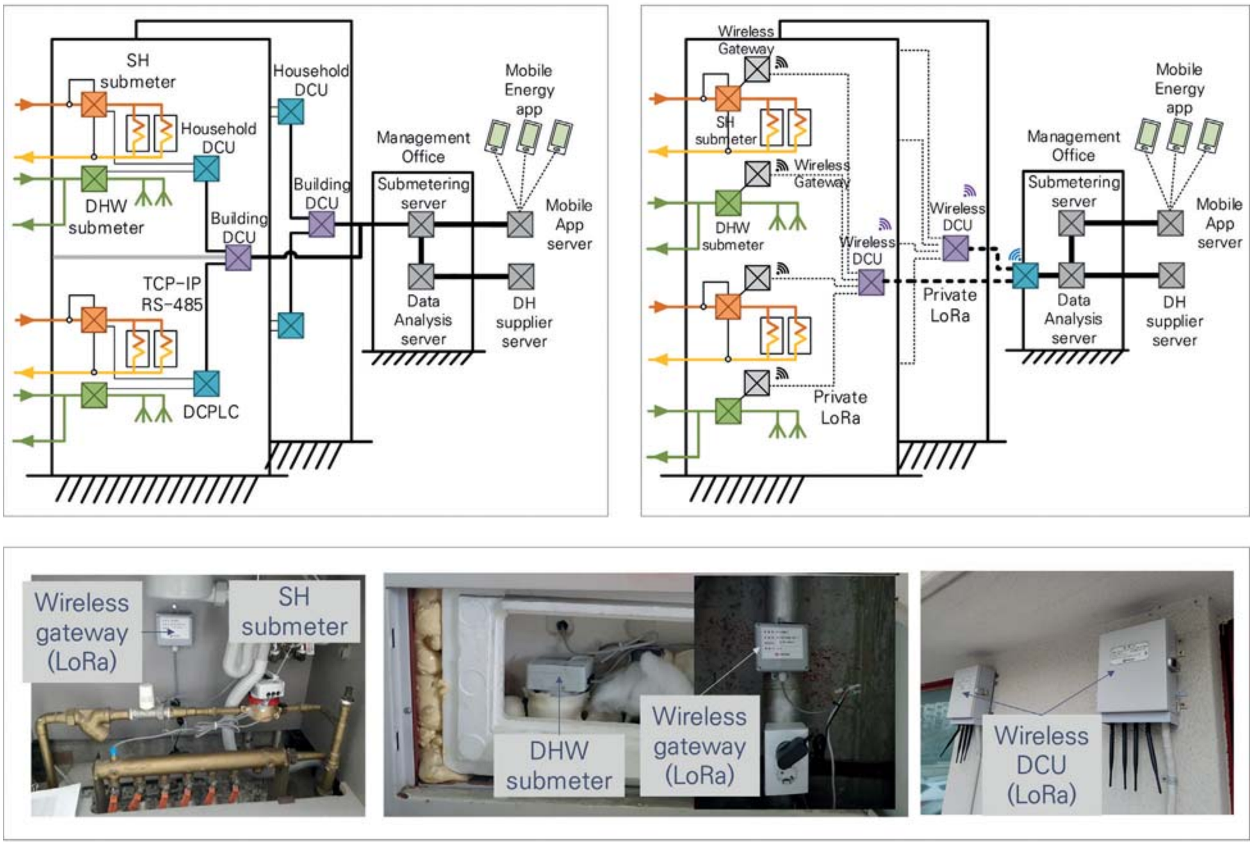


Figure 5.25: Wired communication (TOP LEFT), wireless communication (TOP RIGHT) of SH and DHW smart submetering system, and Installation of wireless SH and DHW smart submetering system for the 2nd pilot site (BOTTOM)

The submetering dashboard for building managers shown in Figure 5.26 is operated from the building management office and automatically checks for abnormal operation in each household every hour using AI (artificial neural network and decision tree) techniques. The diagnostic results provide information on the probable cause of the problem, along with the severity level of the household's abnormal submeter or SH & DHW operation (abnormal flow rate, leakage, power failure, etc.). This information allows the building manager to establish a daily maintenance schedule based on the severity of the problems and the causes of failures, which makes it possible to quickly resolve problems when the households are visited.

Although it is generally accepted in the electricity and gas sectors that the provision of real-time information using in-home displays (IHDs) contributes to energy saving (Ehrhardt-Martinez et al., 2010; UK Department for Business, Energy & Industrial Strategy, 2016), there have been very few studies on district heating demand response. The pilot studies of KIER and KDHC showed the DH demand response when people can access the usage data in real-time. The mobile energy app shown in Figure 5.26, which provides real-time SH and DHW usage and estimated charges, was distributed to APP stores so that users could install it and use it by themselves. Information on whether or not the app was installed and how often it was used was collected for two years and analysed in combination with SH/DHW demand during the winter (November to March). As the results in Figure 5.27 show, households using the mobile energy app saved about 7.1% of SH and 4.7% of DHW during the winter compared to households that did not use the app. These results show that households can actively respond to district heating demand if they have the proper tools to monitor their heat usage.

Figure 5.26: Submetering dashboard for building manager (LEFT) and mobile APP for households (RIGHT)

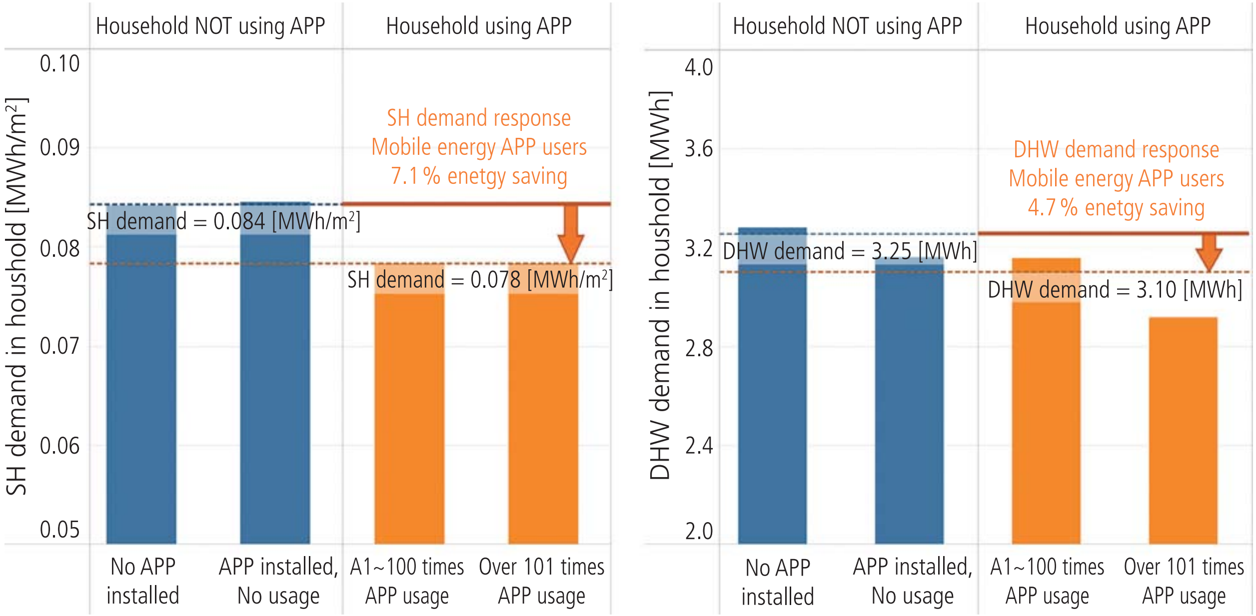


Figure 5.27: SH and DHW demand response depending on whether the mobile energy APP is used and how often it is used

5.2.7.3 The digitalization of main substations in China

The digitalization level of DH in China depends strongly on local policy. As shown in Table 5.1, the DH area has not yet been fully digitalized, which means DH digitalization is still under development. Moreover, most of the digitalization has been implemented in the substations and the building entrances. A high level of digitalization at apartment level is very rare, because detailed flat metering is not always required due to the substantial investment and labour cost

Nevertheless, the most highly developed digitalized DH networks usually combine IoT and AI technologies, and a multi-layer architecture can be applied based on the functionalities required. The topological structure of a typical smart district heating system is shown in Figure 5.28. The bottom layer is the infrastructure layer in which the necessary meters and controllers are deployed. The middle layer is used for data storage and computer modelling. The data collected from the infrastructure layer is transmitted to the middle layer through various interfaces. The computing results are output to the top layer as the

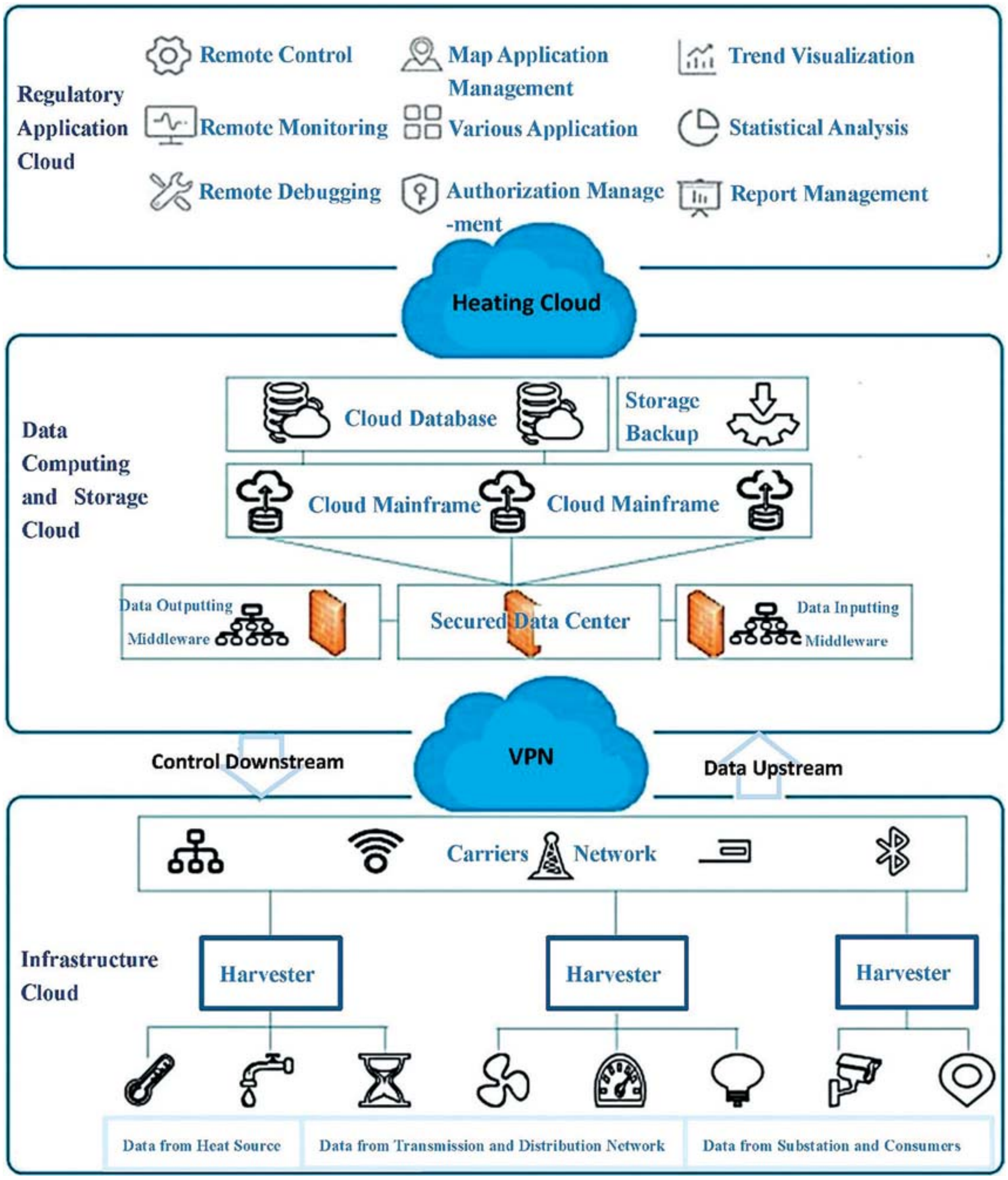


Figure 5.28: SH and DHW demand response depending on whether the mobile energy APP is used and how often it is used

Table 5.1: Scale and status of DH network digitalization in various Chinese regions

Region	Heating area of the Digitalized DH (million m²)	Implementation status
Beijing	20	Various forms
Heilongjiang Province	13	80% on the building scale, 20% extends to the flat entrance
Jilin Province	12	60% on the building scale, 40% extends to the flat entrance
Hebei Province	60	Mostly extends to the flat entrance
Shaanxi Province	40	Extends to the flat entrance (mainly used for heat metering purposes)

information required. The top layer is responsible for the visualization of the results, remote control, monitoring and debugging, and the settings of the top-level control parameters. The connections of the various components in different layers may be wired or wireless. In the case of DH networks, the data from the infrastructure layer are transmitted through 4G or NB-IoT.

Based on the historical measurements of a substation, a model that describes the characteristics of the substation can be established. It then becomes possible to make heat load forecasts by inputting into the model real-time measurements, such as the weather, indoor temperatures, and the parameters of the heat supply (e.g., pressure and temperature). The control strategy for the substation equipment can be updated iteratively with an adjustable cyclic time. This might be about 1 hour, but could be as short as 5 - 8 seconds.

The DH manager can check the real-time measurements, adjust the control strategy, and analyse the system performance using the visualized platform shown in Figure 5.29. In the case of varying weather conditions, dynamic heating generation, or instant heat demands, the AI algorithm can automatically regulate the control variables such as the supply temperature and the flowrate.


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Figure 5.29: The dashboard of a typical smart DH control platform in China

5.3 Conclusion

Historically, the lack of information from substations and heating/cooling systems meant that buildings were perceived as black-boxes. This perception prevented the development of ways of optimally controlling and operating these systems, and limited the possibilities for achieving low-temperature operation and making the green transition of the DE industry.

Although the level of digitalization of the demand side varies across different countries, the new policies introduced in recent years have increased the availability of new remotely readable digital devices. This has opened new opportunities for monitoring and control, securing low-temperature operation and billing transparency for end-users.

The current robustness of smart meters, thermostats, and sensors allows cost-effective data gathering and can already ensure a high degree of control and monitoring. Future software development with artificial intelligence and digital twins will further enlarge the potential for improved control and flexibility.

We have documented that integrating the data from energy meters, heat cost allocators mounted in every radiator, and temperature sensors, it is possible to improve the control and operation of space heating systems and comfortably heat existing buildings with supply temperatures in the range of 42–58 °C for the entire heating season, without deep energy renovation. The minimization of supply temperatures can also secure energy savings that offset the increased pumping power required for the larger mass flow rates.

Moreover, data robustness has helped develop new ways of controlling and designing DHW substations which will make them future-proof, ensuring the expected comfort and hygiene of hot water with network supply temperatures in accordance with 4GDH requirements.

Data visualization – i.e., via mobile apps – is increasing the engagement and awareness of end-users with real-time information about their consumption and their systems, leading to energy savings and transforming users into an active part of the entire energy system green transition instead of being purely passive consumers.

Despite the currently limited implementation of fault detection and diagnosis in utility data infrastructure, some projects in mature DH markets such as Denmark and Sweden have highlighted how data-driven automatic screening is a powerful tool for assessing substations and pinpointing outliers with a view to achieving low-temperature operations and cost savings. Such screening can be a solid tool for utility companies to achieve continuous commissioning of their substations and plan maintenance strategies, and it represents one of the areas with great potential for further innovation.

The commercial development of innovative data-driven products is growing fast. Nonetheless, the handling and integration of data from end-users and energy meters in software may be limited by the classification of the data as GDPR-sensitive, meaning that it must be handled in secure environments. This will very much depend on the specific national regulations. The coordination of a common strategy for data security and transparency must be a highly prioritized task to secure the interoperability and integration of all the various data sources in the future.

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6 Digitalisation at system level

6.1 Introduction

This chapter deals with the role that digitalisation can play at the district heating and cooling system as a whole, and even for the rest of the energy system. In the previous chapters we studied individual elements in the energy chain, whereas in this chapter we focus on the interaction between the different elements, and how one element influences others, in order to optimise environmental and economic benefits of the entire energy system.

Digitalisation at the system level can be split in two fields. One is operational optimisation, whereby we mean that digital assets directly intervene in the control of the network or its components. Operational optimization is online and automated. Digital tools can be used to optimise the operation of the system, in comparison to rule-based control loops that are typically used to control the network components. These rule-based controllers are in most cases designed as individual, isolated controllers that do not consider the overall system, and therefore the system’s performance is often suboptimal. In this chapter, we look into operational optimization of the production of heat and cold, the distribution of this energy, and the consumption of the energy, on the premise of optimisng the entire system's behaviour.

Besides operational optimisation, analytics-based optimisation methods are also investigated. Analytics refer to the analyses of (large amounts of) measurement data to guarantee failsafe and optimal operation of the network. Digital tools for analytics provide information on the system behaviour, often in an off-line manner. Based on this information, action can be taken to improve the behaviour. Two sections on analytics are included further in this chapter as well: one with the focus on fault detection and diagnosis, and one looking a step further, namely at analysis for predictive maintenance and system improvement.

It is worth mentioning that the split-up in operational optimisation and analytics is still somehow artificial, since there definitely is an overlap between the two fields. This is also in line with an analysis made by Gartner (2014) whereby operational optimisation is seen as an advanced form of (prescriptive) analytics (Figure 6.1).

Studying operational optimisation and analytics in the field of DHC, revealed one common theme that came back in all the different subsections, namely forecasting. Therefore, at the end of this chapter, a section is dedicated to this topic.

For each of the sections, after a short introduction we give an overview of the historical perspective and the state-of-the-art in the research on the topic, and a few applications in the form of real-life case studies, concepts and simulation studies.

6.2 Operational optimisation of production

The control of the heat production within DH networks is a challenging task on its own. In the past this was done via simple control loops and logic, and for smaller networks it is still done in this way. With such isolated controllers, it is difficult to achieve efficient control of larger systems. However, with better ICT (Information and Communications Technology) infrastructure, high-level, optimisation-based control concepts are increasingly appealing. In the following an overview of optimisation-based control for the production side of DH networks is given.

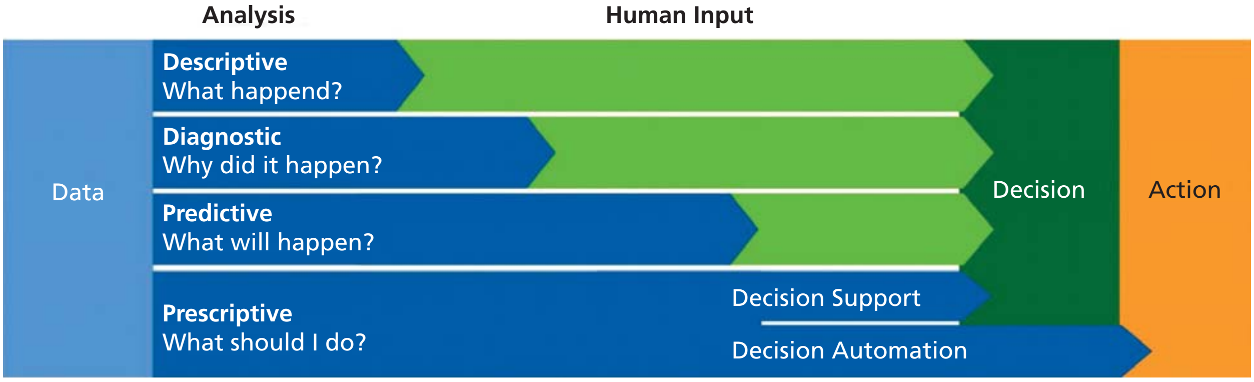


Figure 6.1: Four types of analytics capability (Gartner, 2014)

6.2.1 Historical perspective and current state-of-the-art

State-of-the-art control of small and medium-sized district heating production is still mainly relying on simple rule-based control concepts. These usually only consider current measurements and try to keep the TESs (Thermal Energy Storages) content within certain limits while changing the supply temperature of the network based on the ambient temperature. Most of the control concepts only consider current measurements, however, forecasts of the heat demand or expected yield of a solar thermal plant have also been partly incorporated, see, e.g., Gölles et al. (2021). While these control concepts work well for simple small to medium-sized DHC networks, they have some difficulties with more complicated system configurations such as multiple feed-in points or storages throughout the network, an increase of uncontrollable intermittent renewable energy sources such as waste heat or solar thermal plants, and in the case of sector coupling, i.e., the integration of CHPs and heat pumps with varying electricity prices. To address these challenges, a high-level control approach is needed which coordinates the production units and TES throughout the system. This high-level control is mostly done via experienced human operators. However, an automated approach that considers all available resources and operational constraints is needed to reduce costs and emissions of such DHC networks. A very promising approach for these future challenges is predictive, optimisation-based control approaches.

Optimisation-based control approaches, often also referred to as optimisation-based energy management systems (EMS) solve an optimisation problem in real time, providing optimal schedules for all production units for a specified planning horizon. When new information, e.g., measurements and updated demand and yield forecasts, arrive, the optimisation problem is solved again. Hence, this approach is able to handle disturbances and uncertainties.

The optimisation problem consists of an objective function which should be minimised, and constraints that ensure a physically reasonable solution, i.e., operating strategy of the production plants. The objective function captures economic aspects such as fuel costs and operational costs, but also penalises unwanted behaviour such as frequent startups of, e.g., biomass boilers. CO_2 emissions can also be considered by assigning a specific price to them, thus making them economically relevant. Furthermore, penalties for operating a storage too close to its limits can avoid risky operating strategies, however, in parallel lead to more conservative operation. Penalties for load or yield shedding, i.e., not completely satisfying customer demand or wasting energy, can be introduced to avoid infeasibilities of the optimisation problem, e.g., if there is a very large, unexpected demand that cannot be met. Thus, the cost function weights the different aspects to be considered for the evaluation of the operational behaviour.

The optimisation constraints model the energy system and its operational limitations. This includes the dynamic behaviour of TES, the guarantee that all demand must be met and maximum ramping rates of producers such as biomass boilers. Furthermore, they often also ensure hydraulic limitations in the distribution system, such as maximum mass flow rates through pipes, are not violated. All these intentions can be either formulated as hard constraints or as so-called soft constraints, i.e., by assigning costs to their violation. To avoid fast on/off switching of a producer, for example, one could either specify a minimum on or off time or assign a price to each on/off switch of the producer, see, e.g., (Carrión & Arroyo, 2006). While the former can lead to infeasibilities when unexpected demand needs to be met and the producer cannot yet turn on, the latter is difficult to tune since the price assigned must be well balanced against all other costs in the system.

The complexity and class of the resulting optimisation problem depends on the model. If non-linear models are used, the resulting optimisation problem is also non-linear, which is very hard to solve in real-time. Typically, linear models incorporating integer variables are used, which results in a mixed-integer linear program (MILP) to be solved, see, e.g. (Morales-España et al., 2013). For these, very good commercial and open-source solvers are available, such as (Gurobi Optimisation, n.d.) or (IBM, 2019). Certain non- linearities, e.g., to model efficiency curves, can be approximated using piece-wise affine (PWA) functions, see e.g. (Bemporad & Morari, 1999).

The topic, optimisation-based control, is an ongoing field of research. The research topics can be mainly split into the control of the production

(EMS), of the heat distribution, see section 6.3, and of the consumption (demand side management, DSM), see section 6.4. If just the production side is considered, it is often also referred to as the unit commitment problem, see e.g. (Carrión & Arroyo, 2006). Due to the better real-time performance of MILP solvers, efforts are made to approximate the inherent nonlinearities of thermal systems, e.g., by approximating a mass flow with varying temperature with a mixture of multiple mass flows at constant temperature, see e.g. (Moretti et al., 2021 or Muschick et al., 2022). Nevertheless, also nonlinear models are used, such as (Jansen et al., 2023). Since additional gains can be obtained by considering optimisation on the distribution side, other approaches for coupling production and distribution can be considered (see section 6.3).

All these approaches have in common that an optimisation problem must be formulated based on specifications of the considered network or energy system. The configuration process is often tailored to a specific energy system and requires expert knowledge to perform any kind of change. Thus, for a wide practical application of optimisation-based control approaches very modular frameworks need to be developed, which allow for an efficient, highly automated formulation of the optimisation framework, strictly speaking an efficient implementation and operation.

Commercially available EMS products for DHC networks exist, e.g. (INNIO Jenbacher, n.d.), (Gradyent, n.d.), (Decision Trees GmbH, n.d.), (Fraunhofer IEE, n.d.), (STORM controller, n.d.), (Danfoss A/S, n.d.,a), (EMD International A/S, n.d.). Some of them are also MILP-based. A stochastic optimisation-based EMS is developed by Decision Trees. Danfoss and Gradyent offer complete software suites, with production optimisation and network simulation tools. However, these energy management software tools have a comparatively low market penetration, which is partly due to the traditionally conservative viewpoint of DHC network operators who must have a strong focus on the safety of supply to their customers, and partly due to the heterogeneity of the installed boilers, protocols and existing automation software. This leads to a non-negligible personnel expenditure for each automated network and thus hinders a fast propagation on the market even though the fuel cost savings and CO_2 emission reduction can be considerable. For instance, in (Danfoss A/S, n.d.), on average 1-3% of fuel cost savings are reported and in (Kaisermeyer et al., 2022), 7% of fuel costs savings and a reduction of 35% in CO_2 emissions for interconnected DH networks are reported. Hence, unifying protocols and interfaces will be an important enabler for such intelligent control schemes.

A predictive optimisation-based EMS is beneficial especially if the energy system is diverse, i.e., has multiple different production technologies, incorporates fluctuating renewable energy sources, and if there is flexibility, e.g., in the form of large storage capacities. According to Aschbacher (2013), the initial investment costs for an optimisation-based EMS are too high for smaller DH networks. As such, smaller DH systems, e.g., two boilers and a TES, often still rely on standard control schemes and some kind of merit order. However, if the configuration changes, i.e., a new production unit such as a heat pump with PV and variable energy tariffs is installed, it might be difficult to adapt the control scheme to operate the plant efficiently. If an optimisation-based EMS is used, only the configuration has to be adapted and the new optimal schedules will automatically operate the new system as cost-effectively as possible. However, unified interfaces and digitalisation of the existing DHC network infrastructure is a corner stone of such intelligent control concepts. Thus, not only the R&D on the actual frameworks for predictive optimisation-based control but also standardisation of interfaces and in general the digitalisation of the DHC networks need to be continued.

6.2.2 Applications

6.2.2.1 Application 1: Exemplary approach on optimisation-based control

In Moser et al. (2020) a modular EMS framework is proposed that addresses the aim of efficient and highly automated formulation of the control by providing standardised building blocks that can easily be assembled and connected to represent a wide range of possible systems. The core idea behind this MILP-based EMS framework, developed by the Austrian research institute BEST – Bioenergy and Sustainable Technologies, is to model a wide variety of multi-energy systems, i.e., systems with multiple energy domains. This is accomplished with a component-based approach, where every production unit, consumer, heating demand, TES or battery is an individual component. Connections between the components ensure mass and energy balance. The optimisation problem is then automatically derived from this component-based description of the energy system. Figure 6.1 shows such an exemplary configuration of a heating plant of a simple DH network, with a gas engine, a gas boiler, a solar collector and a TES. Each block performs default actions (yield prediction for solar collectors, state estimation based on temperature sensors in the TES, demand side management inside of the network) and thus provides the required information to the solver of the optimisation problem. Since forecasts are never perfect, their quality is continuously assessed, and the uncertainty considered in a stochastic optimisation problem formulation. This EMS framework has been field-tested for interconnected district heating networks (Kaisermayer et al., 2022), industrial facilities, city quarters (Moser et al., 2022) and single-family homes. The final savings achievable strongly depend on the initial situation and on the chosen focus of the cost function, i.e., economic vs. ecological optimum. The typically achievable improvement is in the range of 5-10%, e.g., 9% in (Moser et al., 2022).

6.2.2.2 Application 2: Heat production optimisation in multi-source district heating systems

Danfoss Leanheat Production is an advanced software for forecasting, planning, and optimising district energy production and distribution. The cornerstone of Leanheat Production is a six-day AI-based demand forecast. The software calculates the cost-optimal production mix from available heat sources based on the estimates and energy spot prices. Additionally, Leanheat Production estimates the optimal supply temperature by a data driven numerical model. The combination of effective load forecasting, production optimisation in combination with supply temperature optimisation leads to a reduction of heat loss in the distribution network, better utilisation of production assets and reduced cost of heat generation.

The solution consists of three modules:

1. Load Forecast - Enabling effective and accurate planning of the operation.
2. Production optimisation – Enabling operating the most efficient heat plant at any given time. Savings range from 1-3% of the fuel cost.
3. Temperature optimisation – Data driven supply temperature minimisation to increase heat distribution efficiency. Savings range from 5-10% of the distribution losses.

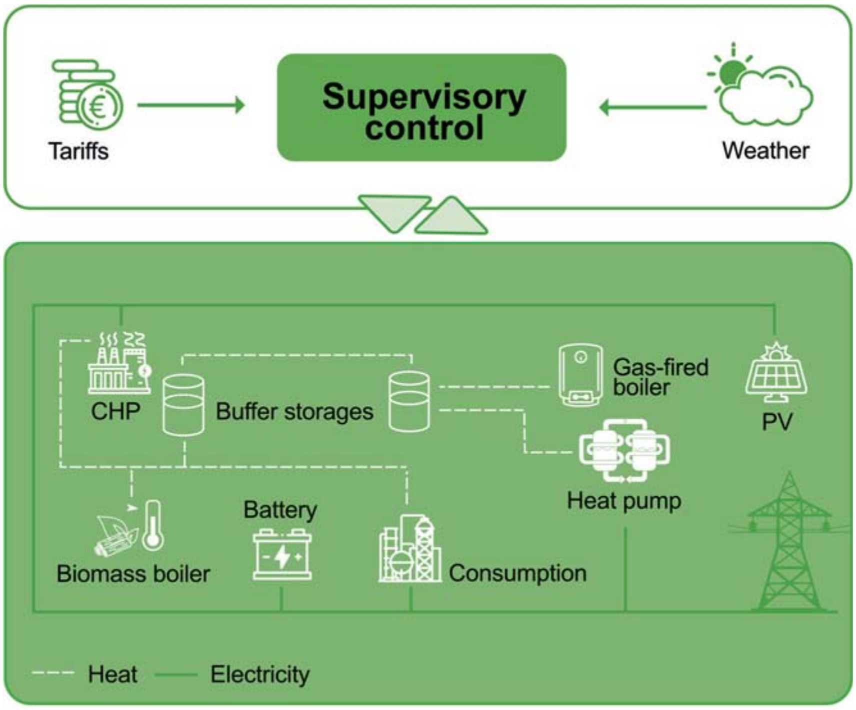


Figure 6.2: Exemplary configuration of the heating plant of a simple district heating network, © BEST – Bioenergy and Sustainable Technologies.

6.2.2.3 Application 3: End-to-end control saves energy and enables better utilisation of green energy sources at a lower cost

Vatajankoski is an innovative energy company at Kankaanpää, Finland, originally based around local hydro power. Besides a bio-CHP plant and gas and oil peak load boilers, Vatajankoski has invested in a new waste heat plant and a large thermal storage.

Increased complexity of Vatajankoski energy sources and their characteristics, as well as increased storage capacity highlighted the need for digital tools to assist operating the various plants in the optimal way, in the perspective of economic and environmental footprint.

Vatajankoski also combined building-level demand response control with production optimisation and hereby they achieve extra flexibility to optimise the production. With the AI-based Danfoss Leanheat tools they can utilise the buildings thermal mass as a virtual energy storage, which minimises their utilisation of peak load boilers and enables increased opportunities to take advantage of fluctuating electricity prices.

Operational data show a clear value compared to baseline operation without AI-based control and optimisation.

"*We have been using heating optimisation since 2018, and our heating customers have benefited from it both in terms of energy consumption and money. Consumption peaks and with them also production peaks have decreased considerably, so fewer peak production facilities are now needed.*

When the price of electricity fluctuates, the optimisation of electricity production is taking the prices well into account. We can prioritise electricity production and transfer production from one plant to another. The virtual heat storage has a lot of adjustment potential, and we have high expectations for it. Although we have a fairly small district heating network, the property mass is large. We expect that we will be able to cover an even larger part of the sold heat with virtual storage."

Lauri Hölttä,
Production Manager at Vatajankoski/Finland

6.3 Operational optimisation of distribution

In some cases, the operational optimisation of production presented in the previous section could benefit from an optimisation of distribution of heat in the DHC network. The objective of the optimisation of distribution is to lower the costs by optimally managing temperatures and mass flow rates in the distribution network, in order to limit thermal losses or pumping costs. This optimisation is constrained by the thermal inertia and propagation delays in the network, which provide an opportunity for storage in the network, but also introduce a more complex management. This section provides some insights on the achievements in this direction.

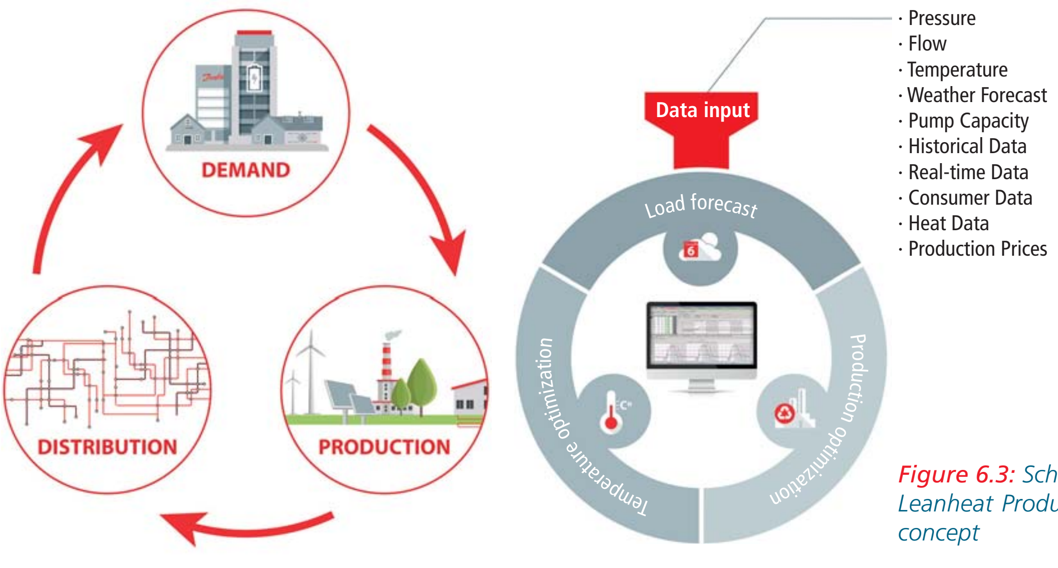


Figure 6.3: Schematic overview of Leanheat Production optimisation concept

6.3.1 Historical perspective and current state of the art

Classic control of DHC distribution networks rely on heat curves to calculate the supply temperature and flowrate necessary to meet the consumer demand, characterised by space heating and domestic hot water needs, typically translated into a valve opening for the primary loop of an indirectly connected type substation. On the hydraulic side, pump operation at production can also be piloted in order to guarantee sufficient heat on distant and/or critical substations, regulation being implemented through appropriate metering of the substations of interest. (Frederiksen & Werner, 2013) consider four types of classic control (supply temperature control, differential pressure control, heat demand control, flow control at substation).

While robust and relatively flexible this method of control can lead to major drawbacks. Because the flowrate in each substation is set locally by each consumer, regardless of the full picture, a heat shortage could induce an unfair heat distribution, as consumers closest to the heat supply would be inherently prioritised.

In addition, classic control is limited as soon as significant intermittent energy sources are connected to the network (thermally or electrically), as it is not able to fully exploit the potential of said sources, therefore leading to an inefficient energy use.

Advanced distribution control strategies have been developed to enable several improvements of district heating network operations. The key element is to unlock flexibility in the network by controlling the heat load based on predictive models (Vandermeulen et al., 2018).

A direct use case of advanced control is an optimal lowering of supply temperatures (Vadermeulen et al, 2018 & Giraud, 2016) , leading to a net decrease of heat losses in the network, an improved efficiency of heat pumps and CHP plants connected to the network and a wider range of waste heat sources. In a similar way, advanced control can also be used to optimally control the differential pressure set by the supply pumps, while it is not yet a thoroughly studied matter (pumping costs are usually negligible), it would become a relevant strategy in the case of constant low temperature networks (Giraud, 2016).

Another use case of advanced control is the exploitation of the thermal inertia of the network itself to shave power peaks in the morning (typically) by overheating the supply water, therefore avoiding start-up of costly and polluting peak heat production plants. It is a rather cheap option, as it requires little to no infrastructure investments and it reduces overall operational costs despite a 0.3% increase of heat losses (Basciotti et al., 2023). But the amount of storable heat is rather limited and temperature cycling may damage the network components (Hennessy et al., 2019). Pipe wear is not yet included in models and no long-term studies on the subject have been conducted. Network storage requires a sufficiently large network to be relevant and there is currently no standardised method to calculate the effective storage capacity of the network. However, (Vandermeulen, 2020) developed a method of quantification and more research on the matter will eventually be conducted.

A preferred flexibility solution is the use of centralised storage tanks as they offer a bigger (up to 10x more) and more controllable capacity at a moderate cost (Hennessy et al., 2019). They allow to reliably optimise CHP production, heat pumps and RES integration in a network.

Advanced control utilises model predictive control (MPC) methods that rely on dynamics models of the controlled system to perform predictions over a set period of time depending on predictions of the system disturbances (e.g., external temperature for a DHN) (Jansen et al., 2023). Advanced controllers solve an optimisation problem to find a set of system parameters to minimise a cost function with respect to physical and operational constraints. Such a controller is able to optimally operate a DHN to fulfil many different objectives (reducing operation costs, reducing CO_2 emissions, etc…).

Compared to the operational optimisation of production, the intrinsic non-linearity of the DHC network dynamics pose significant challenges in terms of optimisation. A popular method is to employ a two-step procedure. In the first step a thermo-hydraulic simulation of the consumers and the network is performed, and in the second step the supply side is optimised. The earliest such approaches for DHC networks dates back to 1995 (Benonysson et al., 1995). This method is close to the one described in the technical documentation of the Termis software (Termis Engineering l Schneider Electric, n.d.), and is used in practice in several operational districts. However, the approximations used in this method are not always suitable and are difficult to calibrate especially in large scale networks.

Over the years, various improvements have been made, especially to integrate more distribution constraints in the MILP optimisation problem used for production, while still employing a two-step approach involving simulation to deal with non-linearities (Giraud et al, 2017, Bavière & Vallée, 2018, Quaggiotto et al., 2021, Capone & Guelpa, 2023).

Due to the better real-time performance of MILP solvers, efforts are also made to approximate the inherent nonlinearities of thermal systems, e.g., by approximating a mass flow with varying temperature with a mixture of multiple mass flows at constant temperature, see e.g. (Moretti et al., 2021) or (Muschick et al., 2022).

Another approach is to gather a large quantity of data from the network operation to build a black box model replicating the dynamics of the network depending on external perturbations. This method, while computationally fast, is not easily replicable as few network operators have access to extensive operation data and the model needs to be re-trained after any modification in the DHN.

A recent development in MPC control of DHN, is the use of non-linear MPC's (Jansen et al., 2023). It is currently limited to small networks due to prohibitive computational times.

Advanced control is a very challenging matter, as it requires extensive data about the operation of the DHN, it is needed to know the state of every valve in the network, the temperatures at critical points and the pressure to be able to perform relevant predictions. The bigger the network is, the harder it is to get a grasp of the system dynamics. Many commercial products now embed solutions for simulating and optimising the distribution of thermal networks, of which a few examples are listed already in section 6.1.2.

6.3.2 Applications

6.3.2.1 Application 1: Optimisation of the network pumps operation

The substation and the heating network age with time. As repairs and renewal of the fundamental infrastructure is very expensive – especially the supply pipes themselves – it is in the interest of the heat suppliers to keep the infrastructure in good shape as long as possible. A range of factors increase the rate of aging of the infrastructure. Some of these are outside the influence of the heat suppliers, but the following factors can be monitored and avoided:

- Unnecessarily high pressures
- Unnecessarily high temperatures
- Pressure peaks and temperature jumps
- Hard water (e.g. through damage to heat exchanger)

Using SAM District Energy (Samson, 2023 & Theiss et al., 2023) or other visualisation systems these factors can be monitored. However, more is possible. Automatically forwarding pressure sensor values to generate a control input to the main supply pump guarantees that unnecessarily high pressures in the network are avoided. Using AI methods to predict the power demand of buildings and to predict the network properties (such as heat demand of all consumers, heat loss from plant to heat consumer and duration of heat front to arrive at consumer), it is furthermore possible to use the network as a buffer. Pre-charging the network before high energy demands allows us to avoid unnecessarily high temperatures and temperature jumps. At the same time the prediction makes it possible to predict situations of sudden low demand, so the network pumps can be reduced before the substations shut down their energy consumption, avoiding pressure peaks in the network (Hartung et al., 2021).

Furthermore, using strategically staggered mass-configuration commands, certain situations that can lead to pressure peaks (such as all substations going into night-mode at the same time) or peak demands (such as all substations terminating their night-mode at the same time) can be avoided all together.

6.3.2.2 Application 2: Optimised control of supply temperature

As presented in section 6.1.3.2, LeanHeat production embeds a solution for optimising distribution. Historically, the supply temperature was optimised based on past experience, often optimised based on number of complaints. With the emergence of computational power, it became feasible to develop theoretical models of the systems that could be used to simulate the operation and find an optimal supply temperature. This is a difficult task that required detailed knowledge of the system and its components as pipes, insulation, components, soil properties, demands, etc. While this method provided a big improvement compared to the prior approach, it was unable to capture the dynamics of the systems and consequently leads to a suboptimal solution. The state-of-the-art solution is to utilise a data driven approach, based on a wide range of measurements within the system and at end-users. This approach combines physical and numerical modelling and creates a computational fast digital twin of the district energy network. The digital twin describes the system time delay, heat losses and system dynamics. By taking the time delay, heat losses and the dynamics into account the supply temperature optimisation becomes significantly more accurate, leading to distribution loss savings in the range of 10-20% compared to the prior theoretical model based approach.

With electrification of the heat supply the temperature optimisation becomes more relevant than before as the supply temperature has a significant impact of the efficiency of heat pumps, where every degree reduction in the operational temperature brings approximately 2% increase in the efficiency of heat pumps.

6.3.2.3 Application 3: Enabling energy storage in the network

Optimal operation of supply temperature to enable energy storage in the network pipes has been investigated in the city of Grenoble, France, using the DistrictLab-H solution. More details on DistrictLab-H can be found in the corresponding section 7.3.1 as well as in the reference (Bavière & Vallée, 2018).

6.4 Operational optimisation at consumer level

DH networks are demand driven, meaning that the control of the production plants ensures that the amount of heat delivered is always equal to the demand. In the end, it is the consumer who drives the demand by adjusting the indoor temperature set point. The controller of the DH substation, typically including a thermostat, will then decide how much water of the DH network is drawn from the district heating system to reach the set temperature of the building. Each end consumer will decide this for themselves, and the aggregation of each of these individual heat demands is the total heat demand of the network, and this heat demand will be covered by the heat production units.

6.4.1 Historical perspective and current state-of-the-art

Normally, heat demand controllers of the different end-users or buildings act totally independent of each other. There is no communication between them. This can lead to unwanted situations where all connected buildings demand heat at the same time, and heat demand peaks occur. This is often the case in DH networks in the morning, when room thermostats switch to day mode after night setback. These peaks lead to high operational costs, and high investment costs since network operators must guarantee that enough heat production capacity is available to cover those high, but often fairly limited in time, demand peaks.

As usual a common solution to overcome demand peaks are the installation of thermal energy storages nearby the heat production facilities. Recently however, more innovative approaches have been investigated, such as the application of demand response. In this approach, the moment of heat extraction from the DH network is coordinated by slightly shifting the individual heat demand of the connected buildings in time. Since the buildings represent a big thermal mass, a small shift in time already can make a large difference for the overall peak heating demand of the network. Demand response can therefore optimise when and which production units must be used, or to overcome (local) capacity constraints or congestions in the networks. This is often referred to as 'load management' or 'load shifting'. Besides shifting heat consumption in a DH network, another application of demand response in the connected buildings is the ‘minimisation of the return temperature’. This originates from the fact that, when manipulating the heat consumption of the building, the return temperature from that building is also inevitably influenced: when temporarily reducing heat consumption in the building, the return temperature will drop, and a short increase in heat consumption will also increase the return temperature. The controller can make use of this effect, and be especially designed for this purpose: the same control signals sent to a building to reduce or increase its heat consumption, can also be used to reduce or increase the return temperature temporarily. By modelling the relationship between the control signal and the return temperature for each building, a control system can be built to reduce the average DH network temperature, by coordinating the actions between the different connected buildings. A recent review study on demand response in DH networks can be found in (Guelpa & Verda, 2021). Besides a discussion about the ambiguously used terminologies and a classification of demand side management options, the work gives an overview of the options to store heat in the DH network, and an overview of both simulation based as well as real-life applications of demand response in district heating. These applications show peak shaving reductions up to 30% and operational cost reductions up to 10%. An extensive overview of research and applications of demand response in DH network was also given by Buffa et al. (2021).

6.4.2 Applications

6.4.2.1 Application 1: Peak load reduction using coordinated load management on 9 buildings

An example of a controller that coordinates the heat consumption amongst the different connected buildings making use of demand response, is the STORM controller. This controller was developed in the Horizon 2020 STORM project (2014-2019) (www.storm-dhc.eu). The controller was demonstrated in the network of Växjö Energi AB, a Swedish network operator in the South of Sweden, and the results are available through Van Oevelen et al. (2020).

The network is a small, rather traditional network of about 200 consumers, in the community of Rottne, which was used as a demonstration site in STORM. This network mainly uses wood chips as fuel, supplemented with expensive bio-oil in their peak boilers. In this network, the aim was to minimise the peak oil consumption by means of peak shaving. In practice, the controller will aim to keep the power demand of the network below 2.5 MW, since this is the threshold for the peak boilers to be switched on. It should be noted that only 9 out of the about 200 consumers were connected to the STORM controller, so only a small share of the connected buildings could be controlled. Nevertheless, these nine buildings are the largest ones in the network and represent about one third of the total energy consumed in the network. This means on the other hand that two thirds of the network energy demand was uncontrollable.

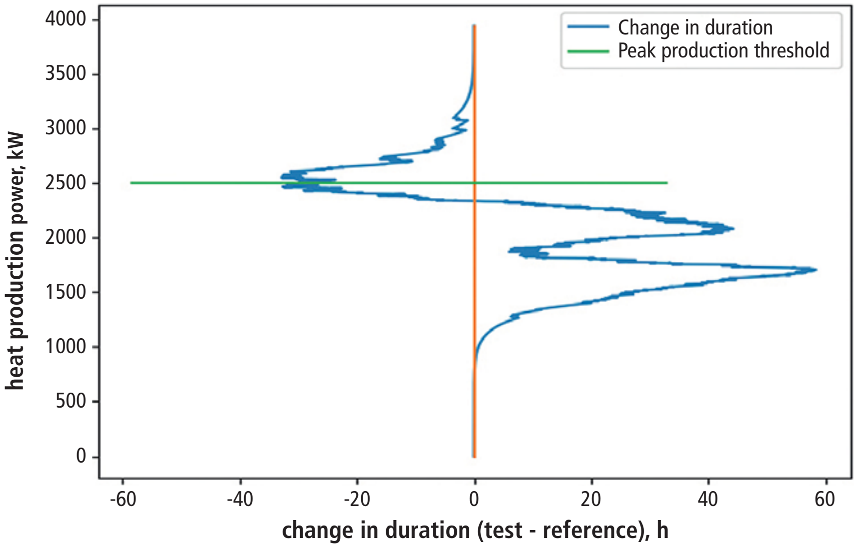


Figure 6.4: Change in the load-duration curve of total network heat load compared to the reference in December 2018

Data was collected from July 1st, 2015, to January 31st, 2019, and the heat demand from periods when the controller was active was compared to reference data from periods when the controller was not operational.

Figure 6.4 shows the results of the peak shaving tests in December 2018. The y-axis shows the heat production in the network, the x-axis shows the difference in duration between the STORM controlled network and the reference, baseline behaviour: e.g. the duration whereby the network used 3 MW was about 5 hours less in the actively controlled case than in the reference case, whereas the duration whereby the network used 1.5 MW was about 20 hours more in the actively controlled case vs. the reference. As can be seen, the controller tries to shift the heat demand above the threshold of 2.5 MW to periods below the threshold. By controlling those 9 buildings, the peak-shaving tests resulted in a reduction in the peak consumption of 3.1% compared to the reference scenario without the STORM controller active.

This peak heat reduction has been achieved despite an overall heat demand increase of the large uncontrolled part of the building stock in Rottne – a difference that could be explained through changing weather and consumer behaviour between the reference and the test period. If this influence is corrected for, then a peak heat reduction of 12.7% was determined. These results on a small subset of the connected DH buildings show that demand response in buildings can significantly reduce the peak demands in the network, without the addition of additional thermal storage tanks in the grid.

6.4.2.2 Application 2: return temperature minimisation

This example was developed and demonstrated during the Horizon 2020 TEMPO project (www.tempo-dhc.eu). As a first step, a combination of black and grey-box models was built describing the behaviour of the building, the heating supply circuit and the substation. In this way, it is possible to simulate the reaction of the building on the change in radiator circuit supply temperature, and as such to predict the return temperature of the building. These models are then used to implement a model predictive controller (MPC), with the objective to minimise the average return temperature of the building.

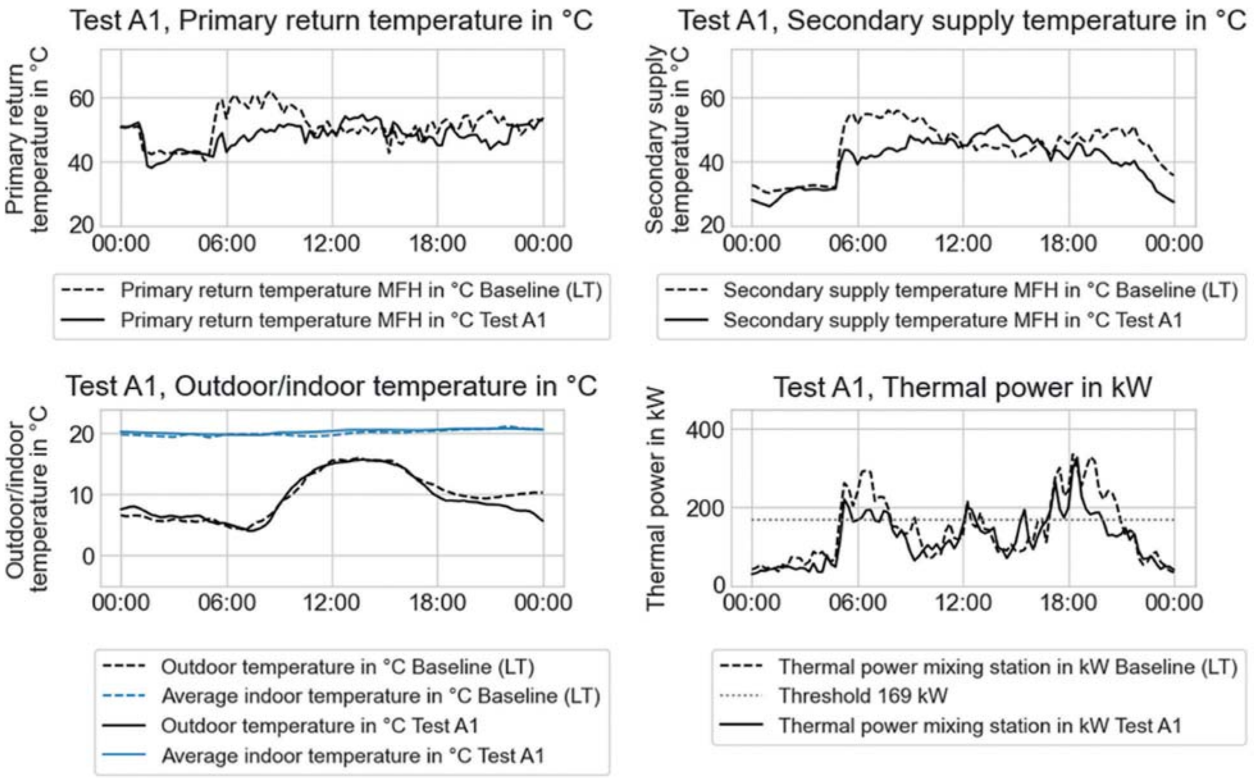


Figure 6.5: Representative profiles for controller test (November 5th, 2021) vs baseline (November 9th, 2021) for similar conditions (outdoor temperatures in average between 9 and 10 °C)

After the development, the controller algorithms were tested on a multi-family building connected to the DH network of Brescia, Italy. In this building, the radiator circuit supply temperature set point can be influenced by the controller, and as a result, the heat demand as well as the primary return temperature are modified.

The smart control feature was tested from 25/10/2021 to 07/11/2021. In Figure 6.5 the behaviour of the controller can be observed. The figure shows the difference between two days with a similar outdoor temperature profile, whereby one day the controller was active (5th of November 2021) and a reference day where the controller was not activated (9th of November 2021). As can be seen, the reference controller will increase the secondary supply temperature in the morning between 5h and 9h, to overcome the night setback in the morning. In this period of heating up the building, the power consumption is high and along with the primary return temperatures are rather high (around 60°C). The smart controller decides to keep these secondary supply temperatures way lower in these first hours of the day, reducing the primary return temperatures by 10-15°C to about 50°C, compared to the 60°C in baseline operation. These lower temperatures are then compensated by higher supply temperatures compared to baseline, in the second phase of the day (12-17h). It can also be observed that the peak consumption in the morning is significantly lower than during baseline operation. This is a beneficial side effect of the smart control. As can be seen, the indoor temperatures between baseline and smart control are very comparable.

Analysing the results over the entire testing period, an average return temperature reduction of 0.7 K was observed. During this test period, the daily peak energy – i.e., the heat load above the baseline threshold – was reduced by 330 kWh on average, corresponding to 60 to 70% of the total daily peak energy.

6.4.2.3 Application 3: Peak load reduction

HOFOR and Copenhagen City Properties & Procurement (municipality's building department) are currently testing the potential of minimising peak heating demand to increase CO_2 neutral base-load heat production usage in Copenhagen by utilising AI-based Danfoss Leanheat building heating control solutions.

The first part of the demonstration took place during the heating season 2021/2022 and included 17 municipal buildings (mainly daycare centres). The buildings were already equipped with communicative heating controllers, and thus the integration to the Leanheat cloud-based AI control was relatively simple. The Leanheat software was used to establish a thermodynamic model of the buildings, which enabled the buildings to utilize the building thermal mass for supporting the district heating system operation.

The main goal of the demonstration was to reduce the peak in heat demand that occurs in the morning (6:00-10:00 am) by making the heat consumption more flexible. Thus, the project has been named 'District Heating Flexumers' since the buildings that previously were only seen as energy consumers have become an active part of the district heating system. Each building acts as a virtual heat storage by increasing its consumption when heat production is cheap and ecological, and decreasing it during times of high demand by providing flexibility on the consumption side.

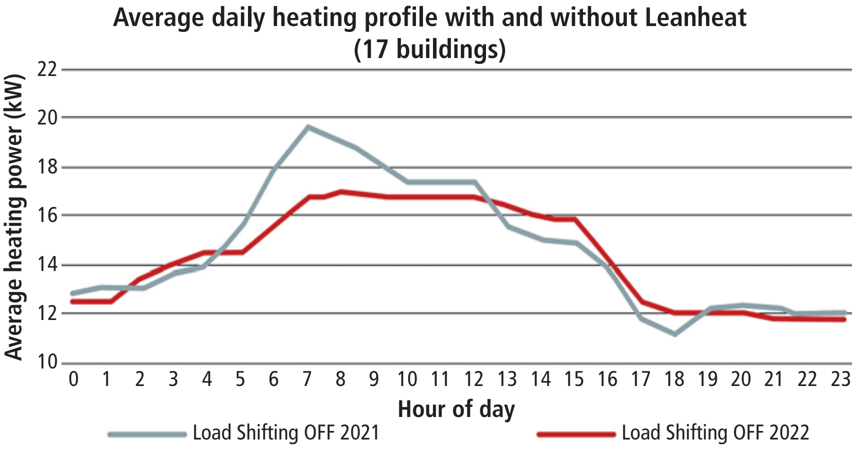


Figure 6.6: The heating profile for two comparable days, without load shifting (2021) and with load shifting (2022).

The results of the demonstration for the cluster of 17 buildings show that the average morning peak in the specified period of 4 hours decreased by 14%, compared with the average peak consumption before the implementation of the smart control, predictively factoring in upcoming changes in weather, such as solar radiation and wind, based on weather forecast data from the AI -based control.

The peak demand data measured at the buildings, show that the maximum peak power has decreased from 27.5 kW/building to 21.5 kW/building (-22%). The calculation compares the highest peak during load shifting to the highest measured peak in the previous heating season at the same outdoor conditions. After extending the demonstration to include 52 buildings, the peak power reduction has proven to be similar. In relation to energy savings for the buildings, evaluations show a yearly energy saving potential of 5% on average.

HOFOR sees ‘District Heating Flexumers’ as an important measure to minimise short-term usage of fossil-based peak load production and to incentivise renewable-based heat-producing units.

6.4.2.4 Application 4: Building level demand response

In 2019 Fortum launched the Smart District Heating pilot project in Espoo, Finland, with the aim to study the benefits of building level demand response, on the basis of Danfoss Leanheat control solutions. 96 housing companies participated, and their heating control was optimised both on property level and for the benefit of the district heating network. After the first heating season, concrete results and lessons had been learned.

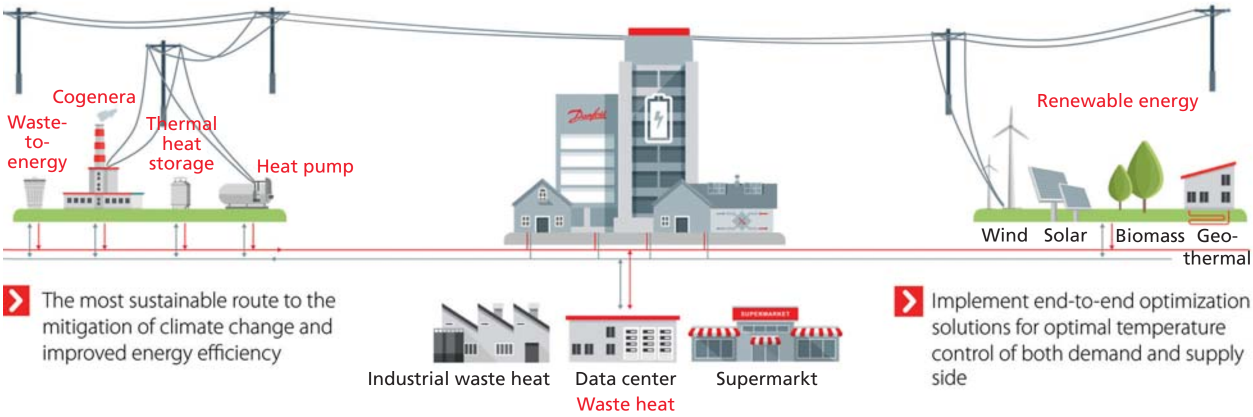
During the project's review period from October 2020 to March 2021, the average temperature-adjusted energy savings for the housing companies were 5.5% compared to the same period of the previous year. In total, the consumption of district heating decreased in 85% of the housing companies. In terms of indoor room temperatures, it was also possible to achieve well balanced conditions, e.g., the room temperature in the measured apartments of the pilot sites has been more than the target of 20°C for 95% of the time.

The customer basis involved in this pilot equals 20MW heating capacity, and experience shows that the virtual thermal storage capacity for this basis is +/-5MW. This shows that AI based building controls, that learn on the building thermodynamic behaviour as well as usage, can be used for optimising the set points of the building thermal installation controls. Knowing how the building responds to changes in ambient conditions and usage enables proactive control of the heat supply, which can be used to reduce the heat consumption, and at the same time optimise the energy plant operation.

"The results of the pilot project have strengthened our previous positive experiences with demand response. The positive thing was that almost all sites were able to reduce consumption during the pilot period.

In addition, demand response supports the transition towards carbon-neutral heating, as balancing consumption peaks reduces the need to use fossil reserve heating plants."

Riitta Ståhl,
Development Manager, Fortum, Finland



The most sustainable route to the mitigation of climate change and improved energy efficiency

Implement end-to-end optimization solutions for optimal temperature control of both demand and supply side

Figure 6.7: AI-driven demand side response scheme for district heating system (Danfoss, N/A)

6.5 Analytics for fault and leak detection

Digitalisation in DHC networks provides opportunities for fault detection and predictive maintenance, which can be performed at various system levels. Chapter 5 presented possibilities for automated fault detection and diagnosis (FDD) on the demand-side, e.g., in building and substations. At the system level, FDD can also take place in the DHC distribution network as well as in the DHC production plant.

Various types of actions are possible to detect, protect and even anticipate faults. Isermann (2006) provides a complete overview on the field and defines most of the terminology related to fault detection and diagnosis. Among the important concepts, we can highlight the following aspects: the time at which the fault occurs and the precision of the fault diagnosis.

A fault can occur at various times in the lifecycle of an industrial system such as a DHC network or production plant. In general, a distinction is made between faults occurring at design, at commissioning, and during operation. Most of the work on fault detection focuses on detection during operation, while faults occurring at design are rather addressed by preventive methods related to systems engineering. Fault occurring at commissioning pose a significant challenge in many situations, because they can be hard to identify from operation data. An example of such faults can be the wrong installation of an equipment, which makes it less efficient. Månsson (2019) identified several commissioning faults in DHC substations. Some commissioning faults can be detected from operational data, e.g., the wrong placement of a sensor could be deduced from the comparison with other sensor readings.

Finally, a distinction is usually made between fault detection and fault diagnosis. Fault detection refers to detecting that a fault is present, without having more information on its characteristics. Fault diagnosis refers to identifying the type of fault more precisely, especially characterising its type, severity, rate of deterioration, and localisation. While fault detection may be relatively easy by monitoring drifts or anomalies in measured data, fault diagnosis usually requires more detailed models for estimating the fault characteristics.

Fault detection and diagnosis benefit from the increased availability of data which can be obtained from a more digital DHC system (Vallee et al., 2023).

6.5.1 Historical perspective and current state-of-the-art

For the production plants in DHC systems, FDD and predictive maintenance solutions are closely related to the ones developed in other industries or in the building domain. In particular, one of the key sources is the IEA EBC report “Building Optimization and Fault Diagnosis Source Book” (IEA EBC Annex 25, 1996). Although it dates back from 1996, it features a comprehensive analysis of faults for most of the DHC subsystems. While this report considers gas burners and oil burners within a building heating system, most of the faults listed apply as well in a DHC plant, although they may be of different scale. A maintenance team should be able to detect and diagnose some of those faults more efficiently in a DHC plant. Examples of such faults are the ones related to pumps and three-way valves which may go unnoticed in a single building system but would be monitored and corrected in an industrial DHC plant. Panday et al. (2021) as well as Hundi & Shahsavari (2020) provide a recent state-of-the-art of fault locations and detection methods in thermal power plants. For faults on heat pumps and chillers the IEA EBC report as well as subsequent work (Bode, Thul, Baranski & Müller, 2020; Kim, Payne, Domanski, Yoon, & Hermes, 2009), consider a list of seven typical faults (related, e.g., to heat exchanger fouling and issues with refrigerants), which can occur in DHC systems as well. All of these faults do not lead to an immediate stop of the device and may therefore go unnoticed. However, they all lead to an impact on the energy efficiency. Kim et al. provides an analysis of this impact efficiency. Kim et al. (2009) provides an analysis of this impact. Although many works in the literature concentrate on air/air chillers, the described faults also apply to water/water devices used in DHC systems.

Several types of faults can occur on the distribution network itself: leakage in the network pipes, insulation damages (thermal loss), hydraulic distribution faults (insufficient pressure difference, unwanted bypasses, valves in wrong position). All these types of faults lead to an overall lack of efficiency of the network. Important leaks may also lead to a complete failure of heat distribution in some parts of the network.

Methods for detecting these district heating distribution faults have been investigated for decades. In the 1990s, two IEA DHC projects investigated methods to quantify heat losses in DHC networks by means of infrared thermography (Jonsson and Zinko, 1993; Zinko et al., 1996). Nowadays, infrared thermography is one of the most efficient ways of localising important leaks and unusual thermal losses in DHC networks. This technique has three main drawbacks: (1) it is usually limited to short-time measurement campaigns, therefore not allowing constant monitoring of new faults. (2) there can be a lot of interferences due to other sources of heat in the city. (3) its accuracy goes down when the weather is hot and/or the temperature of the network is low, so that it can't be applied all year round.

Other methods based on external measurements are available: acousticsensors detecting the noise produced by leaks, injection and measurement of helium gases in small portion of the network. Another widely used option for pipe network supervision on component level is the use of alarm threads precast into the pipe insulation layer, monitoring resistance and impedance to reveal wet foam. However, it is usually not run on a continuous basis, and alarm threads are not present in all parts of the system, and, in particular, not on service pipes.

Recently, more investigations have been focusing on methods allowing constant supervision with the help of internal measurements, such as pressure or temperature measurements (Rüger et al., 2018). A branch of this research has also focused on how to exploit hourly resolved heat meter data to calculate pipe heat losses continuously under operation. For example, Fang and Lahdelma (2014) and Wang et al. (2018) set up network models that were capable of evaluating in-operation heat losses on the single pipe level. Other approaches similarly build hydraulic network models that are compared against measured values to reveal critical heat loss, leakage or fouling - including Manservigi et al. (2022) and Xue et al. (2020). In the coming years, digitalisation of DHC is therefore expected to boost the possibilities for fault detection.

6.5.2 Applications

6.5.2.1 Application 1: Leak detection / localisation in DH network pipes in the Munich DH network

In case of a large spontaneous leakage, heat transport medium (and the thermal energy it holds) is lost. To prevent evaporation due to high supply temperatures, the pressure must be maintained, and losses must be compensated. A fast and targeted action is necessary within several minutes for up to 2-3 hours as there is only a certain amount of medium stored and treatment capacities are limited. Hence the exclusion areas affected by the leakage have to be identified. A solution for localising large, spontaneous leakages in the network was developed in a joint research project of Stadtwerke München and Ostfalia Hochschule. This solution is based on the analysis of negative pressure waves caused by the occurrence of leakages. Each sensor registers the pressure wave at a different point in time depending on its position in the network with respect to the leakage position. Figure 6.8 illustrates the solution.

It has been found that a minimal number of sensors already allows a sufficient localisation (Vahldiek, Rüger, et al., 2021). Five sensor positions (out of 25) were chosen for the given network with a total trench length of 90 km. Furthermore, pressure drop time points (PDTP) can be determined and localisation is still sufficiently accurate even in the presence of surprisingly high noise with 3s standard deviation (Vahldiek, Rüger, et al., 2022a).

The theoretical PDTPs are compared to the ones extracted from pressure measurement data (Pierl et al., 2020). Figure 6.8 (top) shows extraction of PDTPs from data of two sensors exemplarily. Figure 6.8 (bottom) illustrates the comparison of these PDTPs to ones which are calculated based on network topology. Calculated PDTPs are numbered according to distance of sensors to a-posteriori known leakage localisation for illustration. Compared to that, extracted PDTPs show significant errors and sensors appear in a totally different order. An additional challenge is matching the time axes. This is determined by the minimal sum of absolute time differences for all sensors. A detailed analysis of measurement data for all 22 available events was conducted. It was shown that there are several algorithms available for determination of PDTPs. Each of these algorithms benefits from a

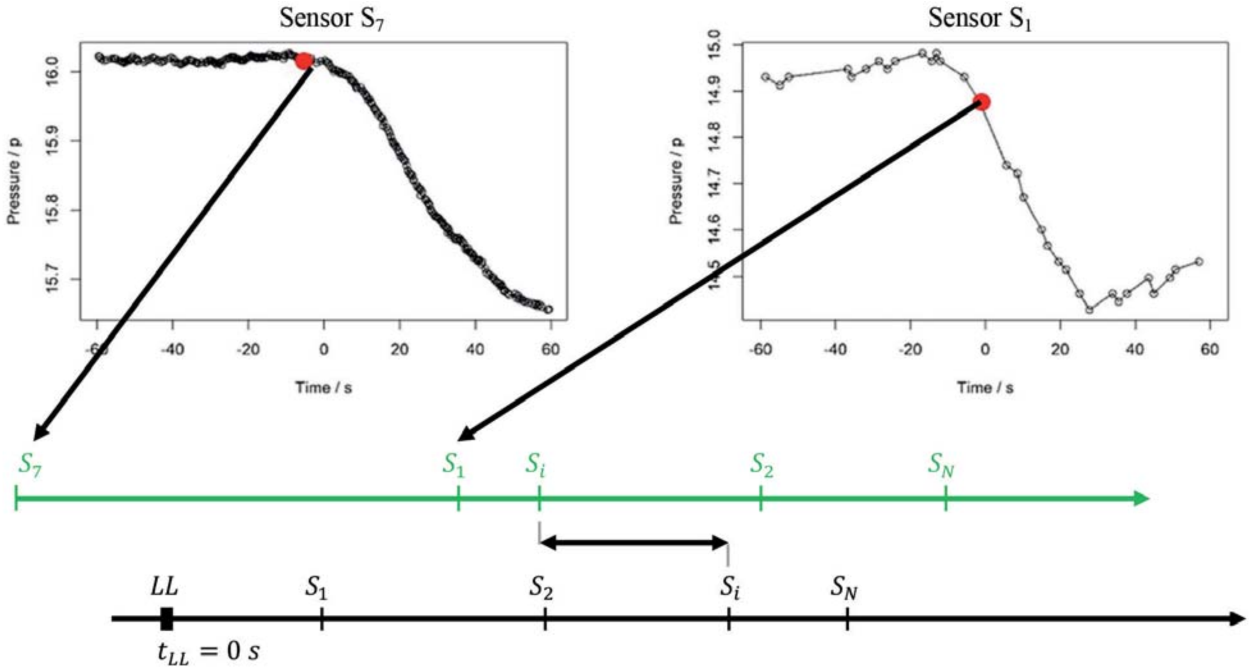


Figure 6.8: Extraction of pressure drop time points (PDTP) from data of two sensors (top); comparison of extracted and theoretically calculated PDTPs (bottom).

carefully selected time frame for its application (Vahldiek, Yao, et al., 2022). The limited number of events is an issue as further events could change the ranking for the algorithms.

Evaluating the pressure wave is demanding because the speed of sound in pressurised water pipes is around 1,500 m/s. Thus, the pressure wave travels across the whole network in about 10 s. For normal operation, new sensor readings every few seconds are sufficient, without the need for perfect time synchronisation, time stamps or fixed data rates. This motivated the analysis of the data quality for different events (Vahldiek, Rüger, et al., 2022b). It was found that leakages above 50 t/h refill mass flow can be evaluated successfully. Furthermore, the developed model for data evaluation (MoFoDatEv) could be employed for direct localisation without a separate determination of the PDTPs.

The proposed solution has been deployed on the actual network in Munich[6-1]. Further details on this implementation can be found in chapter 7.

6.5.2.2 Application 2: Leakage localisation and recovery strategy using “Smart Detection”

Leakage and burst pipes create multiple challenges in district heating networks: costs for lost water and heat, potential follow-up infrastructure damage (e.g., damage to buildings, underwashed roads, etc.) and the challenge of the repair itself. The repair involves sectioning and emptying pipes, opening roads and typically undersupplying sections of the entire network. Here, not only strategies for localising the damage as quickly as possible are needed, but also strategies to minimise the impact on clients and to get the network back up and running as quickly as possible.

Using AI-based load prediction methods, it is possible to find systematic local changes in the supply situation indicating a leak or burst pipe. Further data-based analysis includes full thermo-hydraulic simulations of the network to localise leakages or using meter data in strands to calculate backwards from the meters, finding sections of pipe with abnormally high pressure losses or flow rates.

Once a leak has been localised, the main challenge lies in supplying as many consumers as

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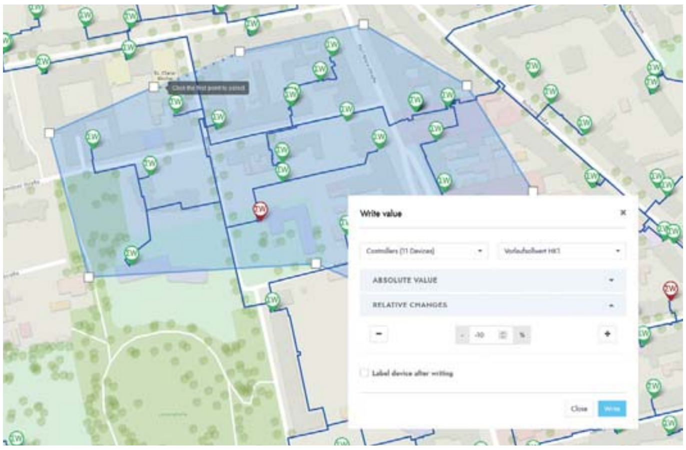
[6-1] Funding by BMWK is gratefully acknowledged (FKZ 03ET1624B and 03ET1236B). Without it, development of this online monitoring approaches would have not been possible.



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Controllers (11 Devices) ▾ Vorlaufsollwert HK1 ▾

ABSOLUTE VALUE ▾

RELATIVE CHANGES ▴

− -10 % +

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Close Write

Figure 6.9: Example of a recovery strategy in case of damage in the network. Using map-based selection devices in strategic areas are selected and their setpoint is throttled by a certain percentage. This makes them less "greedy", avoiding unnecessary pressure drop.

Figure 6.10: Example of typical flow rate profiles at meters in the case of a burst pipe and the subsequent repair.

possible while safely repairing the leak. One aspect of the challenge is that the default setting of building heat controls in demand driven systems is "greedy" - it will try to cover the demand of the building irrespective of the general supply situation. This means that – radiating out from the point of undersupply – successive substations open their valves to 100%, trying to meet their heat demand. For the network dynamics, this has two major consequences:

- There is a pressure drop in the network, that can lead to prolonged supply challenges and create instability that can create difficulties with the mains pumps and the power plants.
- The "greediness" of substations makes it impossible to guarantee supply of critical consumers such as hospitals, schools etc.

The solution is two-fold: using a supply-based map-view it is easy to see which areas of the network are undersupplied. Here, its controllers can be strategically grouped and throttled to manage the supply situation and reduce the pressure drop. This allows the network supplier to distribute the supply shortage evenly or according to client criticality. Throttling is possible both to fixed values (e.g., set valve positions to 30%) or relatively (e.g., reduce setpoint inlet temperature for heating by 10%). In a supply shortage the goal is to distribute the shortage evenly by evenly throttling the demand until the supply can meet it. Without any throttling the most downstream consumer will automatically be the most undersupplied. Attaching labels to the throttled substations makes it easy to set them all back to normal mode at once, once there no longer is a need to throttle power consumption.

6.5.2.3 Application 3: Unwanted bypass detection using "Smart Detection"

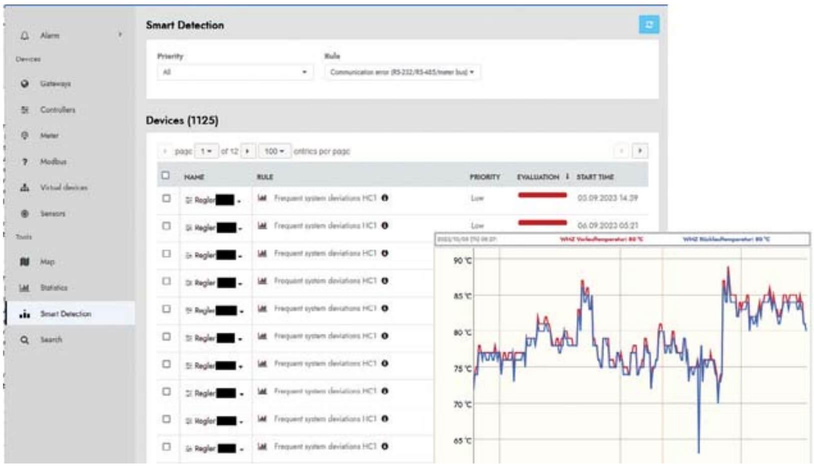
In substations, for comfort reasons in summer, often a small flowrate is maintained by means of an integrated bypass system. This ensures that mainly in summer, domestic hot water preparation is sufficiently fast. However, these bypass systems might be faulty, causing too high flow rates and resulting in an unnecessary power consumption for the main network pumps. Moreover, substations that act as an unwanted bypass or short-circuit are problematic, as they create high flow rates, high return flow temperatures (and hence heat losses) and in some cases even then do not cover the demand of the building. Typically, in larger networks the worst 5% of the substations act as bypass or close to a bypass. These 5% of substations require 60% of the pump power in summer and 20% of the pump power in winter.

Systematic analysis of all substations shows where the most problematic substations with the highest potential exist. "Smart detection" implements such an analysis, weighting the problematic substations both by how bad the bypass is and how important it is for the entire network. These are provided as an accumulated "rating" along with repair recommendations and a link to directly jump to the data of the problematic substation.

The smaller the temperature spread and the bigger the flow rate, the worse the bypass is (both in itself and in the impact on the network). The sum of the weighted inverse temperature spread and flow rate results in an impact score. This impact score can be determined for all substations in the network and then used to identify the "worst" substations.

Two examples of the impact of uncontrolled bypasses in substations:

- A single bypass in a building that resulted in 15% too high heating costs and unnecessarily CO_2 emissions. In this case, a public building had 6 secondary heating loops, one of which was unregulated. An additional primary control loop was added to restrict the return flow temperature to a constant setpoint, however in the history of the building somebody had removed the corresponding electric actuator, creating the bypass. As a short-term measure the electric actuator was re-instated, halving the bypass flow rate (Figure 6.12 (a)) and reducing power consumption by 15%. As a long-term measure a controller was being added to the 6th loop. As this substation was also used as pressure reference measurement for the control of the central circulation pumps, closing the bypass led to a reduction of the entire network pressure by nearly 0.5 bar (Figure 6.12 (b)).
- Using the same impact score a substation was identified that has a flow rate of 36 m³/h with a temperature difference of only 2 K. The reason was poor secondary loop management. The financial impact on the energy provider of this one singular substation was quantified as > € 100,000/year in pump energy consumption.



Priority: All

Rule: Communication error (RS-232/RS-485/meter bus)

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☐	Regler [redacted]	Frequent system deviations HC1	Low		05.09.2023 14:39
☐	Regler [redacted]	Frequent system deviations HC1	Low		06.09.2023 05:21
☐	Regler [redacted]	Frequent system deviations HC1			
☐	Regler [redacted]	Frequent system deviations HC1			
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☐	Regler [redacted]	Frequent system deviations HC1			
☐	Regler [redacted]	Frequent system deviations HC1			

Figure 6.11: Example for the identification and evaluating substations with minimal spread between inlet and return flow temperature at high flow rates. This behaviour can be an indicator for an unwanted bypass.

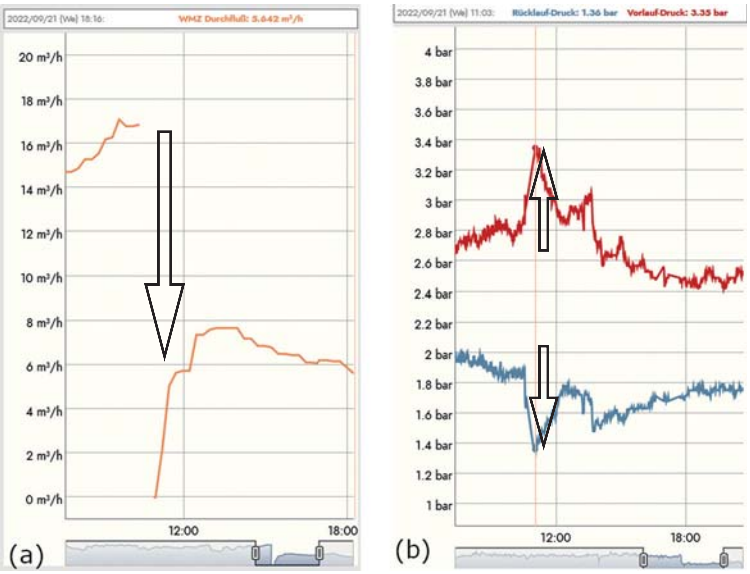

Figure 6.12: Consequences of correcting an unwanted bypass. Both pictures depict the same measurements, however focus on other aspects. (a) focusses on the bypass flow rate in the substation, which was more than halved by the correction and (b) focusses on supply and return pressure in the substation, which show an immediate increase of the differential pressure by 1 bar through the correction. The pressure diagram also shows the subsequent adaptation of the network pumps, reducing the overall network pressure.

6.6 Analytics for predictive maintenance and system improvement

While fault detection consists of detecting faults after they actually occurred, in order to mitigate their impact and recover after they occurred, predictive maintenance, seeks to anticipate the occurrence of faults before they occur. This approach is particularly relevant for faults related to ageing or wearing.

Predictive maintenance is in general less important, and therefore still less explored, for district heating than in the chemical industry because the components and processes are less expensive. One of the difficulties in district heating is that companies operate many substations and several heat production plants located all over a city, making it difficult to detect and isolate faults quickly. In this context, predictive maintenance can help preventing faults as well as accelerate their identification when they occur.

Analytics methods based on data can be used for predictive maintenance, but also for detecting potential improvement in the system. This is exemplified by the applications in the following.

6.6.1 Historical perspective and current state-of-the-art

Compared to the other domains described in this guidebook, predictive maintenance is a relatively new field with limited historical perspective. Furthermore, limited academic state-of-the-art is available, in particular because case studies heavily rely on data from real world systems, which is not generally available. Therefore, mostly concrete applications from the industrial field are available, and described in the following section.

6.6.2 Applications

6.6.2.1 Application 1: Predictive maintenance of heat supply infrastructure

The data provided by heat meters and controllers not only provide insight into the current status, but they also allow the extraction of a trend and the prediction of component failure using predictive maintenance approaches. Such rules are created to diagnose long-term ageing of systems, so they are devised to be robust to short-term fluctuations or changes in the operational state (Theiss, 2023).

One example of application is the detection of premature wear of electrical controller actuators. Often, early failure of controllers can be avoided

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Figure 6.13: Example of predictive maintenance of a substation. Part (a) depicts a real predictive maintenance warning. Part (b) depicts values from the corresponding substation: valve position is shown in grey, secondary inlet temperature in red and setpoint secondary inlet temperature in purple. This substation shows strongly oscillating control, leading to fatigue of elements such as the actuator of the controller.

if they are operated correctly. Oscillation (see example Figure 6.13 (b)) and ambient temperature can lead to early fatigue. Tools can identify and rank such problematic substations (see example Figure 6.13 (a)). Most oscillating substations can be resolved remotely by changing the configuration of the controller.

In addition to the usual measured data points, this predictive maintenance tool also has access to internal data values, e.g., it can identify ageing of electronics by interpreting internal data points such as runtime of the device, internal processor temperatures, internal temperatures of other electronic components and the number of relay clearances.

For predictive maintenance, data in 15 minute increments is perfectly sufficient but higher resolutions are better, otherwise behaviour such as oscillations can be hard to identify and correct. Or, alternatively, predictive maintenance can be performed in the field device itself.

6.6.2.2 Application 2: Data-driven supervision of service pipes

An example of development of digital tools addressing the issue of method-scalability for detection of faulty service pipes in the DH network was given in the recent Danish research and development project "DH Condition control for asset management", supported by the Danish Energy Agency and finalised in 2022 – see Danish Energy Agency (2022). The aim of this project was to develop a software tool that can help DH companies to make well-informed decisions regarding re-investments in the pipe network.

The target of the research and tool was to provide heat loss estimates of all service pipes in the DH network indicative of their current state while in operation and minimising the data prerequisites needed for the utility to lower barriers of implementation.

The technical strategy and solution are depicted in Figure 6.14. The essential data requirements were reduced to heat meter data from all customers at hourly resolution, but accepting non-complete datasets, and geographical information on the DH grid consisting of coordinates of all pipe end points. It was demonstrated how daily average soil temperatures could be retrieved from on-line meteorological services, in this case DMI (Danish Metrological Institute) covering all Danish utilities.

Two core algorithms were constructed for heat loss estimation and calculation of descriptive transmission coefficients, U, in terms of energy loss per meter per degree temperature difference to the ground temperature [W/(m·K)]. The main difference between the two approaches lies in the extent to which GIS-data is exploited, as well as use of additional data sources (soil temperature). Method 1 applied an absolute minimum of GIS-data cut down to the location of service pipes through the addresses corresponding to their affiliated heat meters. In Method 2, a pre-processing algorithm for GIS-data was developed, representing an intermediate detail level regarding topographic data, still circumventing the need for a full flow- and temperature model.

The new methods were executed on a full-scale network in the Danish city, Bording, with 1089 heat meters (Figure 6.15 b) and data from a full year. Although the GIS-preparation algorithm in

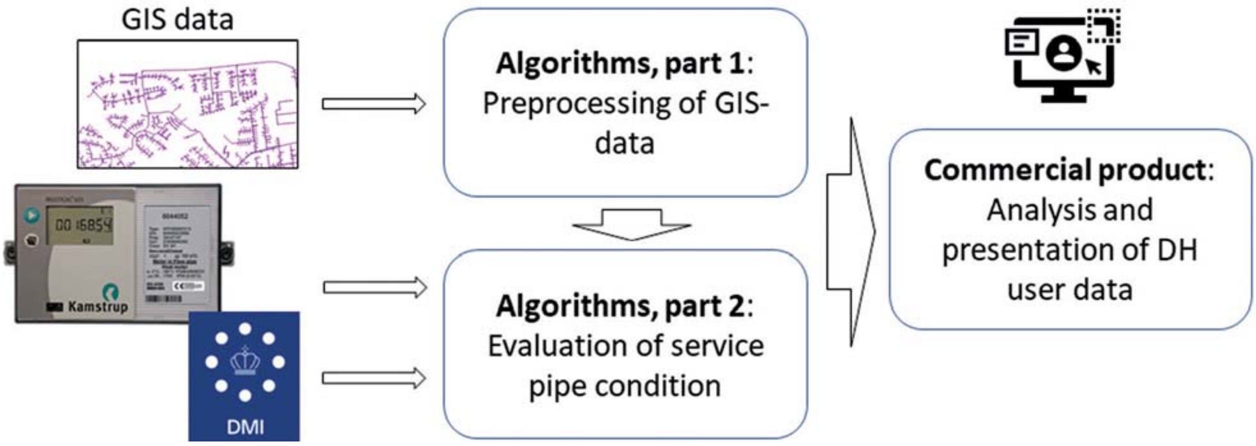

Figure 6.14: Overview of method for heat loss estimation of service pipes in operation.

Method 2 did not succeed in monitoring 100 % of the service pipes, the results showed promising potential to reveal increased heat losses and degraded materials on service pipes. In an appointed "test area" (Figure 6.15 a), extra measurement points (temperature and flow) were established to validate the method.

The results also showed (Figure 6.16) that examples of fracture on service pipes could be detected by inspection of the heat loss since leakage often results in wet foam with failing insulation properties as a consequence.

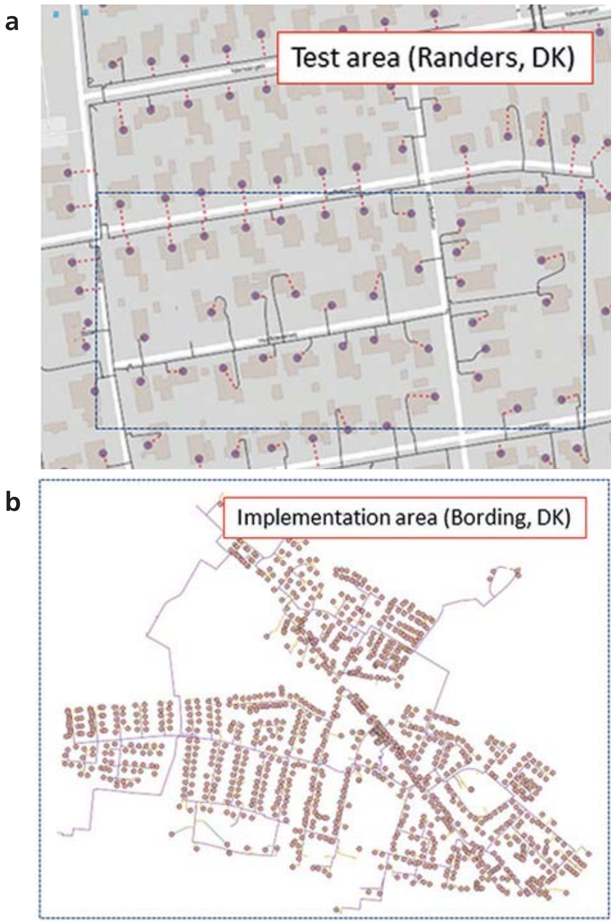

Figure 6.15: Test-area used for validation of model results (a) and implementation area for full-scale demonstration (b).

According to interviews performed with utilities during the project in different countries, it is expected that such a digital service could indeed be introduced to the market, in Denmark as well as in Europe in the coming years.

6.6.2.3 Application 3: Heat supply contract conformity

Heat contracts describe multiple aspects. The main contract content is the heat tariff, based on the energy consumption of the building. However, most contracts also include boundary conditions such as a maximum flow rate and other properties such as a maximum return flow temperature e.g.. All of these properties are important for the network operators since wrong contracts may lead to wrong dimensioning of the power plants or indicate problematic substations.

Traditionally, contractual breaches are only analysed when energy efficiency consultants advise their clients to change the contractual conditions, or if significant breaches cause issues, e.g. by disrupting the energy provision plans for the network or by creating effective bypasses.

SAM District Energy (Samson, 2023) provides tools to automatically detect substations that behave (far) outside their contractual boundaries. Users of SAM District Energy can use smart detection rules to monitor an accumulated state of the last three months.

The annual consumed energy can be weighted with the heating hours to find the base heat consumption. Consumptions that are significantly above or significantly below the contractual base value indicate issues. A value significantly above the contractual value may indicate a substation that effectively acts as a bypass (driving up the return flow temperature and the flowrates), or a substation that requires renewed contract nego-

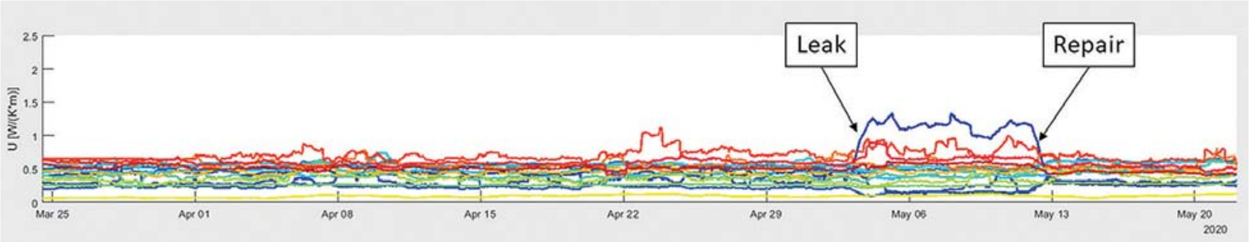

Figure 6.16: Calculated time-resolved-values for a group of service pipes with an example of a damaged service pipe leading to leakage and wet insulation. Data from Energi Ikast (implementation area, Bording).

tiations. A value significantly below contractual obligations may indicate a building that has technical difficulties covering its heat demand or may have undergone renovation such as insulation to reduce the thermal power consumption. In Germany it is legally possible to reduce the base value of your contract by up to 50% without needing to prove the reduction in thermal power consumption – the heat supplier then needs to prove that this reduction is not justified. An analysis such that discussed here can provide the legal basis to defend the said contracts. Analysis shows that up to 50% of contract values may be wrong, whereby approximately 25% of the contracts have errors that benefit consumers and 25% have errors that benefit the energy suppliers. The total errors are of the order of 5% of total contractual value.

6.7 Forecasting

Many of the innovations presented in the previous sections rely on forecasting, i.e., on being able to predict future operating conditions in order to anticipate them and adjust operation to ensure the system will continue operating in a safe and efficient way. In the context of DHC systems, forecasting is particularly useful to accommodate for the thermal inertia and heat propagation delays which are specific to these systems. Forecasting can also play a critical role for improving the efficiency of thermal energy storage, for collecting renewable and waste heat in an optimal way, and for interacting with the power market. In general, we can thus distinguish between load forecasting, renewable energy forecasting, waste heat forecasting, electricity price forecasting and weather forecasts.

Load forecasting has mainly focused on heating and cooling requirements. Heating and cooling needs are usually the main drivers of DHC operation and the ability to forecast them is crucial. Moreover, since they result from complex physics phenomena (building thermal & distribution loop hydraulic behaviours) and stochastic events (occupancy), they represent a suitable application for advanced artificial intelligence algorithms,see (Runge & Saloux, 2023). The granularity and scope of the forecast is also an important aspect: heating and cooling needs could be estimated at the whole district level as well as for specific neighbourhoods or critical buildings, as indicated by Kurek et al. (2021).

In the context of decarbonisation, the increasing amount of available renewable energy-based systems in DHC has offered key challenges for renewable energy generation and energy storage forecasting. Solar energy offers various applications, from solar collectors and parabolic troughs to photovoltaic/ thermal systems and forecasting the portion of energy harvested by the DHC system from such an intermittent energy source could represent a key information for optimising its operation, see (Saloux & Candanedo, 2021, Karimi & Kwin, 2022 or Zheng et al., 2023). Similarly, Saloux and Candanedo (2020) show that energy storage is critical to better manage energy generation and requirements, and that it is important to properly assess the useful part of energy, which remains available after a given period of time for a particular purpose (e.g., space heating, domestic hot water), especially when the storage device deals with thermal energy. The third main application is waste heat forecasting. Waste heat has shown great potential for integration in DHC and

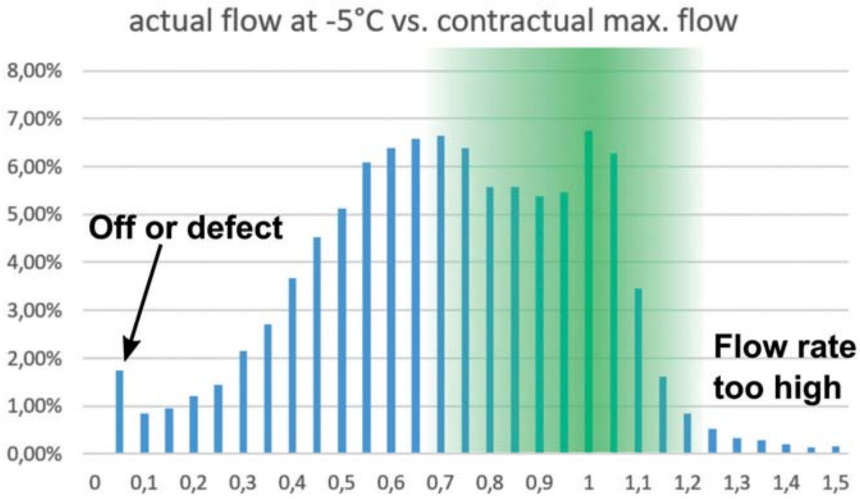

Figure 6.17: Percentage of clients (y-axis) with a given ratio of real flow rate vs. contractual max flow rate (x-axis). A ratio >1 shows a contract breech. This graph contains data from a wide range of networks and uses real flow rates that substations had at -5°C.

becomes a reliable solution for heating and cooling. Nevertheless, since waste heat is mostly originating from batch or continuous industrial processes, it is often easier to forecast than renewable energy.

The model time step and time horizons also have also a large influence on model performance. Forecasting outdoor air temperature one week ahead is more challenging than for the next 6 hours, which necessarily affects heating load forecasts. Similarly, it is more difficult to forecast short-term fluctuations (e.g., 5-min intervals) of solar energy harvested by parabolic troughs, compared to hourly average estimates.

6.7.1 Historical perspective and current state-of-the-art

Modelling has been part of DHC activities for decades, which is also the case of load forecasting. For instance, the heating load can be estimated with a simple linear regression as a function of outdoor air temperature. With the advent of the digital era, operational data have become increasingly available and have offered more opportunities for modelling. Time-series models have emerged as an effective method to account for system inertia and past changes (generally, up to few hours ago) of outdoor air temperature for instance but also the heating load itself. ARX (autoregressive exogenous model), ARMA (autoregressive moving average model), ARIMA (autoregressive integrated moving average model), ARIMAX (autoregressive integrated moving average model with exogenous variables) and other variants are compelling examples of such methods.

More recently, machine learning and deep learning algorithms have broken through and have shown strong capabilities for load forecasting. It includes among others artificial neural networks (ANN), support vector machine (SVM), decision tree (DT) and random forest (RF), gaussian process (GP) but also newer techniques such as recurrent neural networks (RNN), convolutional neural networks (CNN), long-short term memory neural network (LSTM) and advanced tree-based algorithms (XGBoost, LightGBM). A combination of these techniques in so-called ensemble models can also be commonly found. Although these techniques build on finding hidden relationships between inputs and outputs to make accurate predictions, they still rely on a judicious selection of inputs, which also depends on the forecasting application.

A proper selection of model inputs is critical for load forecasting. Examples of inputs are outdoor air temperature and relative humidity, solar radiation, hour of the day, weekday, season, occupant number of occupancy state; these inputs could be evaluated at the current time step, but could also include past values and future values (e.g., weather forecasts). Dedicated techniques can also be used to automate the input selection process such as feature selection (e.g., filters, wrappers) and feature extraction (e.g., encoder/decoder).

Another type of approach is grey-box modelling (e.g., Resistance-Capacitance thermal networks), which relies on physics-based principles but where model parameters are calibrated with operational data. This method aims to benefit from both detailed physics-based simulations and purely data-driven methods; it is usually more robust to extrapolation and requires smaller datasets for training.

New techniques are continuously emerging as potential breakthrough solutions, and a vast number of modelling techniques could be used for load forecasting in DHC applications. However, it is challenging to evaluate which technique performs the best and under which conditions. Some models could be more accurate for tackling the stochastic behaviour of occupancy, some others for handling different load types (space heating, domestic hot water) and large network thermal inertia. This is where modelling competitions play a pivotal role by allowing the comparison between different techniques under the same conditions and datasets, expanding knowledge and expertise on available methods. The M4 Competition has focused on the evaluation of 61 forecasting methods, tested on 100,000 time series from various domains. Similarly, the ASHRAE Great Energy Predictor III Competition was a Machine Learning competition for long-term prediction of building energy usage for measurement and verification applications; datasets composed of over 20 million points of training data were made available for testing diverse techniques. The access to open datasets from existing DHC systems would greatly contribute to such a knowledge development.

6.7.2 Applications

6.7.2.1 Applications 1: heating/cooling load forecasting

In this example by Runge and Saloux (2023), the aim is to forecast the future energy demand of an existing district heating system in Canada. Two different approaches are compared: prediction models and forecasting models. The main distinction between them is the time step between inputs and outputs (Figure 6.18). The prediction model estimates the output at the same time step as the input variables and requires weather forecasts to estimate future energy demand. In contrast, the forecasting model estimates the output at least one time step ahead of the input variables and weather forecasts are not necessarily required. Different machine learning and deep learning algorithms were investigated for each approach, along with different sets of inputs, and they were evaluated in terms of accuracy, stability and computational time. This model aims to be used for decision-making support and uses as inputs weather conditions, time index variables (hour of the day, weekday/weekend, etc.) and a binary occupancy variable (i.e., working hours). The results showed that all models for both approaches showed reasonable accuracy (CV-RMSE of 11% for top performing models for hourly forecasts up to 24 hours ahead), although the prediction models are slightly more accurate than forecasting models. The LSTM and XGBoost were consistently among the top performing algorithms but XGBoost was significantly faster to train.

6.7.2.2 Application 2: Heat load forecasting by means of an expert advice system

The performance of machine learning algorithms as described in the previous case studies is case specific and dependent of the situation. In some circumstances a certain machine learning technique performs better than others, while in other circumstances it might be the opposite. To overcome this, an expert advice layer can be added on top of individual forecasters. As such, this is an example of an ensemble method, described in section 6.7.2. The expert advice layer aggregates the individual forecasts into a new prediction, by assigning weights to the individual forecasts, based on their individual accurateness. Since basically the expert advice layer learns which individual forecast performs better in which circumstances, it can constantly adjust the weights of the individual forecasts to result in an optimised forecast. A case study was provided by Geysen, De Somer, Johansson, Brage and Vanhoudt (2018). In this case study, an expert advice forecaster is used to predict the hourly heat demand in a DH network for the next 24 hours. The network is located in the south of Sweden and has a piping network of about 10,300 m. The production units consist of two wood chip boilers of 1.2 MW and 1.5 MW and a 3 MW peak oil boiler. There are about 200 buildings connected to the district heating system, and of these about 150 are single-family domestic dwellings. The individual forecasters use the following techniques: linear regression (LR), artificial neural network (ANN), support vector machine (SVM) and extra-trees regression (ETR) in combination with three different feature sets, a first one solely taking into account timing information and an outdoor temperature forecast, the second one adding historic thermal load information and the last one

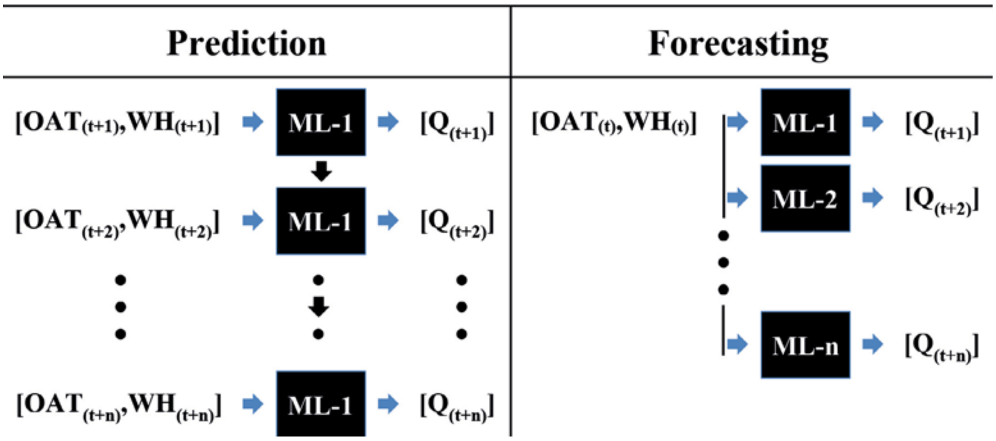

Figure 6.18: Prediction and forecasting model approaches. OAT refers to outdoor air temperature, WH to working hours, ML stands for machine learning, Q is thermal load and t is time.

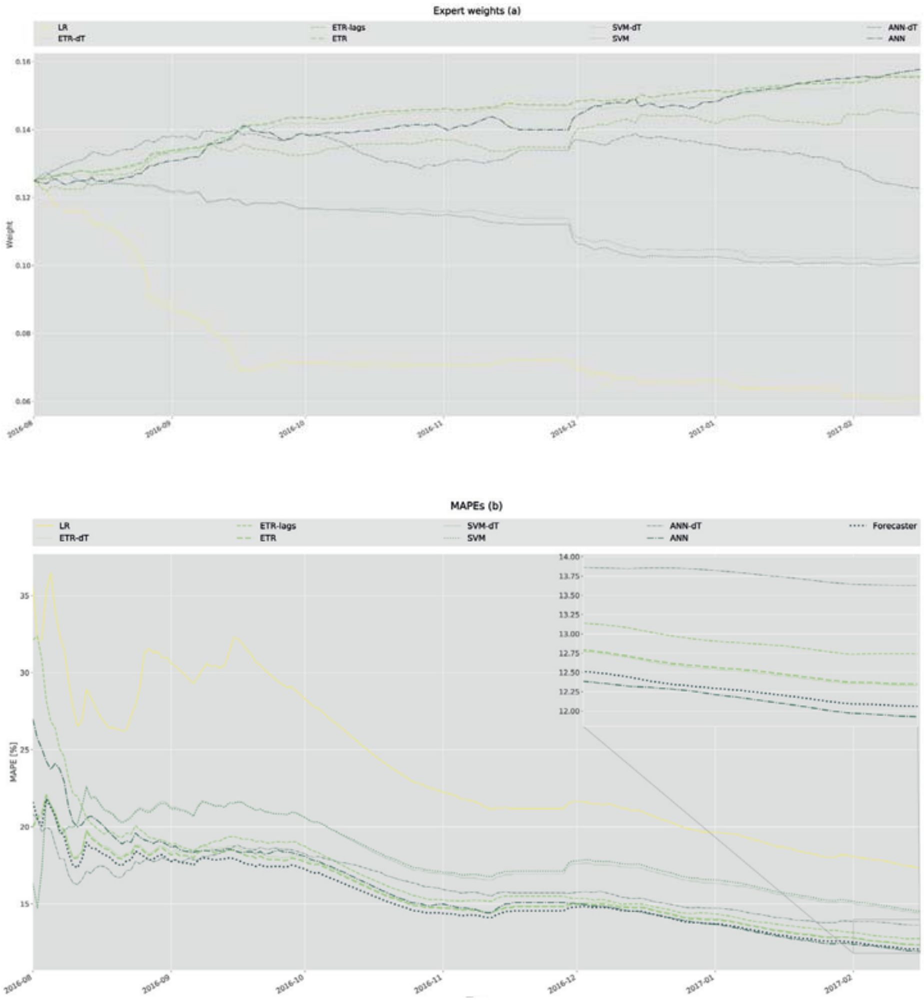

Figure 6.19: Weights of the individual forecasters in the expert forecaster (upper) and mean average percentage errors of the individual and expert forecasters (lower)

adding historic control signals. A dataset of 20 months, containing the hourly energy consumption and the outdoor temperature, was used as training and validation data (ranging from November 2014 up to July 2016). The following 7 months were used as a test set performance analysis. The weights and the mean average percentage error is shown in the picture below.

As can be seen, of all the experts in the system, the LR performs worst (MAPE 17.34%) while the ANNs (11.92%) and ETRs (12.34%) are slightly better than the SVMs (14.54%). Over this test set, the expert system (12.06%) achieves our predefined goal of tracking the best expert, the ANN with full feature set, in the system. Beyond this, combining different experts adds robustness to the forecaster and reduces susceptibility to changes in the DH network.

6.7.2.3 Application 3: Renewable generation forecasting

Saloux and Candanedo (2019) investigated the forecasting of the energy performance of an existing solar district heating system in Canada, composed of solar collectors, water tanks (short-term storage) and geothermal boreholes (long-term storage) to provide space heating to a 52-residential house community (Figure 6.20). The developed model consists of resistance-capacitance thermal networks for solar collectors, borehole thermal energy storage and distribution loops, a nodal method for stratified water tanks and machine learning algorithms for the community heating demand. The model used a time step of 10 minutes and aims to evaluate how much space heating demand will be required by the community, how much solar energy will be harvested, and how much energy will be available in the short-term and long-term storage devices. The model targets system operation optimisation and uses input variables that are controllable (geothermal loop flow rate, temperature difference across solar collectors) and non-controllable but that can be known hours ahead (hour of the day, forecasted outdoor air temperature and solar radiation). It was calibrated using one year of operational data and validated with the data for another year. Results showed good consistency between data and model results, with an annual error of 2.9% for the solar fraction and 4.4% for the pump electricity use over the validation dataset.

6.7.2.4 Application 4: Forecasting buildings + network

Instead of forecasting the heat load of the entire network it is possible to forecast each individual heat consumer (using neural networks on meter data) and network properties (using weighted correlation functions). The network properties include information such as “how long does the water take to reach this consumer?” and “how much heat does it loose on the way?”. Missing consumers can be substituted using static information, e.g., contract values and properties such as “this is an office building, heating is off on weekends, does not use district heating to heat drinking water”. Experience shows that historic data is needed for min. 10% of consumers, the rest can be substituted (Hartung et al., 2021).

Combining load predictions of individual consumers and learned network properties, the heat load at the power plant can be predicted with error margins <5%. This procedure has been benchmarked against thermohydraulic simulations and were shown to be more accurate at predicting the inlet temperatures arriving at buildings.

Separating the load prediction from individual buildings from the network properties makes it possible to build a digital twin that can not only predict the heat load if the plant continues to be managed the way it is currently managed, but also if the plant changes its behaviour. Specifically, the digital twin is able to perform predictive optimisations on the plant behaviour, such as shifting loads and smoothing peaks by exploiting the thermal buffer properties of the network.

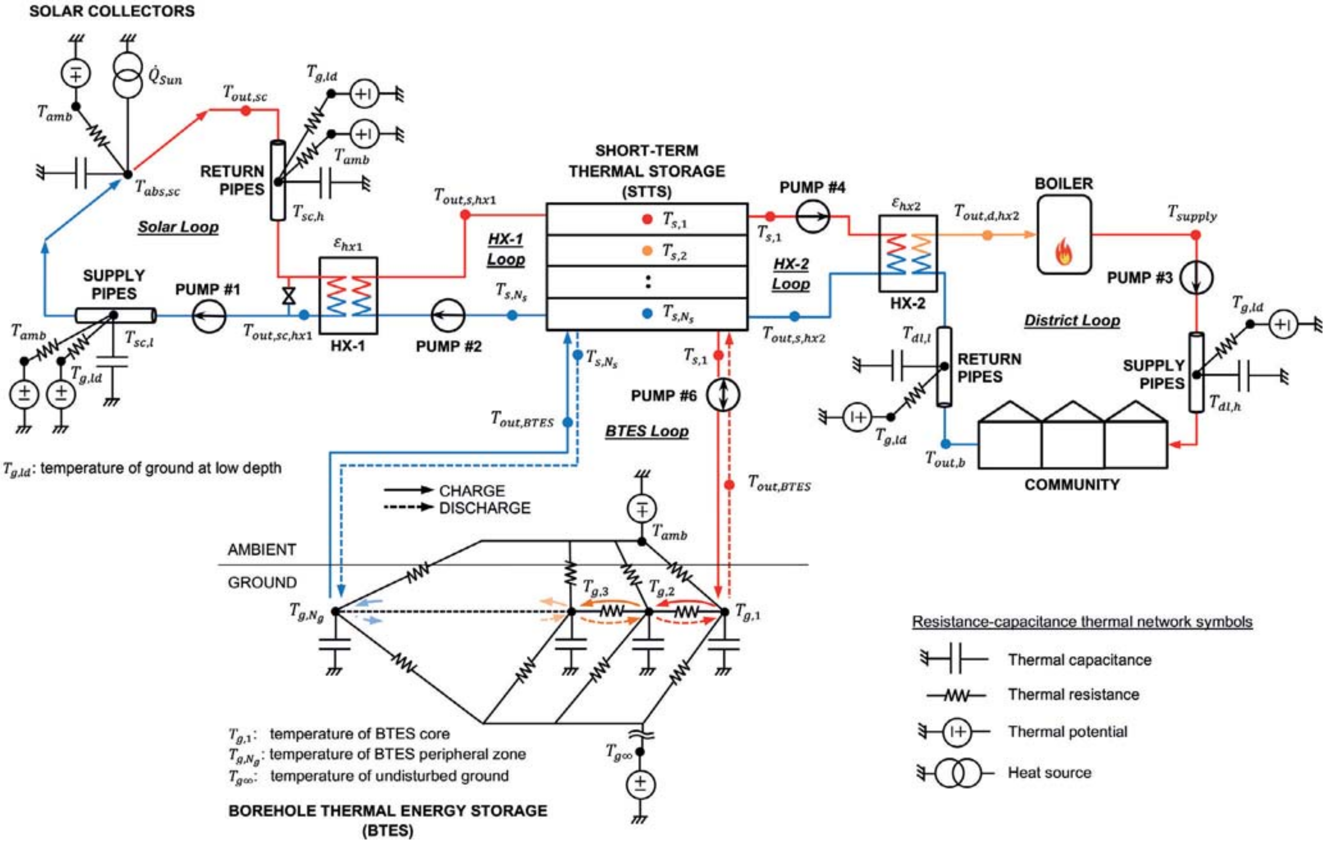

Figure 6.20: Schematic of the control-oriented model of a solar district heating system

6.8 Conclusions

This chapter presented many results which highlight the benefits related to digitalisation in DHC systems. For each of the 6 subtopics, a description, a short historical perspective and several application examples are provided. While the account presented here is not expected to be exhaustive, it provides an accurate overview of how digitalisation is applied in several parts of a DHC system.

The status of current deployment of these technologies in the industry is of course not homogeneous:

- Operation optimisation at the production level is the most widespread, as it provides significant savings compared to more traditional approaches. New developments are directed towards the integration of more diverse energy sources, as well as integrating aspects related to distribution and consumer-side.
- Operational optimisation at the distribution level is still more experimental. Although it can theoretically provide significant savings by exploiting thermal inertia in the network, its deployment is focused on larger networks, which have the most potential and thus a better cost/benefit ratio.
- Operation optimisation at the consumer level has demonstrated interesting potential in deployed cases, be it with regards to peak reduction or return temperature minimisation. It is expected to become more and more widespread in the coming years, with several commercial solutions readily available on the market.
- Analytics for fault and leaks detection is an important area of development with the digitalisation of DHC networks. Research is quite active in order to improve the performance of detection methods based on available data, and to complement methods based on specific fault/leak detection equipment. It is expected that various combinations of technologies will be deployed to match the characteristic of each DHC network.
- Analytics for predictive maintenance and system improvement has been commercially available for several years, providing assistance to DHC operators thanks to the collection, organisation and visualisation of large amount of available data. It is still expected to improve, especially as more insight is gained from practical use.
- Forecasting, although it is already quite widespread, appears to be a requirement for most of the other solutions. Even better accuracy and ability to adapt to local conditions is expected in the near future.

While this chapter insists on describing various digital solutions and their potential benefits, some challenges hindering their deployment are presented in conclusion (chapter 11) of this guidebook.

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7 Digitalisation of infrastructure: Digital Twins

The previous chapters have provided an overview of a variety of applications for improving DHC operation and maintenance that can be enabled by digitalization. This chapter focuses on Digital Twins for deploying these digital technologies in the field, bringing together sensor data, network information, and algorithms to create digital services that support DHC infrastructure operators in their daily work.

This chapter gives an introduction to the concept of Digital Twins and highlights concrete application areas for Digital Twins in the context of DHC operation and maintenance. To showcase the practical value of this approach, a collection of best practice examples of using Digital Twins for the deployment of digital technologies for DHC infrastructure is presented.

This chapter is not a guide for implementing Digital Twins, as this would go beyond the scope of the guidebook. However, the references in Section 7.1.2 and the best practice examples in Section 7.3 provide plenty of clues to follow up on.

7.1 Introduction to Digital Twins

7.1.1 Concept and Definition of Digital Twins

The Digital Twin is a concept that has emerged as a promising approach for simulating and replicating real-world objects or systems in a digital environment. According to (Glaessgen & Stargel, 2012), Digital Twins can be defined as "a virtual representation of a physical system that is used to monitor, control, and optimize its operations". In other words, a Digital Twin is a computer-based model that replicates the behaviour of a physical object or system in real-time. This allows for continuous monitoring and analysis of the system's performance, as well as for testing different scenarios and identifying potential problems before they occur in the physical system.

According to (Jones et al., 2020), a Digital Twin is a replica of the physical world if it satisfies the following three criteria:

1. **Twinning:** the act of synchronizing the virtual and physical states
2. **Metrology:** the act of measuring the state of the physical entity / virtual twin
3. **Realization:** the act of changing the state of the physical entity / virtual twin

A different – yet equivalent – view is to define a Digital Twin via these three properties:

1. **Virtual counterpart of physical entity:** A Digital Twin comprises a digital representation of a physical object or system, providing a refined and validated model for the prediction of its behaviour.
2. **Real-time execution:** The digital representation is synchronized to the physical entity. Its execution is guaranteed to happen within defined time steps of maximum duration and fast enough to affect the environment in which it occurs.
3. **Bi-directionality of physical and virtual domain:** Interaction with the digital representation is possible in both directions. From the physical to the virtual domain, this typically includes the collection of sensor data. From the virtual to the physical domain this may include access to actuators (probably under human supervision).

In recent years, Digital Twins have been applied in various fields, such as manufacturing, where they are used to simulate production processes and optimize efficiency (Tao et al., 2018). In healthcare, Digital Twins have been used to model and predict personalized medicine the effects of different treatments (Kamel Boulos & Zhang, 2021). In urban planning, Digital Twins have been used to simulate traffic patterns and optimize city infrastructure (Hu et al., 2022). According to (Cearley et al., 2017), Digital Twin technology is expected to become a key enabler of digital transformation across industries. The report suggests that by 2021, half of all large industrial companies will use Digital Twins, resulting in a 10% improvement in efficiency.

One of the key features of Digital Twins is their ability to integrate data from multiple sources, such as sensors, cameras, and other monitoring devices, to create a comprehensive and accurate representation of the physical system. This can help to improve decision-making processes by providing real-time information on the system's behaviour and performance. The concept of Digital Twins has become increasingly popular in recent years due to its potential to provide a more accurate and comprehensive understanding of physical systems.

The Digital Twin concept has evolved alongside increasing market demand and technological advancements (Rasheed et al., 2020). By continuously working with sensor data in near real-time, Digital Twins provide the necessary information to support informed decision-making. Additionally, the Digital Twin concept is often used to make predictions about future scenarios. Digital Twins are also commonly used to enhance after-sales services by monitoring the overall operation and maintenance of each physical replica, detecting and reporting unusual performance in the system (Melesse et al., 2020). Moreover, a Digital Twin may provide documentation of the product lifecycle through digital platforms and improve operations by receiving feedback on services and products through customer support.

7.1.2 History of Digital Twins in a Nutshell

The concept of Digital Twins can be traced back to NASA's use of virtual models for their spacecraft in the 1970s. However, the term "Digital Twin" was first coined by Michael Grieves in 2003 as a virtual representation of a physical product, storing information about the said product. Grieves later expanded on this concept by introducing a bi-directional data connection between the physical product and its virtual counterpart, creating a cycle of data flow between the physical and virtual domains (mirroring and twinning). The virtual environment containing this data facilitates virtual operations such as modelling, testing, optimization, and manufacturing, providing similar benefits to those obtained through physical processes (Kritzinger et al., 2018). Any changes made to the physical product are mirrored in its digital twin, and vice versa. However, as technology has advanced, the Digital Twin concept has evolved and is now applied in various inconsistent ways beyond its original definition (Jones et al., 2020).

In the past years the disagreement on definition on Digital Twins urged researchers to do comprehensive reviews on this topic, see for instance (Jones et al., 2020; Liu et al., 2021; Negri et al., 2017). Table 7.1 provides an overview of this historic development of the Digital Twin definition over the years.

7.1.3 Optional Properties of Digital Twins

Digital Twins are rapidly transforming the way industries model and optimize their systems. Beyond their basic capabilities explained above (twinning, metrology, realization), different implementations of Digital Twins provide their own unique properties. Among these “optional” properties, the most common are adaptability, scalability, repeatability, interoperability, and specific data access capabilities. Depending on their scope of application, these optional properties can provide significant advantages for optimizing system performance and reducing operational costs:

- **Adaptability:** The adaptability of digital twins is often a critical feature that enables the adjustment of the virtual representation to a changing physical system based on real-time measurement data. This capability provides a dynamic and accurate view of the system's behaviour that can be leveraged to optimize its performance. Automated or supervised techniques can be used for updating a Digital Twin’s calibration, diagnostic tools can also be used to identify any discrepancies between the digital twin and the physical system, allowing for continuous improvement of the model's accuracy over time.
- **Scalability:** Digital Twins may be scalable, allowing for the modelling of systems of different sizes and complexities. They can also be used to add new branches or plants to existing systems, enabling the optimization of entire industrial processes.
- **Repeatability:** Digital Twins may have the ability to restore the system's state, enabling scenario replay. This feature enables industries to evaluate different scenarios and optimize their systems accordingly, as well as replicate previous scenarios to analyse their impact on the system.
- **Interoperability:** This is often a critical feature of Digital Twins, enabling the interfacing with SCADA/supervision data streams and connection of multiple system.
- **Data access:** Access to historical and realistic environmental data is often essential for Digital Twins to accurately replicate the behaviour of the physical system. Industries must have a database of historical data, while access to environmental data, such as temperature, humidity, and other factors affecting the system's behaviour, is also necessary for scenario execution.

Table 7.1: Historical overview of the Digital Twin definition

Year	Author	Definition of Digital Twin
2010 and 2012	Glaessgen & Stargel, 2012; Shafto et al., 2012)	An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems.
2012	(Tuegel, 2012)	A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including sub-models of the electronics, the flight controls, the propulsion system, and other subsystems.
2012	(Gockel et al., 2012)	Ultra-realistic, cradle-to-grave computer model of an aircraft structure that is used to assess the aircraft's ability to meet mission requirements.
2013	(Lee et al., 2013)	Coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge.
2013	Reifsnider & Majumdar, 2013)	Ultra-high fidelity physical models of the materials and structures that control the life of a vehicle.
2013	Majumdar et al., 2013)	Structural model which will include quantitative data of material level characteristics with high sensitivity.
2015	(Rosen et al., 2015)	Very realistic models of the process current state and its behaviour in interaction with the environment in the real world; product digital counterpart of a physical product.
2015	(Bielefeldt et al., 2015)	Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories.
2015	(Bazilevs et al., 2015)	High-fidelity structural model that incorporates fatigue damage and presents a comprehensive digital counterpart of the actual structural system of interest.
2016	(Schluse & Rossmann, 2016)	Virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services.
2016	(Canedo, 2016)	Digital representation of a real-world object with focus on the object itself.
2016	(Gabor et al., 2016)	The simulation of the physical object itself to predict future states of the system.
2016	(Schroeder et al., 2016)	Virtual representation of a real product in the context of Cyber-Physical Systems.
2016	(Kraft, 2016)	An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin.
2016	(Bajaj et al., 2016)	A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other domain-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories.
2017	(Grieves & Vickers, 2017)	A digital twin is a dynamic digital representation of a physical object or system that emulates the physical object or system's functions, behaviours, and interactions with the environment in real time, and it is continuously updated with sensor data from the physical object or system
2017	(Barricelli et al., 2019)	DTs can be defined as (physical and/or virtual) machines or computer-based models that are simulating, emulating, mirroring, or "twinning" the life of a physical entity, which may be an object, a process, a human, or a human-related feature.
2022	(Botín-Sanabria et al., 2022)	The Digital Twin technology offers the ability to have a deep insight on the inner operations of any system, the interaction between different parts of the system and the future behaviour of their physical counterpart in a way that is actionable for their users and stakeholders.

7.2 Application Areas for Digital Twins in DHC

Chapters 5 and 6 provide an overview of a broad spectrum of digital technologies with high relevance for DHC applications. The concept of Digital Twins as described above is an enabler to utilize these already available digital technologies and deploy them for the operation and maintenance of DHC networks.

From the perspective of operators of DHC networks and related infrastructure, the general definition of Digital Twins from Section 7.1.1 can be translated to a more application-centric view. This applications-centric view focuses on the specific needs, requisites, and benefits of using Digital Twins for DHC applications:

1. **From offline to online:** Digital Twins embrace available digital technologies and make them available online. This opens new opportunities for supporting and / or automating certain aspects of the operation and maintenance of DHC networks and related infrastructure. For instance, digital tools typically used as desktop applications (e.g., simulation tools or machine learning algorithms) can be made available online.
2. **Integration of sensors and actuators:** Remote access to sensor measurements enables an up-to-date view of the current thermo-hydraulic conditions of the network, the suppliers, and the consumers. The same infrastructure used for remote sensor access can typically also be used to actuate controllable assets remotely, such as valves, pumps, or heat sources.
3. **Bi-directional real-time services:** Online tools together with up-to-date sensor information allow to create a digital representation of (parts of) a DHC network, which is synchronized to the real system. This facilitates the provision of real-time services for analysing the system's current and future state. With the integration of remotely controllable assets, the bi-directional, (semi-)automated interaction with the DHC network is made possible, enabling the transition from traditional passive networks to smart energy systems.

Figure 7.1 shows a schematic example of how a Digital Twin could be used to integrate existing digital technologies into the operation and maintenance of a DHC network. Typical desktop applications – such as simulation models or GIS models – can be made available online and linked to metering data and historical data for creating a digital representation of a DHC system. Hence, Digital Twins enable the deployment of new services that can either support operators (open loop) or automate processes (closed loop). The following list provides a (non-exhaustive) overview of typical application areas that can be covered by these services:

- **Monitoring:** The digital representation of a DHC system can be used for data enrichment of unmeasured (or even unmeasurable) things, allowing to estimate the state of the entire system based on a limited number of sensors. Implemented as a real-time service, this can be also used for a diagnosis of the quality of measurements or customer consumption estimation.

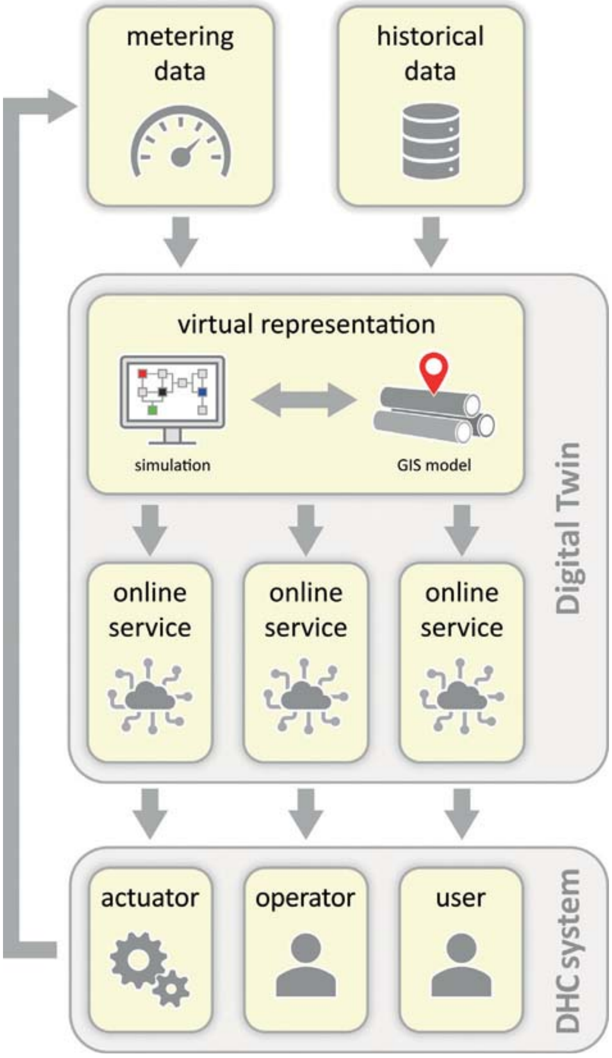


Figure 7.1: Schematic example of a Digital Twin for DHC systems.

- **Diagnostics and fault detection:** Analysing the state of a DHC system can help improve its operation by detecting problems. Implemented as a real-time service, short-term deviations (e.g., high flows, low pressure, high return temperatures can be used for fault detection, promptly notifying operators and maintenance teams. Similarly, modest but significant long-term deviations from the design specification can be identified and reported to the operators.
- **Forecasting:** Up-to-date knowledge about the network and estimates of customer behaviour can be used as a basis for short-term forecasting of expected consumption. Implemented as a real-time service, this can be a significant enabler for effective intra-day flexibility and energy trading.
- **Operational optimization:** The digital representation of a DHC system may be used to apply approaches for model predictive control for optimizing its operation. Implemented as a real-time service, this can be used to automate plant operation or the hydraulic piloting of the network. Alternatively, this can also be used as a decision support system for the network operators, who review the suggested control actions before applying them.

Apart from using Digital Twins for supporting the operation and maintenance of DHC systems, they can also be deployed in the context of laboratories. **By integrating a Digital Twin into a testbed, it can serve as a stand-in for (part of) a real system, basically acting as a virtual component among real hardware.** The motivation behind can either be that performing tests on the real system would not be safe or that the (sub-)system cannot be realized with the equipment available at the laboratory. Typical application areas for using Digital Twins in testbeds are functional tests of new control schemes for operating networks and cyber-physical security testing. For these types of applications, the provision of services is typically less significant, whereas the accurate digital representation of the real system and the possibility to interact with it in real time is critical.

7.3 Example Applications

In the following, examples for applying the concept of a Digital Twin to DHC systems are highlighted, see Table 7.2 for an overview. These examples showcase the different application areas for which Digital Twins are useful and illustrate the challenges they can help overcome and the advantages they provide. They show that depending on the application area Digital Twins require different properties, for instance with respect to the temporal / spatial resolution of the digital representation of the DHC system.

However, it is important to point out that the process of exploring the new possibilities for DHC applications offered by the Digital Twin concept is still in progress. This is reflected by the fact that the examples cover both innovative commercial products as well as pilot sites and proof-of-concept implementations from research projects. Therefore, the examples also address open questions and barriers for roll-out in real-world applications.

Table 7.2: Overview of example applications for Digital Twins in Chapter 7.3

	monitoring	diagnostics & fault detection	forecasting	operational optimization	testbed component
DistrictLab.H™	X		X	X	
Digital Low-Temperature Assistant	X		X	X	
Arteria platform	X		X	X	
Heat Intelligence Solution	X		X	X	
Utilifeed platform	X		X	X	
Leanheat Network	X		X	X	
Leanheat Building	X		X	X	
Leakages monitoring	X	X			
DISTRHEAT platform			X	X	
DigitalEnergyTestbed					X

7.3.1 Real-time decision support and online predictive control with DistrictLab.H™

DistrictLab.H™ (https://www.districtlab.eu) is an integrated software solution aiming at the efficient design, sizing and operation of district heating networks (see Figure 7.2). The DistrictLab.H™ Simulation Studio provides a working environment for the design and simulation of district heating networks (Giraud et al., 2017). Starting from GIS data, DistrictLab.H™ allows to build a full-scale model of an entire district heating network through an oriented graph and detailed component models of all relevant assets (pumps, production units, storage units, substations). Externalities such as consumer profiles and production characteristics are provided through a simple exchange file interface. DistrictLab.H™ relies on a specialized thermal-hydraulic solver for computing the system dynamics at relevant temporal scales, in particular for the prediction of temperature dynamics in the entirety of the network.

7.3.1.1 Example implementation

DistrictLab.H™ has been applied successfully at 2 pilot sites – the district heating networks of Grenoble (France) and Metz (France) – for real-time decision support and online predictive control. Both systems are complex, large-scale district heating networks with a meshed structure and multiple supply points. Based on the online integration of DistrictLab.H™ with an existing metering infrastructure, a real-time service providing optimal control of the supply temperature for each production unit in the network has been implemented. This is achieved through the model-based evaluation and prediction of critical temperatures at substation level (see Figure 7.3) and optimal planning of supply temperatures (see Figure 7.4).

7.3.1.2 Advantages

The online integration of DistrictLab.H™ enables the provisioning of a real-time service for supporting the decision making of the network operators. This allows to control the supply temperature in the network in an optimal way, facilitating the operation of the network with the most cost-effective production plan. Consequently, it assists the operators to satisfy supply contracts, comply with regulations and preserve the integrity of the infrastructure. In addition, DistrictLab.H™ is an enabler for decarbonizing the operation of existing district heating networks by helping to reduce the use of carbon-intensive productions units.

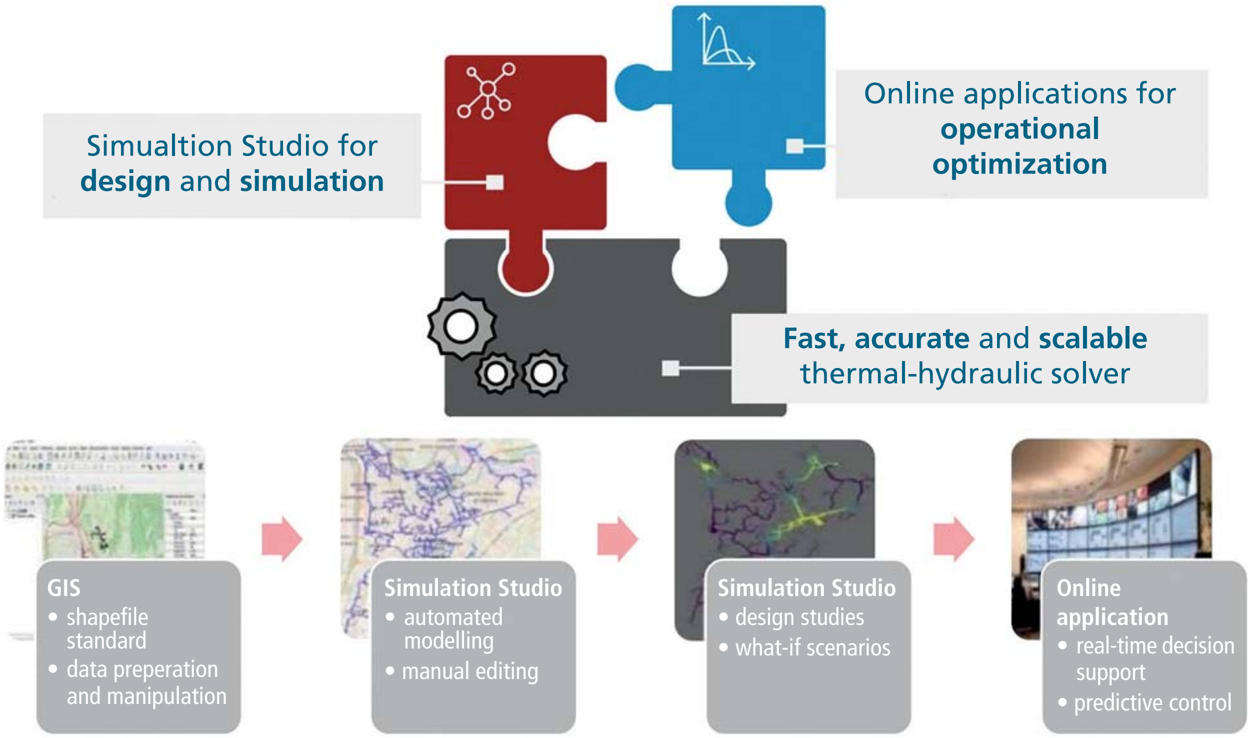


Figure 7.2: Overview of DistrictLab.H™

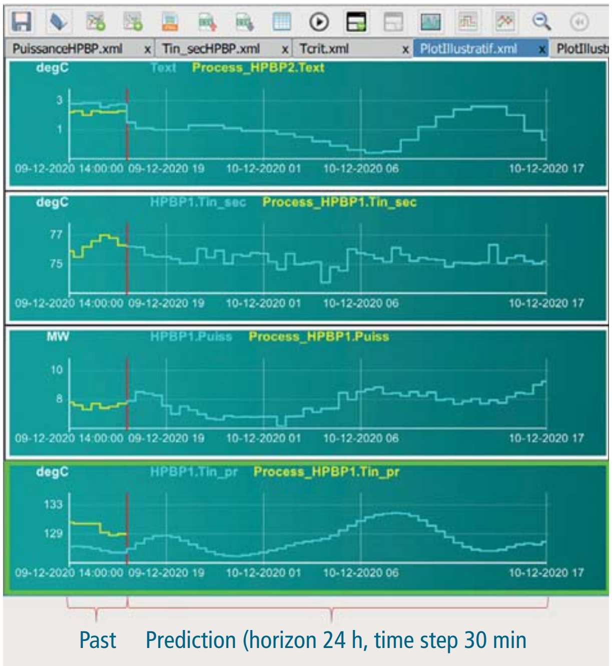


Figure 7.3: Typical example for the prediction of critical temperatures at substation level with DistrictLab.H™.

7.3.1.3 Barriers and challenges

- **Monitoring:** A lack of standardization regarding process data representation makes the integration of real-time metering data with online applications more complex and time-consuming.
- **Life cycle management:** Retrieving changes to the real-world system and updating the simulation models accordingly remains a challenge due to a lack of standardization.
- **Degree of automation:** The questions which processes in the operation of a district heating network should be fully automated or semi-automated (i.e., with human operators in the loop) remains unanswered. At this point, the online deployment of DistrictLab.H™ at the pilot sites involves the computation of optimal values which are then applied manually by operators at production units.

7.3.2 Digital Low-Temperature Assistant

Low-temperature DH requires optimal functioning heat installations in the connected buildings. Only if the buildings efficiently utilize the delivered heat and operate with low return temperatures, the DH operator will be able to lower the supply temperature accordingly. Today, 50-60% of all heat installations are considered faulty or misadjusted, causing inefficiencies in the entire value chain. These faults and mis-adjustments can be identified by smart meter data. However, end-users need to be involved, motivated, and engaged to fix the issues. Engaging end-users and proactively ensuring low temperature operation at scale is a complex and continuous task. This requires a transformation in the way heat installations are monitored and end-users are being approached and serviced. The Digital Twin concept can help in this regard to provide dedicated online services to the network operators, field technicians, and end-users.

The Digital Low-Temperature Assistant empowers utilities that want to ensure optimally functioning heat installations by providing an operational cloud-platform ensuring that faults and potential issues are being identified, prioritized, and corrected in a scalable and efficient way. Based on the continuous monitoring of all heat installations, it provides automated and data-driven diagnostics that translate to actionable insights. This allows to keep a prioritized list of the most relevant heat installations to address, which receive targeted information and suggestions for improvements. The Digital Low-Temperature Assistant also acts as a platform for engaging field service technicians to assist with corrections and feedback and provides transparency in the progress and results achieved at individual end-user level and at system level.

The Digital Low-Temperature Assistant is being developed by Kamstrup in close collaboration with leading Danish DH operators with the aim

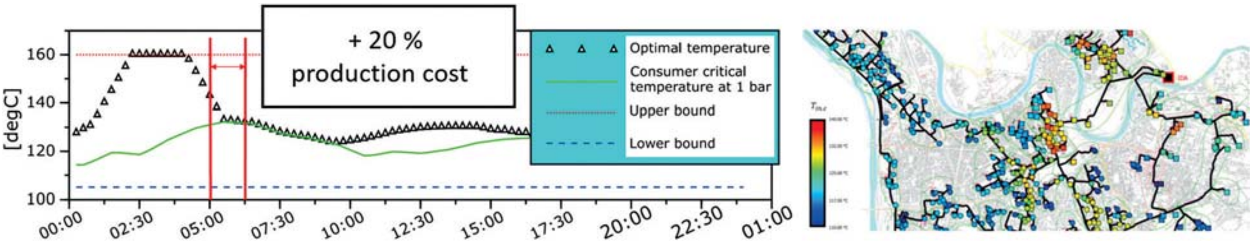


Figure 7.4: Typical example for the optimal planning of supply temperatures with DistrictLab.H™.

to move from reactive fault detection towards proactive low temperature operation. Figure 7.5 shows a screenshot of the Digital Low-Temperature Assistant's graphical user interface.

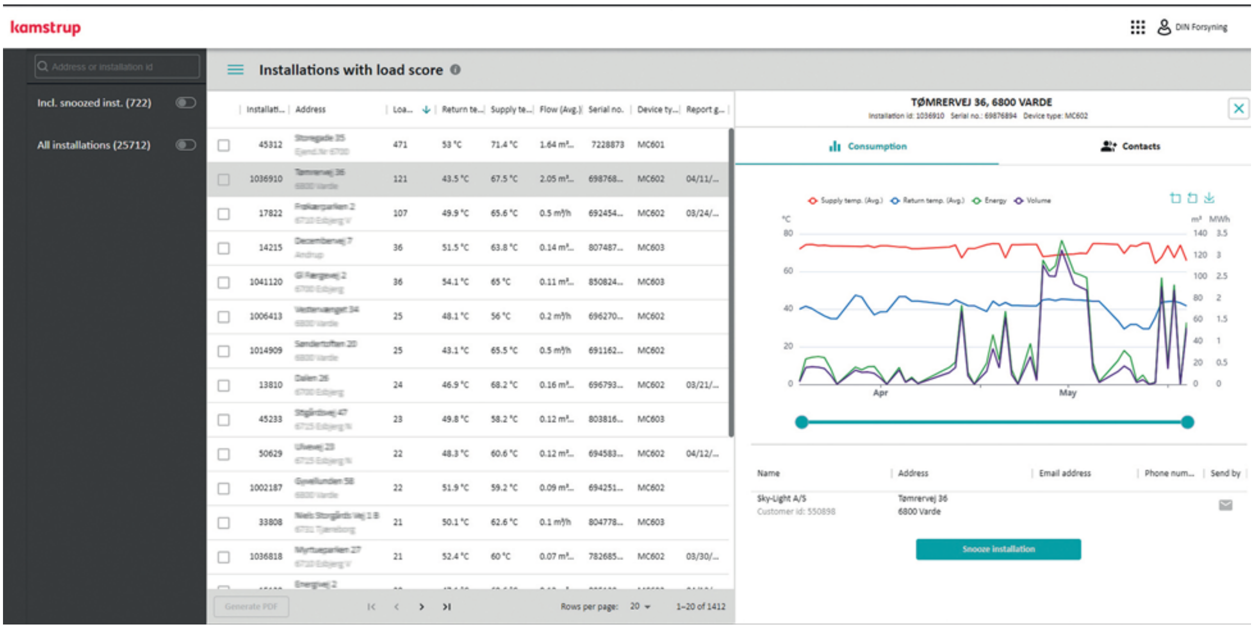
7.3.2.1 Advantages

- **Scalability through automation and digitalization:** The Digital Low-Temperature Assistant relies on machine learning and AI utilizing smart meter data and feedback from previously corrected faults. This avoids manual processes and provides one coherent solution with easy and automated access to identify and engage with relevant end-users.
- **Maximize impact through targeted engagement:** Empower DH operators to maximize the impact of end-user engagement by providing end-user specific information, diagnoses, and suggestions for improvements, as well as tracking the overall end-user engagement progress and low-temperature achievements.
- **Bring DH operators ahead of their business through deep understanding:** Allow DH operators to proactively engage with the most relevant end-users by avoiding an ad-hoc approach and provide the necessary insights for prioritizing both existing faults and the heat installations that will become a problem tomorrow.
- **Create transparency and trust to lower supply temperatures:** Empower DH operators to lower supply temperatures by providing the transparency needed to predict and document that end-users can maintain the comfort level at lower supply temperatures.
- **Learns from other DH operators having the same approach:** Support DH operators by including learnings and feedback from multiple other DH operators into the self-learning diagnostics and forecasting algorithms.

7.3.2.2 Barriers and challenges

A prerequisite for the deployment of the Digital Low-Temperature Assistant is the integration between smart meter data and customer contact information (CRM), which is required to automize the workflows.

In practice, the organizational aspects of fault handling pose the biggest barrier for an efficient deployment. Only a few DH operators have clear roles and responsibilities in their fault handling processes. In many cases, DH operators experience this to be a problem, since no one follows up on the fault handling process and makes sure that the work is being carried out.



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☐	1036910	[redacted]	121	43.5 °C	67.5 °C	2.05 m³...	698768...	MC602	04/11/...
☐	17822	[redacted]	107	49.9 °C	65.6 °C	0.5 m³/h	692454...	MC602	03/24/...
☐	14215	[redacted]	36	51.5 °C	63.8 °C	0.14 m³...	807487...	MC603	
☐	1041120	[redacted]	36	54.1 °C	65 °C	0.11 m³...	850824...	MC603	
☐	1006413	[redacted]	25	48.1 °C	56 °C	0.2 m³/h	696270...	MC602	
☐	1014909	[redacted]	25	43.1 °C	65.5 °C	0.5 m³/h	691162...	MC602	
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Figure 7.5: Screenshot of the Digital Low-Temperature Assistant's graphical user interface.

7.3.3 Arteria Platform

The Arteria platform (www.arteria-tech.com) helps energy companies plan and operate their heating networks more efficiently and thus save costs and reduce CO_2 emissions. Based on a Digital Twin concept and dedicated online services it provides the digital infrastructure for transforming heating networks into smart thermal networks through:

- GIS-integrated digitalization of heating network components (tubes, generators, consumers, etc.),
- fast and easy return-of-investment analysis of heat network planning (new consumer connections, waste heat integration etc.), and
- optimal control signals for decentralized producers and substations (merit-order principle).

The Arteria platform provides a user-friendly interface that eases the virtual representation of the heating network, see Figure 56. For instance, networks can be defined by drawing individual system components (such as tubes, heating plants, consumers, etc.) in a graphical editor. Associated time-dependent supply and consumption data can be uploaded. Arteria provides both SaaS and consulting services to its clients. The platform can be either hosted in the cloud (MS Azure) or integrated into a company's local infra structure (on-premises solution).

7.3.3.1 Example implementation

- complete GIS integration and analysis of the operational efficiency of DH network in Caslano (Switzerland) using a digital twin analysis, resulting in the detection of high losses due to inefficient control
- planning of a new DH grid in Brussels (Belgium) as part of a master plan to phase out gas by 2040
- real-time control of a DH network in Mischendorf (Austria) based on digital twins of substations and heat plant components
- dashboard for the DH operator in Bottrop (Germany)

7.3.3.2 Advantages

The Arteria platform relies on a novel thermo-hydraulic solver combined with self-learning AI models which allows to simulate meshed, complex, and distributed DH networks of any size or complexity. Through a smart combination of physics and AI, a minimum amount of operational data is needed to setup the digital twin.

Operational efficiencies are based on energy and exergy cost analysis, providing information on the true cost of supply at every point in the network. This information allows to identify inefficiencies in the operation not detectable by traditional temperature analysis.

7.3.3.3 Barriers and challenges

Current barriers involve the quality and availability of data at the DH sites themselves as well as missing routines and best-practices to use software-based engineering services. Examples are missing or erroneous time stamps in time series data as well as wrong or missing GIS data of networks.

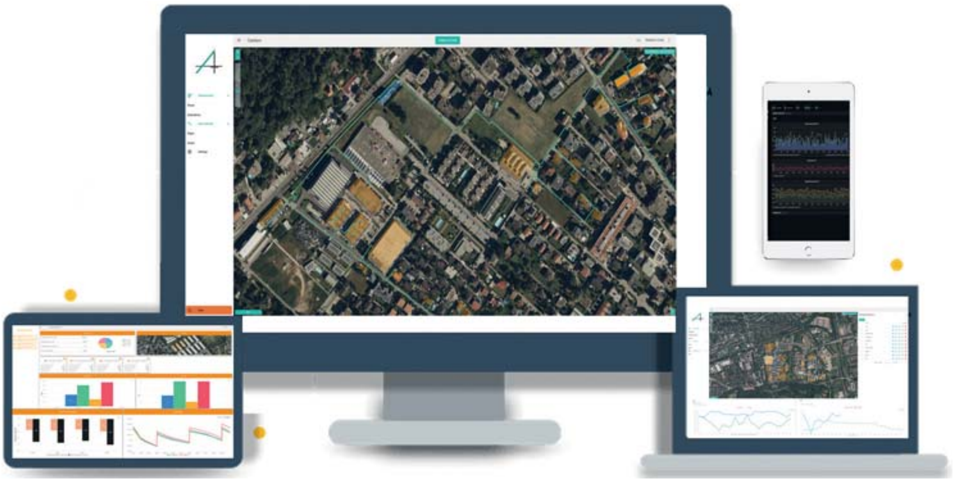


Figure 7.6: User interfaces provided by the Arteria Platform.

Furthermore, many use cases are currently handled with the help of spread sheets and data transfer via email. This leads to long turnaround times and misses the chance to quickly assess scenarios based on fast changing environments.

7.3.4 Heat Intelligence solution

The transition to the 4th generation of DHC requires new ways of planning, operating, and maintaining DHC systems. Systems need to be operated closer to the limits while still delivering on security of supply and comfort to the end-users. Being able to document what you have delivered is only the result. Ultimately, optimization and security of supply is about getting to the point where you can also measure and optimize the very process and flow of heat. How is the heat distribution throughout the network? Where are the bottlenecks? How fast can you detect incidents and outliers?

The savings potential in running a DH system closer to the limits is enormous and the use of data and digital tools allow you step aways from simulations-based tools only and into solutions which are fully data-driven.

Heat Intelligence is a cloud-based analytics platform from the Danish company Kamstrup, that provides unique insight into a DHC distribution network – the most valuable asset for DHC operators but hidden underground and hard to manage. Heat Intelligence combines the basic GIS model of the pipe network (pipe length, dimension, insulation, etc.) with online data from smart meters to create a data-driven and always updated digital twin of the distribution network. The model provides virtual temperature and flow measurements throughout the distribution network, without the need for adding additional sensors (besides the smart meters in every connected building).

Heat Intelligence uses huge amounts of data collected by smart meters to monitor load and capacity and identify what stresses your network. This can help you reduce heat loss, lower temperatures in the heating system, or optimize pressure in the network. And it can help you prioritize pipe sections where you will get the best return on your investment by adjusting, repairing, or replacing old pipe sections with new ones. Furthermore, Heat Intelligence helps you to identify households where heat installations might need to be adjusted or repaired.

From an organizational perspective Heat Intelligence gives more people access to see and understand what happens underground in the distribution network. Often this knowledge has been tacit and limited to a few people. A digital twin allows more people to share a common picture and discuss facts rather than relying on few datapoints and gut feelings.

7.3.4.1 Example implementation

Heat Intelligence is commercially available and can be deployed by any DHC operator. It’s a prerequisite to have a GIS model (e.g., shape file) and smart meter data at daily or hourly interval. Deployment has mostly taken place in mature DH markets like Denmark and Sweden, where remotely readable smart meters are widely implemented. However, at least Heat Intelligence pilots have currently been deployed in most DH markets.

7.3.4.2 Advantages

Heat Intelligence is fully data-driven (compared to simulation-based tool that are calibrated up against very few real data points) and offers an easy and intuitive user interface to dynamically visualize the entire distribution network and end-user data. All the way from heat source to end-user is covered. Also, the last-mile service connection pipes, which are normally not simulated in traditional tools. This makes it possible to:

- Analyse supply temperatures: document supply temperatures at end-user level, spot weak spots and possibilities for lowering supply temperature, see temperature in all different pipe sections without additional sensors etc.
- Analyse return temperatures: which end-users with highest negative impact on the general return temperature?
- Analyse load and capacity: see flow rates/velocities and pressure drop in all different pipe sections to evaluate distribution network performance and bottle necks. Can be used to verify the original simulation-based model and design criteria. Also, the transition time from production source to end-user is calculated. This provides good information about the dynamics in the DH system

- Analyse deviations: when something deviates in the Heat Intelligence model (digital twin), something is wrong or deviates in your "real" distribution network. Deviations can be used to identify heat loss, bypasses, and leakages (to some extend) and thus improve both operation and asset management

7.3.4.3 Barriers and challenges

Typical barriers and challenges for implementing Heat Intelligence are:

- GIS model (shapefile) of the distribution network is not available or incomplete (e.g., pipe type and sizes are not present)
- Smart meter data should be available on daily or hourly (preferably) interval for >90% of all meters

Besides this there is a general need for more digital maturity and competence at the DH operators. Many DH operators recognize that digitalization is needed, but often they don't have the time and resources to start using new solutions and tools – even though there is a positive business case and a short return-of-investment.

Heat Intelligence can and will be further improved with more features and services. The Heat Intelligence visualization is a good step to get started on the digital journey. However, it is also clear that Heat Intelligence can be developed further in the direction of automated recommendations and focus areas, rather than "just" being a visualization and analytics tool.

7.3.5 Utilifeed energy system optimization for DHC

The energy system is getting more and more complex, electricity prices are more volatile, and the number of market participants is increasing. These factors make it more complex to optimize the district heating production and a traditional merit order is facing serious problems. By following the electricity prices better, and making use of flexibility in the system, the revenues for sold electricity can increase and the production costs can decrease. These things are difficult to optimize without advanced software.

Utilifeed's optimization is developed to optimize the electricity, heat, and cooling production for the upcoming days as well as minimize the operational costs during the period (https://www.utilifeed.com/). This is achieved by considering the spot prices of electricity, the district heating and cooling demand, the available flexibility in the system, and the status of the production system. The optimization relies on a digital twin of the production units in the DHC system, the distribution grid, and all individual buildings on the demand side.

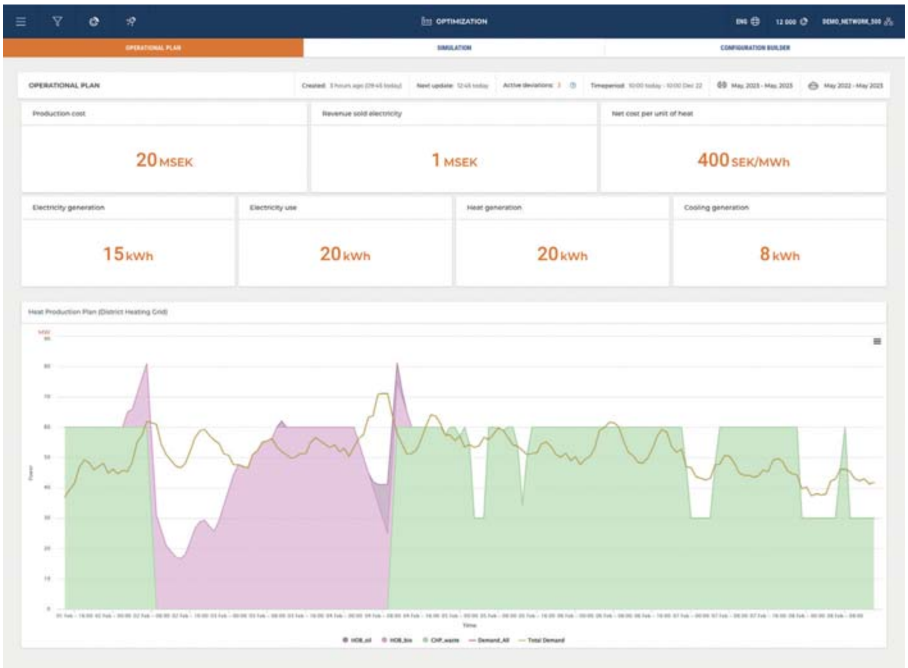
The optimization software is a cloud-based solution, that is built into Utilifeed's platform for district heating and cooling analytics, see Figure 5.7 for a screenshot of the user interface. This enables the optimization to have access to the needed data in a standardized format. The optimization is using an expanded system boundary, by not only taking to account the production units in the district heating system, but also the demand-side flexibility in buildings in the system. The software can use buildings as thermal storage, and/or cooperation between building heat pumps and district heating, as part of the optimization.

To get a prediction of the future heating and cooling demand, which is needed as input to the optimization software, Utilifeed's machine learning algorithm EnergyPredict is used. EnergyPredict uses the historical consumption of each individual substation in the network, together with weather and calendar data, to forecast the load.

7.3.5.1 Example implementation

Five different cities around Europe have live-tested the operation of their district heating grids in combination with demand-side flexibility with the help of Utilifeed's optimization. Testing has been done within the ERA-Net project Flexi-Sync on both small (<5GWh) and large grids (>500GWh). The output from the testing is that both the Optimization and the demand side flexibility work well and that the users see great potential in the tool.

Production planners have used the software to optimize production and distribution together with flexibility in the buildings by sending a control signal from the tool to the building control system. These features are now being implemented in more cities.



OPERATIONAL PLAN

Production cost: 20 MSEK

Revenue sold electricity: 1 MSEK

Net cost per unit of heat: 400 SEK/MWh

Electricity generation: 15 kWh

Electricity use: 20 kWh

Heat generation: 20 kWh

Cooling generation: 8 kWh

Figure 7.7: Screenshot of Utilifeed's platform for district heating and cooling analytics.

7.3.5.2 Advantages

Creating a digital twin of the district heating and cooling system to optimize production will decrease operational costs. The advantage of Utilifeed's optimization software is that it expands the system boundaries of the district heating and cooling system to also include the buildings in the optimized energy system. The flexibility offered by the buildings can reduce the operational costs of the system and at the same time provide a load reduction in a shortage situation.

Utilifeed also uses historical consumption data, to forecast the consumption. Using historical consumption instead of historical production is necessary if the flexibility in the building is to be used in an optimal way. It also reduces the impact of abnormal operation of production units due to shortage. The distribution grid needs to be modelled separately in this case, to account for losses in the grid. But this is only an advantage because then it is also easy to use the flexibility in the grid as a resource in the optimization.

The tool can also be utilized to realize significant savings on capital expenditures related to production and distribution capacity. This is done by simulating the design conditions in the system with very high accuracy which helps optimize the sizing of all components in the energy system as well as decking what types of components are the most cost-efficient.

7.3.5.3 Barriers and challenges

One challenge for using Utilifeed's production optimization to its full potential is that it's not enough to have the energy companies using it, they need the building owners' agreement to be able to use the demand side flexibility. In some cases, there will also be a need for an installation of a building control system. But the more installations that are made, the easier it will be for the next building owner to also connect to be part of the energy system optimization.

7.3.6 Leanheat Network

As the complexity of district heating networks increases the importance, and benefits, of digital twins increases. Leanheat® Network is part of the Leanheat® Software Suite & Services developed by Danfoss[7-1]. It is a thermo-hydraulic modelling tool developed specifically to support district energy system planning, design, and operation. The tool enables utilities to simulate the hydraulic and thermal states (pressure, flow and temperature) in district heating/cooling networks.

Leanheat® Network is used for designing of new networks, extension of existing network and hydraulic analysis of district energy systems and development of contingency plans using what-if scenario analyses.

The software can be applied in three stages:

- as an off-line design and analysis tool
- as an online supervisory tool
- as an online supervisory and optimisation tool

7.3.6.1 Example implementation

Fjernvarme Fyn in Denmark is using Leanheat® Network for various purposes. "Danfoss Leanheat® Network Online (LHN Online) was chosen because of its fulfilling features as a planning, design, and optimization tool. By enabling the identification and quantification of strategies for design and operation, LHN Online will help increasing efficiencies, reducing operating costs, and cutting emissions. Fjernvarme Fyn employs LHN Online to provide decision-ready information that allows our staff to make the best possible decisions", Peer Andersen, Plan and Project Manager, Fjernvarme Fyn A/S.

Stanford University chose Leanheat® Network for optimizing their newly transformed university campus energy supply system, district heating and cooling, and ensure cost-efficient operation capable of fulfilling pay-back obligations. Stanford uses the Leanheat® Network digital twin of the supply system to monitor and optimize their operation, using a combination of temperature, pressure, flow, velocity, and losses, in real-time. In addition, the digital twin supports the energy system operators with troubleshooting, provides analytics to improve operation and maintenance, as well as helps developing scenarios for future expansions of the building stock. In other words, to produce and distribute exactly the energy needed in the buildings, today and in the future, at the lowest possible cost.

7.3.6.2 Advantages

With the help of the Leanheat® Network digital twin in the planning and design process, the software offers the capabilities of:

- optimizing new system designs
- planning of future network extensions
- identify hydraulic bottlenecks
- what-if analyses to explore impact of disruptions and development of contingency plans
- By utilizing measurements from production sites, inputs from sensors in the network, smart meters as well as load forecasts, the Leanheat® Network digital twin supports the network operator to accomplish number of things, for example:
- predict, and understand the impact of, future load conditions
- dynamic pressure and temperature optimization
- identification of design and operation faults
- optimal planning of maintenance tasks
- database of knowledge about network
- analysis of impact of expansion, refurbishments, and new connections to the existing network
- what-if analyses to explore impact of disruptions and development of contingency plans

7.3.6.3 Barriers and challenges

Depending on the size and the inhouse capabilities of the utility the implementation can be perceived as complex. A certain level of hydraulic modelling understanding is a prerequisite. In addition, a certain level of measurements must be available for successful implementation, which is not often the case. Therefore, additional sensors need to be installed in the network or production sites with automized recording, transfer, and storage of data. Maintenance of the hydraulic model after network changes is required to conduct valid calculations and simulations.

7.3.7 Leanheat Building

The operation of district energy systems is inevitably limited by the building thermal demands and the operation of the building technical installation. It is only by holistically including all aspects of the heat supply system, production, distribution, and end-users, that the true optimization potential can be unlocked.

Leanheat Building® is a software solution for optimizing the operation of heating installations of buildings with a centralized heating system. It utilizes the latest AI and machine learning developments to generate accurate thermodynamic

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[7-1] Danfoss Leanheat® Software Suite & Services: https://www.danfoss.com/en/products/dhs/software-solutions/danfoss-leanheat-software-suite-services/

models of the buildings it controls based on a grey-box digital twin. It combines indoor climate monitoring and weather forecast to achieve energy savings and decrease the volatility of indoor temperature associated with traditional heating control strategies, improving living conditions for occupants. Furthermore, the control algorithm can optimize consumption and temporarily shift demands, while maintaining desired indoor comfort.

7.3.7.1 Example implementation

Vatajankoski, an energy services provider in the Kankaanpää region in Finland, has applied Leanheat® Buildings in several building for the implementation of demand response solutions at building level.

The heating systems in approximately 40 properties in Vatajankoski are optimized by Leanheat®. As a result, their energy consumption has decreased by 12 percent, which corresponds to the annual consumption of around 100 single-family houses. When energy consumption in building is optimized, it also affects energy production in a positive way, allowing end-to-end optimization.

On the production side, the district heating utility can accurately create a load forecast, that can help with the optimization of the production and the prioritization of energy sources. On the other hand, the demand side response solution can use the thermal mass of the buildings as a virtual energy storage. In this way, peak loads are reduced, and the heat demand is flattened enabling a larger share of renewable energy sources in the systems.

7.3.7.2 Advantages

Leanheat® Building brings state-of-the-art AI and machine learning capabilities to the building operator, which enables automatic, and continuous, commissioning of the technical building installation. Additionally, the autogenerated thermodynamic model of the building enables effective utilization of the thermal energy storage potential of the building thermal mass.

With these capabilities Leanheat® Building will:

- provide accurate load forecasts
- minimize energy consumption, without sacrificing comfort
- identify minimal supply temperature required for fulfilling the building heating demands
- minimize district heating return temperature
- enable utilization the building thermal mass for temporary load shifting for minimizing peak demands

7.3.7.3 Barriers and challenges

The main challenges for the application of Leanheat® Building is that most DH operators are not responsible for building heating control and cannot actively operate at building level. The application requires new responsibilities on the DH operator side, and new competences need to be developed to assess the real impact of these new solutions. Furthermore, since DH operators do not own the buildings directly, different stakeholders are involved when there is interest in implementing solutions that would optimize the energy consumption at building level. That can complicate the implementation process.

The definition of the value of demand side flexibility/management for the DH operators is not always straight forward, because it is a complex combination of OPEX and CAPEX savings. Therefore, DH operators are sometimes hesitant when considering new solutions.

Lastly, the current tariff structures might not support sharing the value fairly between stakeholders, which can stop the implementation process if there is no interest in one of the parts.

7.3.8 Online monitoring for large spontaneous leakages

In case of a large spontaneous leakage medium is lost. To prevent evaporation due to high supply temperatures, pressure must be maintained, and losses must be compensated. A fast and targeted action is necessary within several minutes up to 2-3 hours as there is only a certain amount of medium stored and treatment capacities are limited. Detection of the leakage is easily possible by evaluating mass flow of supply and return or a direct measurement of the refill mass flow. A Digital Twin collecting and analysing measurement data in real-time provides an adequate platform to deploy leakage detection systems for DH network operation.

A quick separation of the damaged network part is possible if the network is equipped with remote controlled motor-driven valves bordering exclusion areas. Hence, identifying the affected exclusion area is sufficiently accurate for localization. Identification is done by an evaluation of the negative pressure wave. Each sensor registers the pressure wave at a different point in time depending on its position in the network with respect to the leakage position. Because signal analysis is a demanding task and leakages can occur at any time, a fully automized evaluation procedure is required.

In practice, this requires the sophisticated interaction of different digital technologies in the ongoing network operation, including the integration of measurement data in real time, the continuous monitoring of the system, or the initiation of remote countermeasures.

7.3.8.1 Example implementation

Online monitoring is applied for a district heating network in Munich (Germany)[7-2]. This is realized by Stadtwerke München's Internet of Things (IoT) and Big Data platform, which enables the creation of digital twins (see Figure 7.8) and thus allows real-time monitoring and advanced analysis in the form of calculation services. Process data is transferred from a given DHC network part to a central database. An online calculation service is continuously running to evaluate the measured mass flows for leakage detection (Figure 7.9 left). In case of a leakage, the starting time is determined, and another online calculation service evaluates all available pressure data within a certain time frame. Combination with network topology data allows an evaluation of the exclusion areas.

The network operator can access the resulting ranking online (Figure 7.9 right). As there could be multiple detections during one event, the temporal course of the refill mass flow is displayed and starting points of the pressure waves are indicated by red lines (cp. Figure 7.9 left). This allows the network operator to compare and rate multiple detections. Larger and faster changes of the refill mass flow indicate more distinct pressure waves traveling through the network.

7.3.8.2 Advantages

In case of a large spontaneous leakage, separation of the damaged network part is now possible directly after its occurrence. Previously, reports of customers were the best available information. If there were no reports, exclusion areas had to be separated in a given order as the last option.

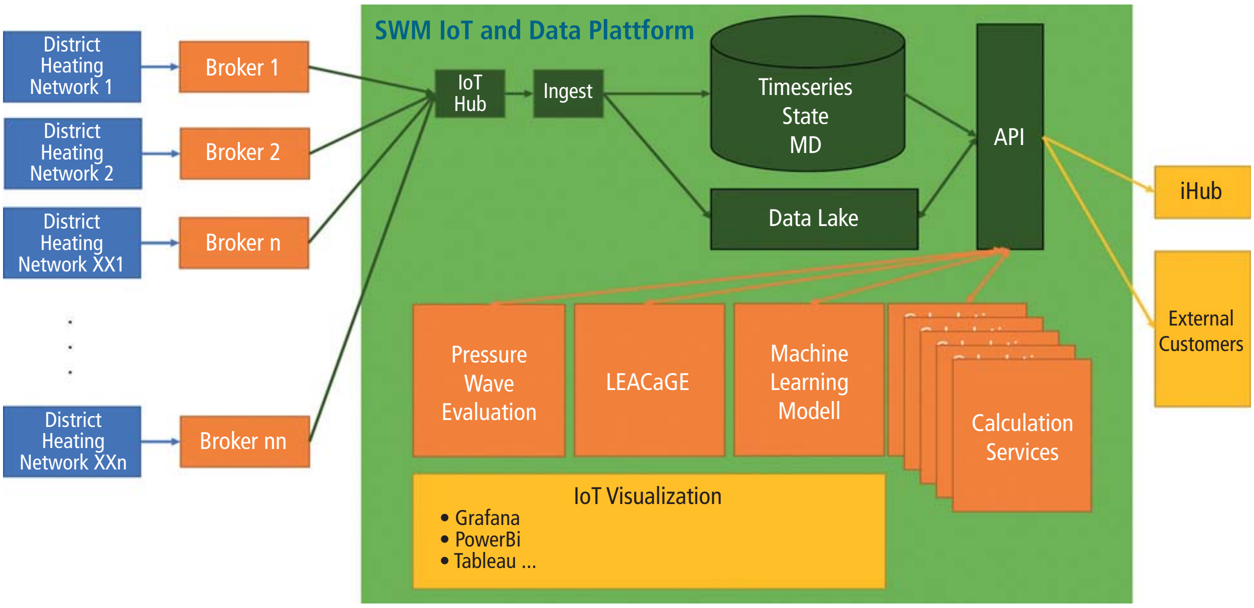

Figure 7.8: Stadtwerke München Digital Twin Architecture

[7-2] Funding by BMWK is gratefully acknowledged (FKZ 03ET1624B and 03ET1236B). See https://www.enargus.de/detail/?id=354658 and https://www.enargus.de/detail/?id=1038936.

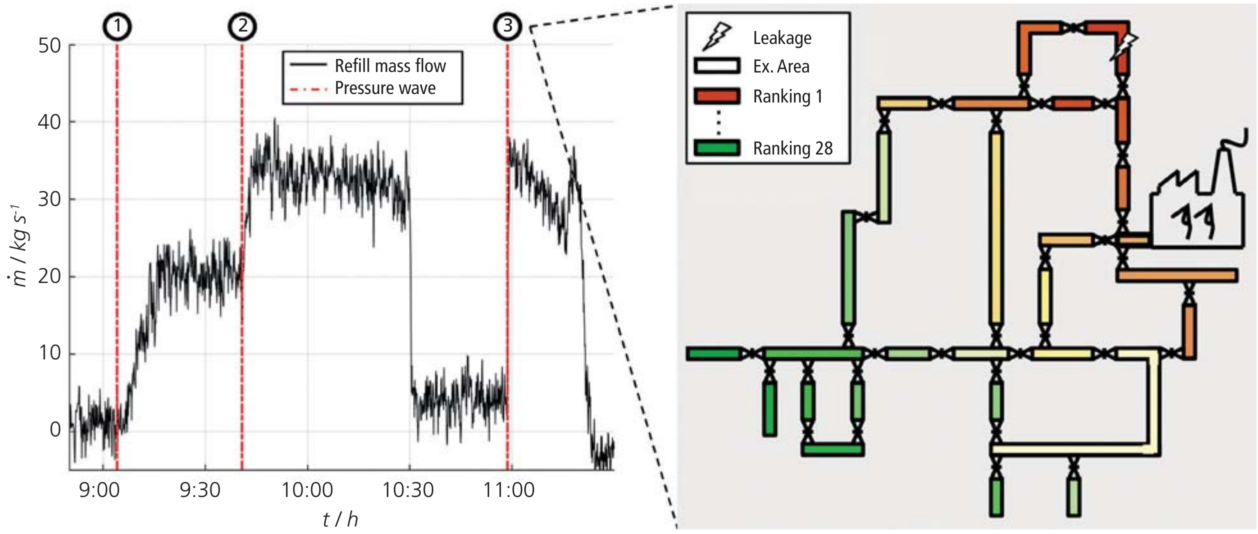

Figure 7.9: Refill mass flow with three detections (marked 1 to 3) of pressure waves (left); network topology with exclusion areas (right). Colouring indicates the ranking (first place red, last place green) calculated for pressure wave #3.

Good performance of the solution has been demonstrated with a minimal number of sensors and with a high-level of noise (see Section 6.5.3.1). First practical results have been achieved within a relatively short time (Rüger et al., 2018; Vahldiek et al., 2021). Already existing networks can be retrofitted with this kind of online monitoring without installing new hardware.

7.3.8.3 Barriers and challenges

The working principle relies on the evaluation of several test leakages (TL) located in a maximum distance of 10 m across the whole network. Pressure waves starting from these TLs lead to theoretical distinct PDTPs at the sensors. To this end, detailed information about the network topology and sensor location is necessary. Linking of sensor locations and data requires unique IDs of assets across all systems and documentations.

The most prominent challenge is data quality. Data with a higher quality can lead to further improvements. As only a minimal number of sensors is needed, five sensor positions have been equipped with new sampling and transmission technology in the test system.

7.3.9 Smart Management of Integrated Energy Systems Through Model Predictive Control

The transition toward a decarbonized energy system is gradually phasing out fossil fuels in favour of a higher penetration of renewable-based energy production technologies. This is giving rise to systems of increased complexity as well as to new challenges in system management, due to the volatile nature of renewables based on solar and wind. Moreover, the interconnection, interaction, and integration of all sectors of energy production, distribution, and consumption (i.e., heating, cooling, electricity, and gas), is gaining interest in order to exploit the synergies arising among them.

The potential of these multi-energy infrastructures can be fully unlocked through smart control systems which autonomously optimize and update the management strategy in real-time, depending on the availability of the renewable energies, network state and consumer demands. Within this context, the Digital Twin concept can help to deploy innovative smart energy management system.

The research project DISTRHEAT (www.distrheat.eu) addresses this issue through an innovative control strategy for multi-energy systems feeding district heating and cooling networks (Saletti et al., 2022). This control strategy implements an approach based on model predictive control (MPC) which relies on metering data and a digital representation of the system to evaluate the future behaviour or the system. Based on forecasted disturbances, an optimization algorithm tests several control sequences and chooses the one with the best performance.

The three interacting space and time control layers of the control architecture are (see also Figure 7.10):

- **Distribution modules:** for minimizing the energy distributed to a section of the heating and cooling network
- **Short-Term Supervisory module:** low-level supervisory controller which controls the thermal power station in real time, based on the minimization of operating cost on a few days horizon
- **Long-Term Supervisory module:** high-level supervisory controller which solves the yearly scheduling problem of the thermal power station with a daily time resolution, including long-term factors (e.g., threshold performance parameters for incentives)

7.3.9.1 Example implementation

The Italian test site of the DISTRHEAT project is the Sant'Anna Hospital of Cona, located close to the city of Ferrara (Italy), see Figure 7.11. The site requirements are represented by the demands for space heating and cooling, the electrical demand for the hospital appliances as well as the steam demand for other hospital special utilities such as the laundry, the sterilization department, and the kitchen. The system comprises:

- a small-scale DHC network that distributes heating and cooling energy to the hospital buildings as well as
- a thermal power station, where heating, cooling and electrical power, and the thermal power for steam, are produced through a trigeneration plant, four boilers, four electric chillers and three steam generators.

The controller has been implemented in a dedicated industrial PC and the communication with the existing Building Management System (BMS) has been set through the Modbus TCP protocol (De Lorenzi et al., 2020). Every 15 minutes, the control set points are updated and set automatically on the BMS.

7.3.9.2 Advantages

The controller has been operating autonomously the Hospital energy system since March 2022 and its performance has been monitored. Comparing its operation with the business-as-usual operation, despite a slight increase in natural gas consumption for heating use (due to a more intensive use of the cogeneration plant), electricity consumption has been reduced by better exploiting the absorption chiller during summer. Moreover, the application of the MPC controller had a positive impact on the economic performance, reducing the operational costs and increasing revenues from incentives, coherently with the optimization goal set in the controller. This has been achieved with a negligible investment cost on new hardware and only by changing the way in which the existing thermal power station is operated.

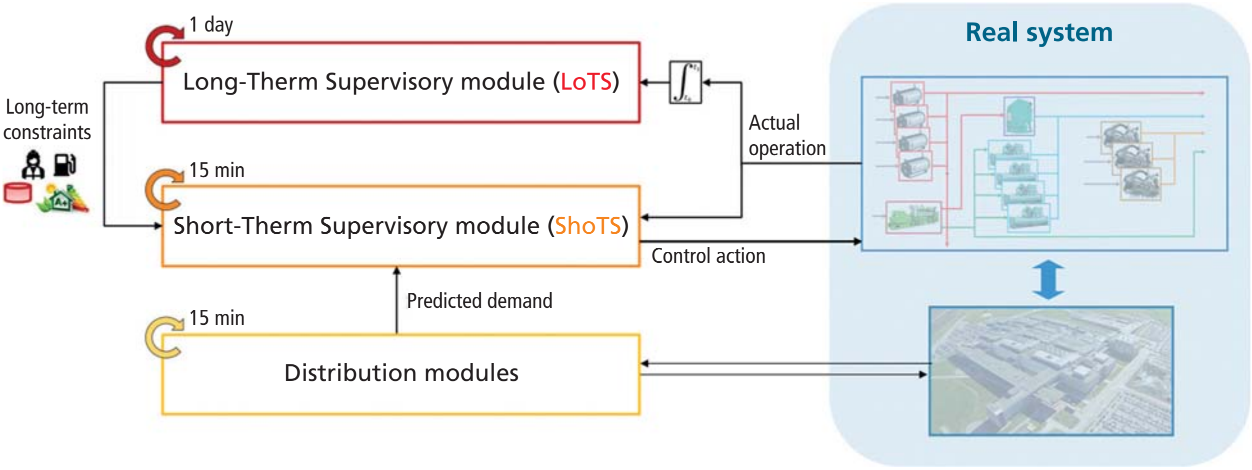

Figure 7.10: Overview of the control layers of the DISTRHEAT control architecture.

Figure 7.11: Overview of the DISTRHEAT test site at the Sant'Anna Hospital of Cona.

7.3.9.3 Barriers and challenges

The MPC technology has been demonstrated in the DISTRHEAT project in a hospital, i.e., a very delicate operation environment, and some other successful examples are available. Nevertheless, it is not well known, and it faces scepticism probably due to the perception from the operators of a lack of control on their plants.

The implementation of MPCs needs some preparatory work for model set up and identification and for the optimization algorithm selection. This can be sped up by developing standardized architectures.

Moreover, the communication between the MPC and the BMS needs to be tailored for each application. The definition of a data interoperability standard in the energy sector could help to eliminate this issue.

7.3.10 DigitalEnergyTestbed

The digitalization of the heat sector poses new challenges for the development of new components and the deployment of automation and control solutions. Even though the enabling technologies are well understood on the component level, their effects on the system level are still subject of investigations. Within this context, the research project DigitalEnergyTestbed (Widl et al., 2022) has introduced the concept and prototype implementation of a testbed for the lab validation of smart applications in thermal networks.

The DigitalEnergyTestbed prototype comprises a DH substation test stand. The commissioning of the DH substation test stand as part of the prototype for a fully automated and unattended operation over longer periods is complex and time-consuming. Hence, a fully functional digital twin of the test stand has been used as replacement for performing preliminary assessments. In addition, availability of the test stand is limited, and its operation requires trained personnel. Therefore, the Digital Twin can be used for rapid development and testing of new applications.

7.3.10.1 Example implementation

The DigitalEnergyTestbed prototype is a proof-of-concept implementation of an open testbed for applications in the context of integrated energy system. It enables the deployment of cross-domain test applications in a real-time environment, using a combination of laboratory equipment and simulation models. The enabling technology behind the DigitalEnergyTestbed prototype is Lablink, an open-source middleware responsible for the management of and data transfer between distributed clients. Lablink provides various clients that have been specifically developed to access hardware (e.g., laboratory equipment) and software (e.g., simulation tools).

As proof-of-concept, a test case has been selected that evaluates the impact of a demand response (DR) scheme on a DH system. During times of high heat demand, the heat flow from the DH network to the heat consumers is reduced by lowering the substations' secondary supply temperature by 5°C. The resulting temperature difference with respect to the nominal supply temperature is compensated by local booster heat pumps. This DR scheme is implemented using a simple controller, which sends a signal to the substations for triggering the temperature reduction. Figure 62 gives a schematic view of this system configuration (with most of the DH network not shown due to space limitations).

Figure 7.13 shows how the system configuration from Figure 7.12 has been mapped to an actual DigitalEnergyTestbed setup. Included are the Digital Twin of the DH substation as device under test in the test stand, linked in real-time to detailed simulations of its supply side (DH network) and demand side (booster heat pump and building). The digital twin comprises an OPC UA server, whose endpoints correspond to setpoints for the test stand (primary supply temperature, secondary return temperature, secondary mass flow rate, etc.) and measurements from the test stand (primary return temperature, secondary supply temperature, primary mass flow rate). However, rather than linking these endpoints to real hardware, a thermo-hydraulic model of the test stand is executed internally, synchronized to real time with a fixed communication step size (10 seconds).

7.3.10.2 Advantages

The DigitalEnergyTestbed enables the evaluation of digitalization solutions on the system level. It provides a platform for rapid development and testing with the help of the Digital Twin. The latter can be easily replaced with the real test stand performing for validation testing. Using Digital Twins as part of the testbed has two key advantages:

- The commissioning of a test setup using a Digital Twin can be done without the risk of misuse or damage to the replaced device or (sub-)system. This is especially useful when testing critical operating conditions.
- Using Digital Twins can improve the availability of test setups. Whereas setups with hardware components are typically more costly and complex to replicate, Digital Twins can be in many cases replicated with less effort.

7.3.10.3 Barriers and challenges

The Digital Twin's internal model must be carefully matched to the real system and calibrated. This matching must be done with high fidelity, replicating the real system's dynamics with high accuracy. The calibration of the model is especially challenging for off-design situations.

7.4 Conclusions

Digital Twins are enablers for utilizing digital technologies and deploy them for the operation and maintenance of DHC networks. Digital Twins embrace available digital tools and make them available online. Digital Twins facilitate the provision of real-time services that can either support operators (open loop) or automate processes (closed loop). With the integration of remotely con-

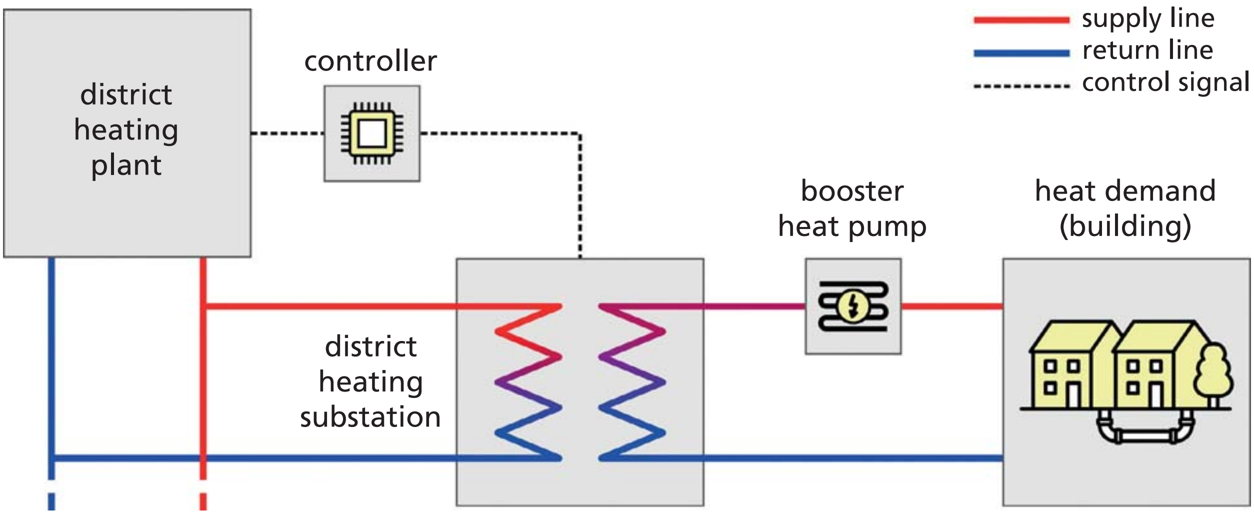

Figure 7.12: Schematic view of the proof-of-concept test case for the DigitalEnergyTestbed prototype.

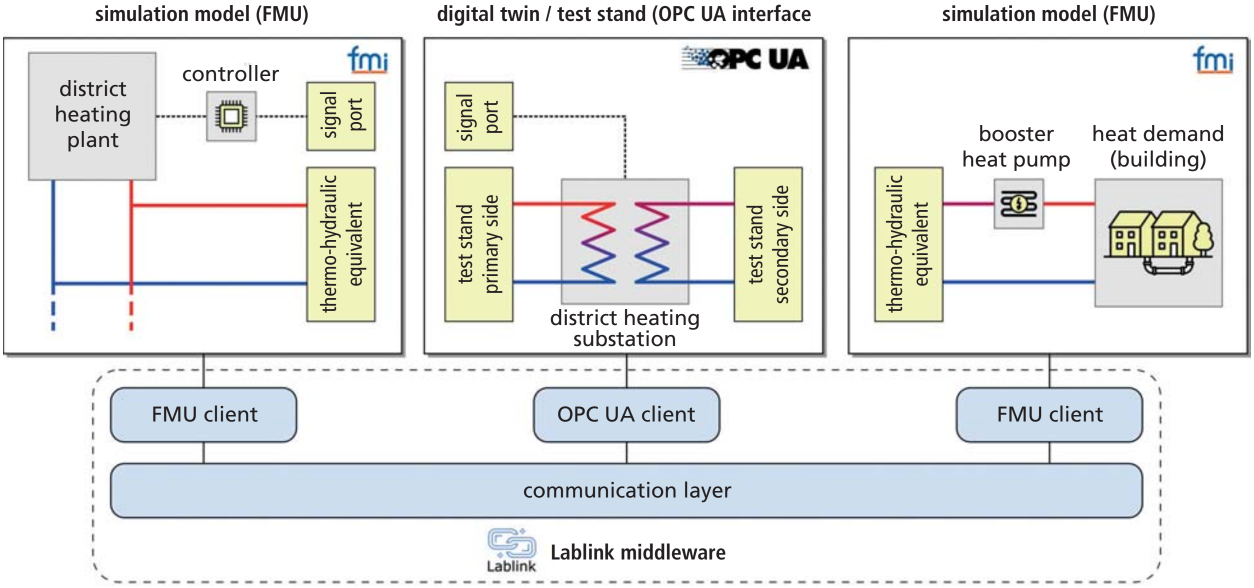

Figure 7.13: Mapping of the proof-of-concept test case to the DigitalEnergyTestbed setup, using the Digital Twin of the DH substation test stand as central component.

trollable assets, the bi-directional, (semi-)automated interaction with the DHC system is made possible, enabling the transition from traditional passive networks to smart energy systems. This opens new opportunities for supporting and / or automating certain aspects of the operation and maintenance of DHC networks and related infrastructure, especially for monitoring, diagnostics and fault detection, forecasting, and operational optimization.

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8 Business models and concepts

New, disruptive technologies – such as the digitalisation for district heating networks – not only require technical implementation in existing infrastructures, but also need a restructuring of current operating strategies. At the same time, processes must be initiated to monetise the new technologies. A business model is a descriptive representation of the rationale behind how an institution or company can create value for customers and secure a return for itself. In the following, we will explain how digitalisation can open up new and innovative business areas in the operation of existing district heating networks (DHN).

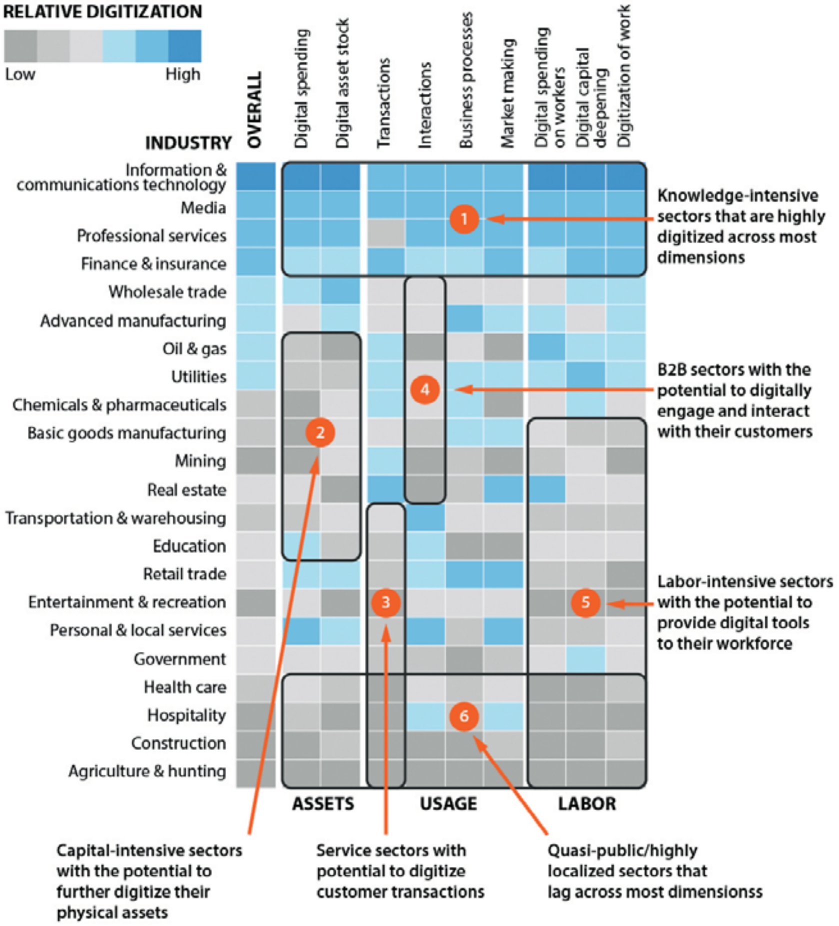
8.1 Subject of this chapter

Since the digitalisation of DHN is a novel technology, its beneficial effects on the operation of contemporary DHN are unclear to a certain extent. To what extent digital twins can contribute to an increase in the efficiency of the operation of DHN, digital measured values to a more targeted distribution of investments or a more effective predictive maintenance still needs to be clarified.

In order to discuss the general role of the digitalisation of DHN with regard to new business models, the first following chapter provides a basic definition of digitalised business processes. The general advantages of digitalised processes are explained and the resulting effects for digitalised DHN are described. Furthermore, exemplary business models for the individual stages of the generation, distribution and consumption of district heating are presented. This is followed by a brief outlook on the business models of other digitalised sectors and markets, respectively (see chapter 8.3). In chapter 8.4, various case studies are presented, in which different aspects of digitalisation are investigated within the operation of DHN on the basis of real balance areas. The balance areas are located in Germany, Denmark and Austria. The literature sources are listed in chapter 8.5.

8.2 Digitalisation of business processes

A widespread digitalisation can fundamentally drive changes of business processes (Deloitte, 2016) as it provides a new way of acquiring and processing information and data. With the help of this data, key figures can be derived for process monitoring, with which the entire process chain can be optimised and thus become more efficient. Optimisation can be realised through improved allocation of resources, better investment timing and adjustment of product flows (Rossato and Castellani, 2020). Finally, it enables the way for process automation, that minimises human errors and operational costs. It further enhances the understanding of customer experience needs (Rossato and Castellani, 2020) and changes in the earning logic and pricing models in business operations. Digitalisation enables the building of a fully digitalised service path and a personalised multichannel customer experience.



SOURCE DATA ANALYSIS AND EXPERT INTERVIEWS CONDUCTED BY THE MCKINSEY GLOBAL INSTITUTE © HBR.ORG

Figure 8.1: Overview of quantitative digitalisation potentials of different industry sectors. Based on Gandhi et al., 2016

The transition from analogue to digital processes typically necessitates a comprehensive understanding of the existing processes, a clear vision for the future state, and a meticulously planned strategy for the transition (Mueller and Lauterbach, 2021). This transition involves the identification of processes that are suitable for digitalisation, the selection of relevant digital technologies, and the re-engineering of processes to capitalise on these technologies (Kar et al., 2019).

Processes that are highly suitable for digitalisation often belong to industries characterised by a significant digital involvement in assets, usage, and labour (Gandhi et al., 2016). The accompanying graph delineates the degree of digital advancement across various sectors. (Kraus et al., 2021) also concluded that media and entertainment were among the first industries to embrace this transformation, with banking, retail, and healthcare trailing behind, and the oil and gas sector being considered late adopters.

However, the process of digitalisation comes with its own set of challenges. These might include capital availability with unplanned transitions potentially leading to unexpectedly high investments, particularly in the realm of cybersecurity. The transformation often mandates an infrastructure upgrade to accommodate advanced manufacturing technology. There may also be a reluctance to change within the organisation, a necessary learning curve adaptation time, and potential issues concerning data security and privacy (Paulsen, 2020).

In conclusion, the digitalisation of business processes, while complex, is a worthwhile endeavour. It calls for careful planning, substantial investment, and a readiness to tackle the inevitable challenges. However, when executed effectively, it can yield considerable benefits in terms of efficiency, accuracy, and customer satisfaction.

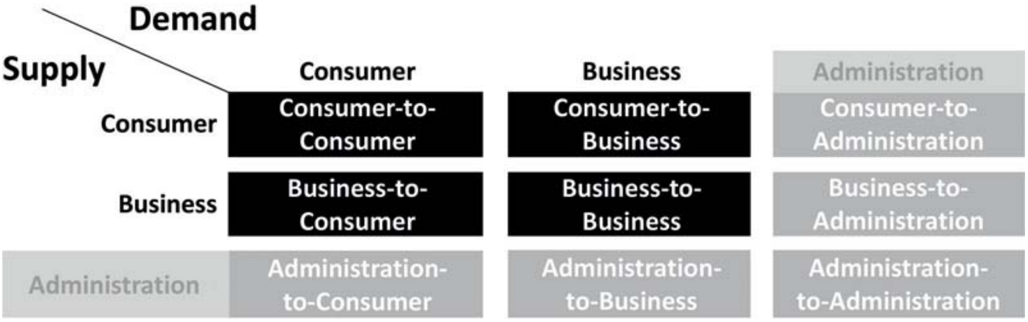
8.3 Digitalisation of DHN

For the transition from 3rd generation district heating (3GDH) to 4th generation district heating (4GDH), there are challenges like increased efficiency of energy use and the emerging concept of smart energy system (integration of electricity, gas and thermal grid) (Lund et al., 2014). Digitalisation can be helpful in this process. A research of six cases throughout Europe was conducted by (Lygnerud, 2019). It concluded that, comparing the technological shift from 3rd generation district heating to 4th generation district heating, only limited changes have made the shift to business logic. In all six cases, the companies offered heat and hot water instead of a green, indoor climate service, which is a typical, outdated logic of the 3rd generation district heating. To realise the change in the service mode, a strong customer dialogue and relationship must be established, in which digitalised tools can play an important role.

8.3.1 General overview of business models for district heating systems

When planning a business model, it is important to determine where the boundaries of business side and customer side lie (see Figure 8.2). The general infrastructures such as the DHN with its generation plants and the piping for both supply and return can be considered to be on the business side. The in-house heating and hot water circuits are owned by the clients and are therefore to be allocated to the customer side. Substations act as an interface between customers and the DHN. However, ownership in this area varies greatly and depends on the heating network, the type of customer, the connection schema and other factors.

In a classic, non-liberalised market, business-to-consumer relations predominate. The flow of energy and value creation is directed from centralised generation via centrally regulated distri-



Supply \ Demand	Consumer	Business	Administration
Consumer	Consumer-to-Consumer	Consumer-to-Business	Consumer-to-Administration
Business	Business-to-Consumer	Business-to-Business	Business-to-Administration
Administration	Administration-to-Consumer	Administration-to-Business	Administration-to-Administration

Figure 8.2: Differentiation of Business Models

bution to decentralised consumers. Here, the commodity heat is the focus of value creation and is exchanged directly for a currency. In business-to-business relations, district heating is one of the further process steps in the overall value chain; especially in the case of customers who use district heating to obtain process heat for the production of intermediate or final goods. In a classic district heating network consisting of private and commercial customers, these two business models play the main roles. Such systems are characterised by a monodirect heat flow from the operator to the customers. In transformed heat grids, as propagated for example in (Lund et al., 2014), bidirectional heat flows are conceivable due to e.g. technical progress and liberalisation, which can open up new business areas.

For example, prosumers, as examined in the work of Brand et al. (2016), can open up the consumer-business relationship by selling decentralised generated heat. For this to happen, however, the heating market must first be liberalised, or customers could possibly enter business relationships with each other in the future. They can form energy cascades, as Köfinger et al. (2017), for example, technically investigated in their work, in which a downstream customer can still use the return flow of an upstream customer to supply heat. With the concept of multilevel district heating, the parallel operation of different heating networks with different flow and return temperatures would be conceivable (cf. Bachmann and Kriegel, (2016)). This could establish a new business sector in the business-to-business area.

As a result of digitalisation, large amounts of data can be collected and intelligently analysed. Depending on the depth of the digitalisation, data can be collected on the primary side of a substation or on the secondary side. With data from the primary side, heat quantities can be determined by supply and return temperatures and mass flow rates. This can simplify billing, as the customer no longer has to manually record the meter readings and transmit them to the supplier, as is usually the case. The process becomes more concise and more efficient through digitalisation. Building on digital consumption recording, a bonus-malus tariff system can be established, which monitors whether the contractually specified return temperatures are adhered to. Customers who adhere to these specifications are paid a bonus, as lower return temperatures on the DHN side make heating network operation more efficient. Data collection on the secondary side can contribute to the integration of demand-side management (DSM) using actuators. DSM can be used to modulate the space heating and hot water demands and thus increase the flexibility of the entire DHN. The flexibility gained can be utilised, for example, in connecting new customers, which contributes to increased sales.

8.3.1.1 Business canvas before and after digitalisation

For the analysis from a business point of view, the business canvas developed by Osterwalder et al. (2010) is an effective tool. Based on the contribution of Lygnerud (2018) and District Energy - Information page (2020), a business canvas for conventional district heating without digitalisation is summarised in Figure 8.3. The new ele-

District heating with or without digitalisation

<table>
<tr>
<td rowspan="2">Key Partnerships
District heating provider
Distribution network operator
Local public authorities
IT service provider</td>
<td>Key Activities
Production
Distribution
Maintenance
Services
Active control</td>
<td rowspan="2">Value Propositions
Providing heat and hot water
Reliable supply
Flexibility and openness
Green energy with lower costs</td>
<td>Costumer Relationships
Prodvider to consumer
Closer collaboration
Costumer-supplier partnership</td>
<td rowspan="2">Costumer Segments
Residential buildings
Business & industries
Public buildings</td>
</tr>
<tr>
<td>Key Resources
Production unit
Distribution network
Maintenance staff
IT Infrastructure</td>
<td>Channels
Invoice
Local media, website, …
Distribution network
IT interfaces</td>
</tr>
<tr>
<td colspan="3">Cost Structure
Heat production and distribution
Maintenance and staffing costs
Marketing
Additional costs on IT infrastructure
Possibly reduced staffing costs
Cost saving due to increased efficiency</td>
<td colspan="2">Revenue Streams
Connections fees
Revenue from heat sales
Maintenance and operation contracts
Consultation to meet individual needs</td>
</tr>
</table>

Figure 8.3: Effects of digitalisation. Based on Osterwalder et al. (2010)

ments (in red) brought by digitalisation are also listed in the corresponding blocks.

In principle, digitalisation requires an investment in measurement sensors, actuators and a central IT infrastructure that collects, processes and analyses the accumulating data. However, these additional costs in IT infrastructure and personnel are offset by reduced personnel expenses elsewhere. Not only the increased efficiency of the DHN leads to savings, but also the reduced personnel expenses for the annual billing of the heat. Digitalisation brings suppliers and consumers closer together, and contact becomes closer. Issues and problems on both sides can be addressed more quickly, which reduces downtimes and fundamentally improves service quality.

8.3.2 Business models of digitalisation in different areas of DHN

The digitalisation of DHN can take place at the level of generation, distribution and consumption of district heating. At the individual levels, different effects can be realised through digitalisation. In principle, these can be divided into active and passive effects.

Active effects are those effects that can be lifted through a deliberate implementation of processes and information. The prerequisite for this is planned and systematic intervention. Passive effects, on the other hand, occur on their own, but usually require an initial event, e.g. a previously implemented active intervention. The following is a brief explanation of active and passive effects in the different value-added areas in the operation of DHN.

8.3.2.1 Generation on daily operations

As the general value creation of DHN is realised in daily operations, digitalisation has the strongest impact on this aspect of business. The main goal is to optimise operations in such a way, that it gets more efficient. Costs and emissions are to be saved, additional flexibilities are to be generated and the heating networks are to become more resilient to future challenges. The main effects, that can be achieved are:

- active: peak loads can be reduced by regulating customer capacities (DSM), which can favour higher shares of e.g. CHP generation. This can improve the ecology of the entire DHN.
- active: enables the effective integration and control of small, decentralised generation plants that lead to an increased share of renewable energies and reduction of transport-related dead spots and bottlenecks within the network.
- passive: lower DHN-sided supply and return temperatures can be achieved via active failure monitoring and incentivised tariff structures which will result in increased electrical and thermal plant efficiencies. Higher plant efficiencies lead to reduced fuel consumption and their associated CO_2-emissions.

With the intelligent control system, the energy for space heating can be predicted by calculation based on weather forecasts (Lund et al., 2014). Moreover, the intelligent control system also makes demand-side management (DSM) strategies like peak shaving possible, and these two functions can improve the efficiency of heating system.

Later on, the STORM project verified their prediction. Johansson et al. (2017) applied, in two demonstration sites, three machine learning algorithms for heat demand forecasting with training data including continuously accessible weather forecast data on an hourly basis. The algorithms worked well when relevant training data was available, and their accuracy to predict improved when new data became available for scenarios not covered by the training data. Further tests with intelligent control hardware, the so-called “STORM controller”, were later discussed (van Oevelen et al., 2020). They performed peak shaving tests in one of the sites and got a reduction of 3.1% in peak heat production. Two other DSM control strategies were also examined, and they summarised the following benefits of intelligent control system as: reduction in operational costs, reduction in CO_2 emissions, and increase in system capacity.

Digital twins (see also chapter 7), often co-operated with other technologies such as data analysis, narrowband IoT (NB-IoT), and machine learning, is also a powerful tool to improve daily operations. Kohne et al. (2021) proposed the technical concept and operating strategies of the industrial heat transfer station utilising industrial waste heat, together with an energetic balancing and a digital twin concept. With the application of digital twin and data analysis based on it, the case study of the industrial site shows a potential waste heat utilisation of up to 70% while reducing operating expenses of up to 6%. An innovative smart and transparent heating mode that integrates a 3D-GIS digital twin model and an NB-IoT wireless communication system were introduced by Liu et al. (2020), which has load self-prediction, scheduling self-optimisation, fault self-diagnosis as the mean features. The 3D-GIS digital twin made it possible to simulate different operation strategies and even accidents in heat sources or pipe networks, which helped preparing response strategies. Additional to the simulations, a self-learning algorithm was used to realise the above-claimed features. Comparing to the traditional heating mode, a 26.11% reduction of energy consumption on DHN was achieved. O'Dwyer et al. (2020) presented a tool denoted Sustainable Energy Management System (SEMS) which comprises of model predictive control, machine-learning-based forecasting algorithms, and digital twin. The SEMS was able to raise the network and thermal store temperatures in advance of a future electricity price spike, and switch between different heating strategies with predicted fuel cost and CO_2 intensities. The digital twin, in this process, offered an opportunity to test several options prior to implementation in the real system, which presented a clear Pareto Frontier to a decision maker.

8.3.2.2 Expected effects on targeting investments

Digitalisation increases the possibility of achieving optimal design and planning of DH systems, resulting in investment savings. Li et al (2010) utilised genetic algorithm (GA) to achieve optimal design of the DHC network with seawater-source heat pump. Comparing to the traditional design, the optimised design resulted in less hydraulic unbalance of the system, enhanced operation efficiency, and a reduction of about 8.54% in the annualised converting cost.

Digitalisation enables a novel method of asset management, namely the Smart Asset Management (SAM). Grzegórska et al. (2021) mentioned that applying SAM may be beneficial in social, technical, and economical areas, including increased durability and usage safety of the networks, reduction of number and frequency of failures, and economical benefits. Based on the Lithuanian normative depreciation period of a DH section, which is 35 years, they estimated a one-year prolongation of operational time can roughly result in savings of about 1/35 of the initial cost. They also provided information about economic benefits from a Swedish district heating company, Örresundskraft, who reported that installing the moisture bands on the pipes in the Helsingborg region results in about 250,000 EUR saving per year.

Predictive maintenance is also a rising research field brought by digitalisation. Mortensen et al. (2022) performed relative fault vulnerability prediction with the help of geospatial data processing and machine learning on a district heating network and an electrical distribution network. Thanks to their novel data-level imbalanced learning technique, their model effectively identified failure-prone pipes and cables, and outperformed the currently industry-practised, age-based vulnerability ranking. According to their results, they suggested to the utility that there might be an economic gain in thermographically imaging the identified pipes more frequently.

8.3.2.3 Business models towards distribution

The distribution of district heating is mainly realised through hot water that is circulated in supply pipes. At the customer, the supply is cooled down for heating purposes and fed into the return at a lower temperature. The network of a DHN is defined by the route, length and diameter. The essential optimisation variables for the operation of a DHN are the minimisation of heat and pressure losses while maintaining a complete supply to all connected customers. Digitalisation can realise the following effects at the distribution level:

- passive: through digitisation, lower network-side temperatures can be achieved. Lower heat and pressure losses lead to an increase in transport efficiency.
- passive: digitisation reduces peak loads, thus freeing up transport capacities for redensification and network expansion, if necessary enables cost-efficient expansion of district heating.
- active: monitoring of distribution network driven by measurement data enables early identification of dead points and supply bottlenecks. Therefore, the operator gains deep insight into the operation of the DHN and the possibility of realising efficiency potentials. Vial predictive maintenance, the associated cost can be reduced.
- active: supply of flexibility services in other

energy markets (e.g. electricity via the coupling of heat pumps and thermal energy storages) opening new areas of revenue.

8.3.2.4 Business models towards end-users

Substations are the link between the consumer and the heating network. With their numerous components, they often suffer damage, errors and suboptimally operated controllers. If this is where measured value-driven digitalisation comes in, significant optimisation potentials for the heating network can be realised.

Decentralised intelligent metering enables a closer link between the heat and power production and the energy used by the buildings. Wireless gathering of heat meter readings over short time intervals make the continuous commissioning and paying possible (Lund et al., 2014). This may also include metering the sale of surplus heat from e.g., solar thermal from the individual building to the grid as well. They can also be utilised to monitor the building sided return temperatures. Which typically need to be within a certain, predetermined range, in order to not reduce the overall efficiency of the entire DHN (see also chapter 5). With the implementation of Demand-Side-Management, the traditional view of heat in “kWh” can be replaced with a more open, flexible “heat as a service” point of view. It enables a production-based consumption of renewable heat and creates additional flexibilities, that also can be used within other district energy forms such as gas and electricity networks. On the consumption side, the following active and passive effects can be identified:

- active: metering enables the introduction of incentive-based pricing models. With these tariffs, the consumers are encouraged to reduce temperatures on the building side, thus leading to efficiency increases for both the customer and the DHN.
- active: metering enables dynamic identification of bad point consumers and consumers with faulty substations stations. This can lead to a more efficient and stable control of the DHN.
- active: supply of flexibility services for DHN operator opening additional areas of revenue for customer by coupling the DHN with other distribution networks such as electricity or gas.

8.4 Case studies

8.4.1 Cases of business model innovation and value creation in digitalisation of district heating systems in Denmark

8.4.1.1 Business Model for Power-to-Hydrogen with excess heat utilisation in Denmark

The operational paradigm of Power-to-Hydrogen with the additional provision of surplus heat to district heating systems principally derives its core structure from existing Power-to-Hydrogen business models, as explicated in Table 8.1. It is imperative to acknowledge that electrolysers, intrinsic to this process, do not possess perfect efficiency. Specifically, Alkaline electrolysers have been reported to exhibit up to 16.4% recoverable heat[8-1], a noteworthy aspect of their performance metrics. This recoverable heat can be effectively integrated into the district heating infrastructure, consequently generating a supplementary revenue stream, thus enhancing the economic viability of hydrogen production.

The most prevalent business model adopted by the majority of Danish companies, referred to as "Constant Hydrogen Production", is largely shaped by the prevailing conditions in the hydrogen market. This approach signifies a prominent pattern of consistent hydrogen generation irrespective of market fluctuations and demands.

In 2022, the usage of hydrogen as a source of energy was relatively minimal within the European context, constituting less than 2% of the continent's energy consumption. Primarily, hydrogen served as a critical raw material in the production of chemical products such as plastics and fertilisers. Interestingly, a significant 96% of this hydrogen was sourced from natural gas (Hydrogen, n.d.), indicating a potential deficit in the application of greener hydrogen alternatives.

As it currently stands, there is no distinct market structure that caters explicitly to green hydrogen and its potential future applications. This is indicative of the existing gaps within the hydrogen market, which may present potential opportunities for improvement and growth. The European Union, acknowledging this gap, has outlined the creation of an efficient hydrogen market as one of its recommended policy actions. This is aimed

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[8-1] Danish Energy Agency, "Technology Data – Renewable fuels", 2017.

Table 8.1: Business models of Power-to-Hydrogen production

Business model	Description
Constant hydrogen production	The current hydrogen market is mostly using hydrogen as a product in the value chain, therefore, a constant and reliant delivery of hydrogen is produced at a fixed price.
Flexible production following electricity prices	The electricity prices vary each hour and might result in hours that are too expensive to profit from producing hydrogen with electrolysers. This business model considers expensive hours and produces an operation schedule daily based on the day-ahead prices.
Hydrogen production from own renewable energy sources.	Green hydrogen must come from green energy sources for it to be considered green. In the short term, this requires production directly from renewable sources since the power in the grid is a mix of all currently dispatching technologies including coal and gas. This model, however, considers the cost of producing its own electricity for the electrolyser and the limitations of the weather's effect on power production.

at supporting the integration of green hydrogen into the broader European energy system.

Despite these initiatives, green hydrogen, at present, remains part of the larger gas market and is often incorporated within conventional supply chains containing hydrogen. Depending on the terms of the contract, this could entail on-site hydrogen production at the manufacturing facility or the sale of hydrogen at a pre-agreed price to the customer.

A second business model, known as "Flexible Production Following Electricity Prices", mirrors the current hourly electricity pricing scheme for Danish electricity consumers, including households. This model incorporates dynamic pricing, where the cost of production fluctuates in line with the prevailing electricity prices.

The third business model, termed "Hydrogen Production from Own Renewable Energy Sources", encapsulates the pilot projects facilitated by Danish DSO – Energinet. This model allows Power-to-X (PtX) production to access cheaper electricity prices due to its associated renewable energy generations. These experimental initiatives underline the drive to blend sustainable practices into energy production and distribution strategies.

8.4.1.2 Case study - HØST PtX project in Esbjerg/Denmark

The HØST Power-to-X (PtX) initiative in Esbjerg/Denmark represents a significant effort towards implementing electrolysis technology on a gigawatt scale for large-scale industrial ammonia production. This project, slated to be operational by 2028/2029, boasts an electrolyser capacity of 1 GW, complemented by an on-site conventional Haber-Bosch process for green ammonia production. The strategic location of the facility allows it to harness green power derived from the proposed 10 GW offshore wind infrastructure in the North Sea. In addition, the local utility company, DIN Forsyning, has pledged to absorb a portion of the excess heat for their district heating system (HØST PTX Esbjerg, n. d.). Projections suggest that the quantity of waste heat generated could potentially satisfy approximately one-third of Esbjerg's total heat demand.

A preliminary analysis has been conducted based on the aforementioned case study, comparing two scenarios – one without and the other with waste heat from PtX supplied to the district heating system. Electricity pricing in both scenarios corresponds to the hourly spot prices obtained from the Danish Transmission System Operator, Energinet, specifically from price area DK1, representing the prices in Jutland and Funen (Energinet, n. d.). The tariffs encompass the 'Transmissionnettariff' and 'Systemtariff', both correlating with the amount of electricity consumed (Aktuelle Tariffer, n. d.). Hydrogen pricing has been configured to align with 37kr./kg as per source (H2Valleys, n. d.). The heat provision cost is set at 334.8 kr./MWh (or 93 kr/Gj), a rate determined by the Danish Energy Agency (DEA) (Energistyrelsen, 2022), which has established a cap on the sale of excess heat. According to the DEA, the

Table 8.2: Results of scenarios without & with waste heat supplied to district heating system

Scenario	Without waste heat	With waste heat
Capital Investment (million DKK)	4,83	4,83
Expected income (million DKK)	4,31	5,06
Expected cost (million DKK)	3,478	3,46
Revenue (million DKK)	0.834	1.597
Payback (Years)	6.59	3.26
Internal rate of return (IRR) (%)	13	28.6%

heat demand for Esbjerg approximates 398,527 MWh per year (Dansk Fjernvarme, 2022), and it is anticipated that a 1GW electrolyser facility could supply around a third of this demand. The operational schedules for the electrolysers remain constant across both scenarios. However, the scenario involving waste heat extraction generates additional revenue from the sale of waste heat to the district heating system. This scenario also encompasses supplementary costs associated with heat pump operation during hydrogen production phases.

The outcomes of this analysis are illustrated in Table 8.2: Results of scenarios without & with waste heat supplied to district heating system, which shows that the utilisation of waste heat from PtX to the district heating system not only increases revenue but also improves the economic feasibility of the project with a shorter payback period and higher internal rate of return (IRR).

8.4.2 Business models for heat pumps in district heating grids

In IEA HPT Annex 56, opportunities and challenges for IoT enabled heat pumps, were analysed. One of the tasks was dedicated to describing market opportunities created by connected heat pumps and to identifying success factors and further development demands for software and hardware based on literature and market research. More than 40 different use cases, for IoT enabled heat pumps, were collected and analysed: Factsheets and further information are provided on (Annex 56, 2023). The use cases differ in the use of connectivity, type of data and data analysis and in the interaction with other “things” in the network. Connectivity and IoT are necessary preconditions for each use case. The use cases were grouped, based on their main purpose, into five IoT categories. Business models and services have already been implemented for four IoT categories:

- Heat pump operation optimisation e.g., by monitoring and remote control, by adaption to user habits, by adjustment of the heating curve, by scheduling of production and downtimes, by continuous set-point tuning, by interaction with other components (e.g., PV, solar thermal, storage, etc.) or to use flexible tariffs.
- Predictive maintenance e.g., by learnings from performance benchmarks, grey box modelling, advanced data analytics, etc.
- Flexibility provision e.g., by pooling of household heat pumps, by providing flexibility as balancing reserve or flexibility to DSO/TSO for other services such as congestion management or voltage control.
- Heat as a service e.g., by a different model of ownership (leasing, renting, buying heat instead of heating equipment).

For heat pump operation commissioning (e.g., by set point tuning, comparison to performance benchmarks, learnings about the system layout and possible improvements for future installations, installation error analysis, grey box modelling, advanced data analytics, etc.) there are not yet any details available on implemented business models and services. However, research projects geared at developing and testing the prerequisites for these services are available in the collection of use cases.

IoT enabled heat pumps can provide different IoT services connected to various business models. In a smart grid, IoT enabled heat pumps can be applied for smart demand response to reduce peak load and/or to optimise electricity consumption as a function of the electricity price. Preventive analytics are of interest for operators, providing for example, what-if analysis for operation decisions and information for predictive maintenance. IoT enabled heat pumps can be integrated in larger energy management systems, for example in buildings (BEM), in industrial processes or district heating systems, where the provided data can be used for overall optimisation of the process.

The analysis of the business models showed that multiple stakeholders are involved. Nine different stakeholders were identified. Their main contributions are visualised in Figure 8.4 according to the life cycle of a heat pump (construction, installation, and operation).

- Heat pump manufacturer: designs and constructs heat pumps, sells them to vendors or end-users, also offers maintenance services, usually does not act as an installer.
- Heat pump vendor: sells heat pumps to end-users, also offers maintenance services, usually does not act as an installer.
- Installer: installs and commissions heat pumps, can also offer maintenance services.
- Consumer: both residential and industrial end-users, consume heat (and cold) at a place where a heat pump is operated, can also be responsible for the operation of the heat pump, can provide specifications for the design of the heat pump (mostly for industrial heat pumps).
- Operator: responsible for the operation of the heat pump, provides heat (and cold) to consumers.
- Aggregator: pools a large number of small assets into a large one to market flexibility to electricity markets or as grid services and thereby influences operation of the heat pump.
- Supplier: supplies customers with electricity by trading at electricity markets and sometimes producing electricity e.g. from fossil fuels or renewable energy sources.
- Power system / grid: transmits and distributes electricity, connects utilities and end-users, requires balancing of supply and demand.
- Energy service company (ESCO): offers service-based propositions for energy such as heat contracting, efficiency contracting, heat as a service, energy as a service, etc., can come from various sectors including energy suppliers, heat pump manufacturers and specialist startups.

Operation optimisation includes the interaction with energy suppliers and consumers at the site, where the heat pump is operated, as well as the integration into higher-level systems (building energy management, industrial process control system, district heating network). These interactions are the responsibility of the operator of the heat pump (end-user or operator or ESCO).

Heat pump operation optimisation, commissioning and predictive maintenance involve the traditional stakeholders in the heat pump sector: consumers, manufacturers, vendors, and installers. There is no difference between residential and industrial or district heating applications of

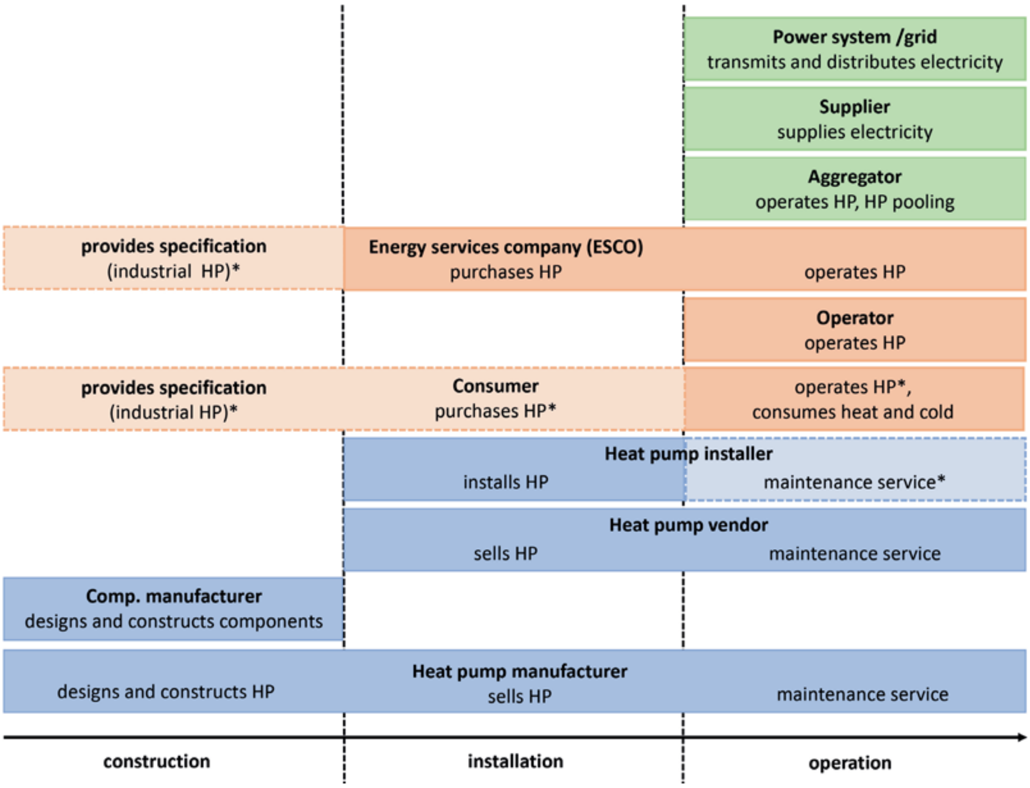

Figure 8.4: Business models of temperature reduction in the grid

heat pumps. By contrast, flexibility provision involves considerably more stakeholders related to the energy system. Aggregators are especially needed for small-scale residential heat pumps, heat pumps with larger capacities can provide grid services without an aggregator. Heat as a service or heat contracting is offered by ESCO and is based on a different model of ownership of the heat pumps.

The main value proposition for consumers are lower costs, more efficient heating systems and higher reliability. For the heat pump value chain (component manufacturers, heat pump manufacturers, vendors, installers) digitalisation leads to new products and services that make heat pumps more attractive and more future proof. Compared to traditional business models, they have more responsibility for the efficiency of the IoT enabled heat pump systems. The energy system (aggregators, suppliers, grid, etc.) has a strong need for flexibility provision to compensate for fluctuating renewable generation. Heat pumps allow for sector coupling by combining the heat and the power sector and can offer flexibility at various scales, which is a valuable asset for the future. Energy service companies (ESCO) are a rather new actor in buildings but are already established for industrial contracting and for heat pumps in district heating grids. They help spread heat pumps as their service reduces the involvement of consumers.

The complete task report on business models is available at (Annex 56, 2023).

8.4.3 Business models of temperature reduction in the grid

Alternative energy sources for district heating networks usually include waste heat, solar and geothermal energy as well as heat pumps. In contrast to heat generation in classic heating plants (i.e. heat only boilers, combined heat and power plants), these energy sources only develop their full potential at low temperature levels and their efficiency drops substantially with increasing heating network temperatures[8-2] (Geyer et al., 2021).

In the area of new district heating network constructions, low-temperature networks have been discussed and tested for about 10 years (Averfalk et al., 2021). This development is important and necessary, but in areas with existing district heating networks, different strategies are needed. Although in existing networks, the causes for high network temperatures are well known and manageable, they usually are to be found on the customer side (e.g. defective components or control strategies). The person supposed to bear the investment for optimisation (building owner) is often different from the person profiting from lower return temperatures (operator). Therefore, temperature reduction strategies need to focus on existing buildings, heating systems, customers and their contracts.

Business models as an incentive for temperature reduction

The feasibility of measures to reduce return temperatures depends not only on their cost-effectiveness, i.e. the cost savings achieved compared to the costs of the measure, but also on technical restrictions and ownership of or access to the customer installations. As mentioned above, in general, the savings due to lower network temperatures are in favour of the heat supplier, but the costs are generated by the customer installations.

To take these factors into account, within the Austrian project T2LowEx (Müller, 2021) different business models were developed and discussed with the heat supply companies involved in the project. (see also Leoni et al., 2020 and Geyer et al., 2021a):

1. **Own investment:** the heat supplier takes over the investment and implements the return-temperature reducing measures at the customer's side. The "repayment" of the investment is realised through savings in the operating costs.
    a. This is the “standard” or reference business model. Utilities normally have the know-how for correcting faults and can implement the business model directly.
    b. However, the investment risk lies with the utility, and they might face access restrictions to the customer substations. Sometimes there is a lack of interest and / or are liability issues when in investing in

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[8-2] This contribution is the result of the project T2LowEx (project no. 858747) within the framework of the 3rd call of the Energy Research Programme of the Climate and Energy Fund.

   customer stations. Also, some installations are complex and smaller utilities in particular might not have technical staff available.

2. **Customer motivation / motivational tariffs:** the customer takes over the investment or carries out the measures himself, "repayment" of the investment is realised through a bonus depending on the return temperature (see also chapter 5):
   a. For this business model there are many best practice examples available. It can also be implemented directly by the utility and is easily scalable all across the network. It can encourage behavioural change and the investment risks remain with the customer.
   b. On the downside, motivational tariffs are not always easy to understand for the customer and in case of a malus (if return temperatures are too high) this can result in low customer satisfaction. Also, the customer sometimes has little knowledge of and access to the system. Finally, existing heat supply contracts are often long-term and not easy to adapt and, in some cases, billing according to temperature levels might be not permitted.

3. **Loan, e.g. crowdfunding:** external investors take over the investment, repayment including interest, is carried out over an agreed period of time.
   a. This business model offers a new financing channel for the utility, including possible citizen participation, and might also be attractive for cooperatives. One option could be to realise an online crowdfunding platform, increasing the visibility of the utility, the transparency as well as allowing for additional services to be offered.
   b. On the other hand, there are missing guarantees for the external investors regarding repayments, also there could be issues regarding data protection for the customer installations.

4. **Contracting:** an external contractor implements the measure at the customer's premises. The measures can be tendered and awarded according to the best bidder principle; the repayment of the investment can be carried out by sharing the real savings.
   a. This business model could allow the correcting mmeasures to be cost-effective due to economies of scale (the contractor could optimise many DH networks). The risk is shared between the contractor and the utility. Also, the utility companies can act as contractors outside their own network area for increasing their staff utilisation.
   b. Negative aspects include the often-short-term view of many contractors and a possible negative relationship between utility and customer in case of failure. The contract design could be complicated and measures for customer data protection are required.

One of the main conclusions were, that the first two business models (own investment and customer motivation) are considered as the most realistic. However, it should be noted that the effects of reduced return temperatures can only be measured indirectly in large heating networks, so that savings due to individual measures can only be assessed theoretically.

Finally, the cost-benefit ratio was calculated for each business model using concrete case studies using a dedicated excel based calculation tool. As a result, it became apparent that the heat networks considered are very different in terms of the savings achieved. Particularly in the case of heating networks with high shares of renewable heat sources (e.g. geothermal energy), reasonable business models can be found for return-temperature reducing measures.

Digitalisation as an enabler

The ongoing digitalisation of heating networks can be an essential measure for realising such business models. On the one hand it would be necessary to further develop low-cost heat meters, which, in addition to the amount of heat, are calibrated to other relevant parameters (e.g. volume flow, temperature differences) as standard. This may require further development of the current measurement and calibration regulations. Using this data, digitalisation can support the identification of customer installations with high return temperatures. On the other hand, digitalisation can support visualising possible causes for high return temperatures, suggest counter measures to the customers and possible impacts regarding e.g. in motivational tariffs.

Low temperatures as the key to long-term success

Low temperature levels are an essential prerequisite required to strengthen the role of district heating also in a future CO_2-neutral energy system (see Figure 8.5). The biggest challenge is the current dominance of high-temperature generators, and that the optimisation of customer-supplied plants is often the responsibility of the customers. The methods and concepts developed and tested in the T2LowEx project can support heat supply companies in identifying temperature reduction potentials at the consumer side, evaluating them economically, implementing them for the benefit of the customers and the energy supplier and thus setting the course for a sustainable district heating network.

8.4.4 Digital building service package: Calculation Tariffs in principal

The aim of this section is to present the experience of Aalborg Forsyning the local utility company that manages and operates the generation and distribution of heat in the local district heating network in the municipality of Aalborg, in northern Denmark. The Aalborg Municipality has 76,179 buildings with a total end-use heat demand of 2,027 GWh/year and the heating of the city of Aalborg and its surrounding areas has been based on a comprehensive district heating supply (Nielsen et al., 2020). DH covers 80% of the total demand and the main heating sources have been excess heat from the coal-fired power station (60%) in combination with excess heat from the local cement industry (20%) and the local waste incineration plant (20%) (Lund et al., 2022, Thellufsen et al., 2020). However, as part of the green transition, the coal-fired power station will be decommissioned in a few years, and thus, Aalborg municipality is planning to change the heat supply as a coordinated action in terms of a green transition for the entire energy supply.

Aalborg Forsyning started replacing all meters – more than 46.000 – with remotely readable ones in 2021. Hence, since the end of 2022 hourly measurements have been available with a high accuracy of close to 99,5%. The data gives Aalborg Forsyning the unique possibility to continuously monitor all the consumers and the opportunity to contact them – either by phone, email or on-site inspection – if data indicate a deviation from optimal operation in their heating systems.

On average, Aalborg Forsyning contacts approx 200 consumers evey month, that potentially have new faults in their heating systems. The data are made available through a dashboard linked to the geolocation of the users, making the analytics of each individual user easily accessible as illustrated in Figure 69. This helps reduce costs for consumers and the operating temperature in the distribution system. After reaching the customers and fixing the faults, a reduction of the return temperature in the range of 16-18 °C is typically achieved.

At the same time, the end-users have the possibility to freely download and install the Aalborg Forsyning App, "Watts" on their mobile. The following of everyday habits and consumption patterns affecting consumption as well as receiving important notices, for instance interruption of water supply due to failure in the network or planned maintenance. It also provides a visualisa-

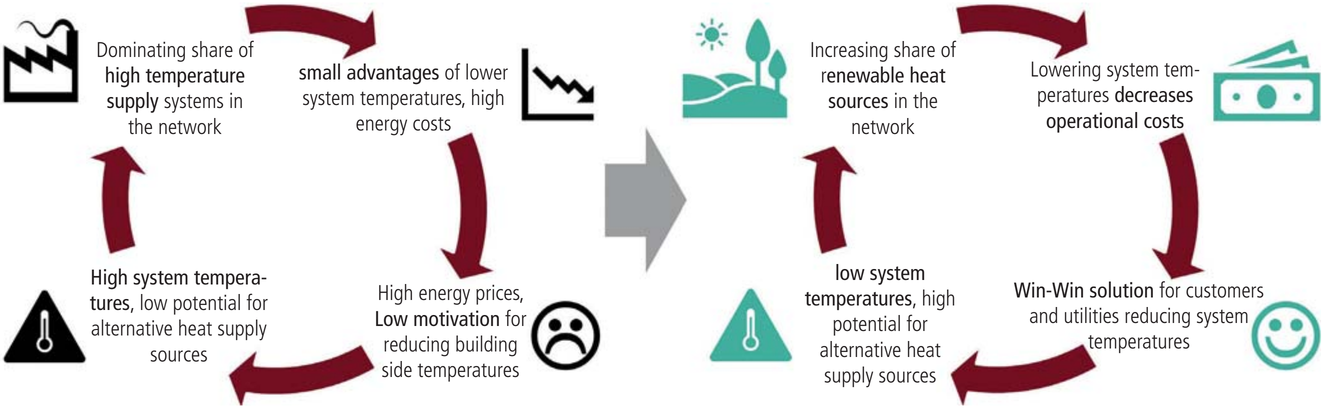

Figure 8.5: Left: The vicious circle of high system temperatures (lock-in), right: The added value of low system temperatures. Source: AIT (own representation)

tion of the current operating temperature of the substation and how the overall performances are, based on expected values and historical data (Aalborg Forsyning 2023). The app also provides and integrates a real-time overview of the electricity and water consumption of each end-user.

The district heating service scheme is an easy and cheap way offered by Aalborg Forsyning to ensure that the end-users district heating systems have optimal performance – irrespective of the thermal effectiveness of the building envelope. More than 60% of substations and heating systems have faults, therefore incorrectly operated systems can cause extra costs in energy bills and force the entire network to be operated at higher temperatures than necessary.

The district heating service scheme is offered to customers living in single-family homes up to approximately 300 m^2. It has a subscription cost of 75 € plus a monthly fee of 4.3 € (Aalborg Forsyning 2023a). Typically, these costs are offset by improved operation of the systems and lower temperatures that can result in a discount of the energy bills according to the heat tariff structure.

The current district heating price structure across all of Demark is based on a balance, according to local conditions, between a fixed part – accounting for the costs of investments, depreciation of existing assets and for being connected to the network; and a variable part – representing the energy consumption (Aalborg Forsyning 2023b). Since January 1st , 2022, Aalborg Forsysing has reduced the fixed costs – both for the subscription price and the impact contribution and switched the variable costs from m^3 to energy use in kWh. This was partly the result of having replaced all energy meters in the customer systems connected to the DH network.

Table 8.3: Yearly expected return temperature for motivation tariff estimations

SUPPLY TEMPERATURE	EXPECTED RETURN TEMPERATURE
50 - 52 °C	40 °C
53 - 56 °C	39 °C
57 - 60 °C	38 °C
61 - 64 °C	37 °C
65 - 68 °C	36 °C
69 - 72 °C	35 °C
73 - 75 °C	34 °C
76 - 78 °C	33 °C
79 - 80 °C	32 °C
81 - 83 °C	31 °C
84 - 85 °C	30 °C

In addition, part of the heat cost structure includes a motivation tariff to further engage with the end-users by providing a discount or a penalty in their energy bills according to resulting operating temperatures measured in each connection. The bonus or penalty in the energy bill is equivalent to 2% per each °C above or below the yearly expected return temperature estimated by the DH operator for each supply temperature, as summarised in (Aalborg Forsyning 2023c).

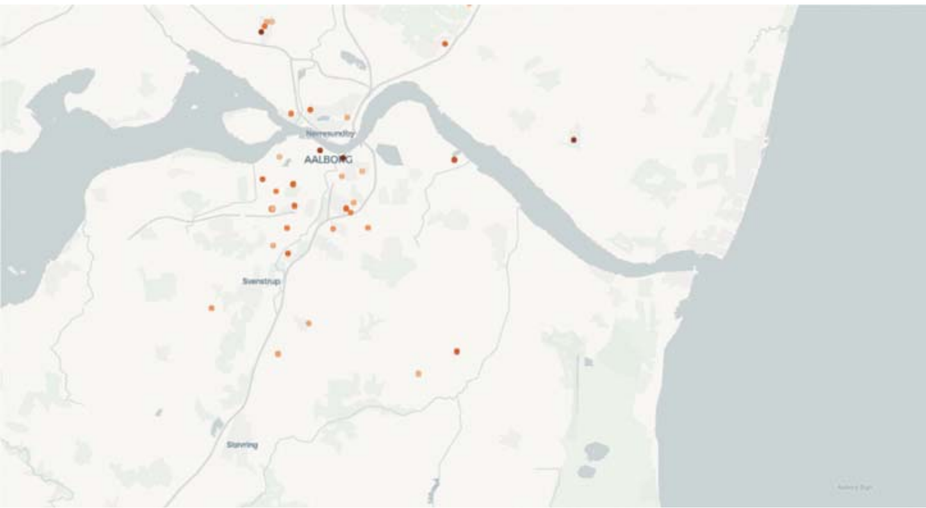

Figure 8.6: Aalborg municipality heating map showing customers with high return temperatures)

Aalborg Forsyning developed an in-house machine learning algorithm to investigate and categorise all faults and errors detected in the consumers heating systems – whether in the domestic hot water production, in the radiators or underfloor heating. The current results showed an accuracy of 60% in the automated fault diagnosis that is improving the efficiency of the maintenance teams as they can surgically focus on the specific part of the heating systems where errors are more likely to occur. An extract of the potential outcomes of the analysis is shown in Figure 70, where the specific faults in the radiator's system or in the heat exchangers are pinpointed and made available for the maintenance team.

8.4.5 Cost of digitalisation of substation and effects in a local area

In order to meet the decarbonisation targets of the national heating sectors, a transformation from mainly fossil-fuelled to efficient renewable based low-temperature district heating networks (DHN) is indispensable. As a promising technology, the digitalisation of DHN can contribute to their transformation by measurement-driven identification of optimisation potentials as well as through a more flexible DHN operation by means of an intelligent Demand-Side Management (DSM). However, in practice-oriented research as well as in real economic application, there is a lack of knowledge about the technical and economic effects achievable by the extensive digitisation of energy infrastructures. The aim of the referred study is therefore to systematically investigate the digitalisation of DHN, respectively the digitalisation of substations in particular, and to evaluate its effects on the operation of DHN from a techno-economic point of view. In a first step, the costs for the digitalisation of intelligent substations is determined and the potentially achievable effects are discussed. Subsequently, the potentials of these effects are quantified on the basis of dynamic building models and profound literature research. Using a probabilistic load generator, heat demand profiles are then simulated both with and without the flexibility of DSM. These are the main components of the thermo-hydraulic DHN model, which is used to simulate the generation, distribution and consumption of district heat in both a high temporal and spatial resolution. Finally, the costs associated with digitalisation are compared to the effects

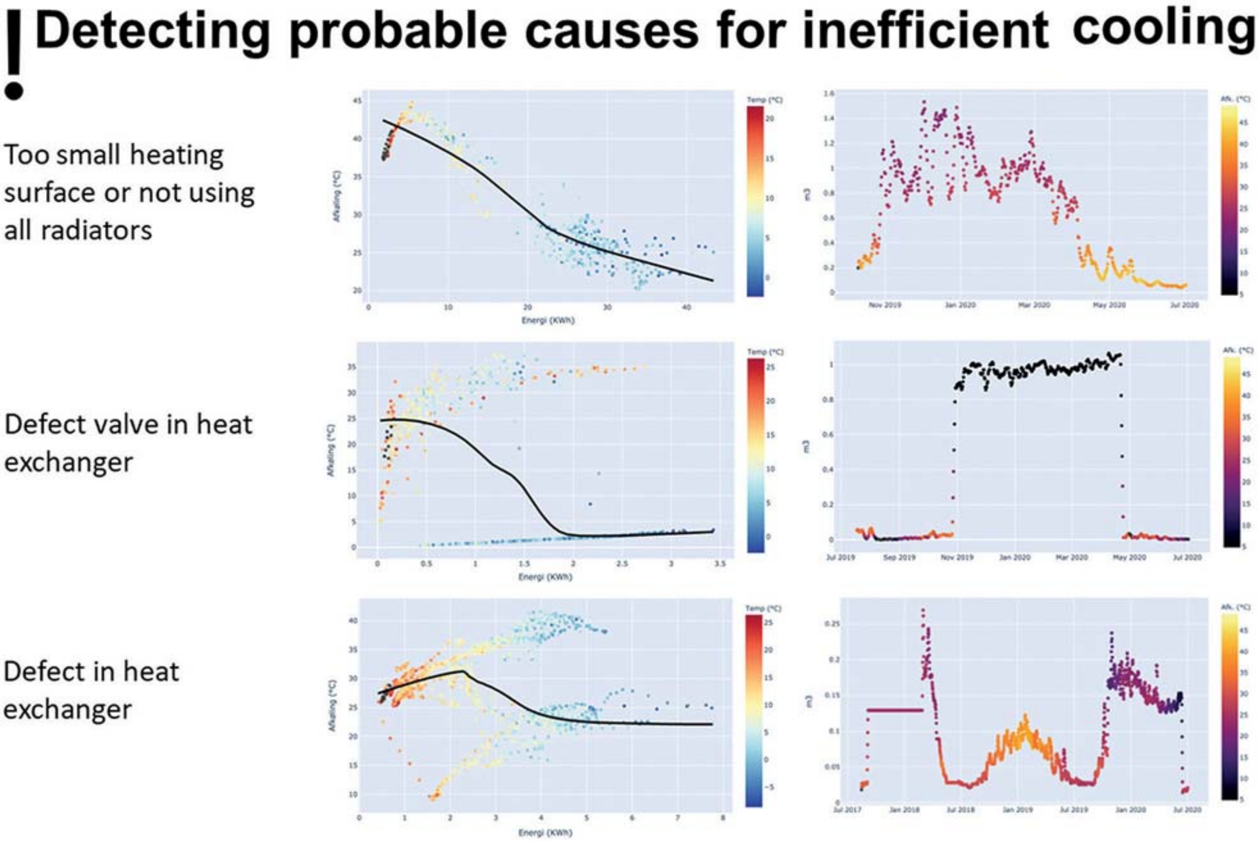

Figure 8.7: Machine learning algorithm for automated fault diagnosis

that may occur in the operation of the DHN in monetary terms. During digitisation of substations, different stages are distinguished through scenario simulations in which the effects resulting from:

- an error detection through digital measured values,
- recognition of the need for hydraulic balancing,

are systematically investigated.

Substations are typically prone to malfunctions and suboptimal control strategies. These can lead to higher overall return temperatures that exceed the heating system specific optimal return temperature. The potential effects of measures to reduce return temperatures are displayed in Figure 8.8. The errors of the individual substations accumulate in the DHN. Here, the number of affected substations and their position in the DHN is decisive. Since there is no exact information about the actual errors and suboptimalities in an area, assumptions must be made about their distribution. The distribution of errors, sub optimally operated controls and the need for hydraulic balancing is taken from the distributions of Schrammel et al. (2018) and Müller et al. (2021).

According to Routledge et al. (2012) and Rapp et al. (2020), the capital and operational costs of a Smart-Heat-Meter amount to an average of about 163.8 €/a. A useful life of 20 years with an interest rate of 7.0 % was assumed. The annual costs consist of 40 % investments and 60 % operating costs. For the active control units of a SHM, an investment of 50 €, 5,000 h annual full load hours as well as a specific power demand of 15 W was deemed to be reasonable. According to Ernst & Young (2013), investment in a central IT infrastructure was assumed to be 293,000 €, considering an annual inflation rate of 2.0 %. For the operation of the data centre, an electrical output of 1500 W and an annual availability of 8,760 h was estimated in a simplified manner.

The use case is a real district supplied with district heating in a city located in southern Germany. Across an area of 0.59 km^2, a total of 333 buildings, including 130 detached and semi-detached houses, 153 small and 35 large multi-family houses as well as 15 public or commercial properties are located. In total, 330,000 m^2 of residential and 69,500 m^2 of non-residential space is connected to the DHN with a total capacity of 26,7 MW. The annual demand for space heating and domestic hot water amounts to 29.6 and 7.1 GWh/a, respectively. The DHN is a sub-branch of a regional hot water DHN with an average supply and return temperature of 82 and 62 °C. The total length of the investigated sub-branch is 5.5 km.

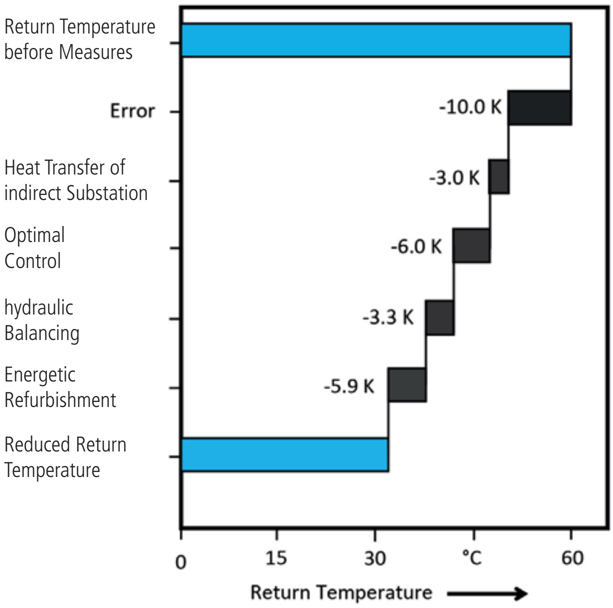

Figure 8.8: Estimated Potentials for Return Temperature Reduction Measures, based on the findings of Van Oevelen et al. 2018 , Lauenburg 2016 as well as Averfalk 2017

8.4.5.1 Analysis of techno-economic effects

Since it is assumed that the digitalisation of consumers takes place in stages, the shares of consumers to be digitalised are successively increased in the scenario analysis. The increase takes place in shares of 10% of the total heat demand. The larger the share of a consumers heat demand, considering of the overall heat demand, the greater its potential influence on the DHN. Therefore, a possible strategy would be to first digitise the largest consumers within a DHN. For this purpose, all consumers were sorted in descending order according to their heat demand. It is also assumed that the costs incurred for hydraulic balancing are paid by the consumers. Therefore, these costs are not considered in the following analysis.

Figure 8.9 shows the results of the thermo-hydraulic DHN simulation for the investigated balance area. The figure shows the specific heat production costs in €/MWh as a function of the

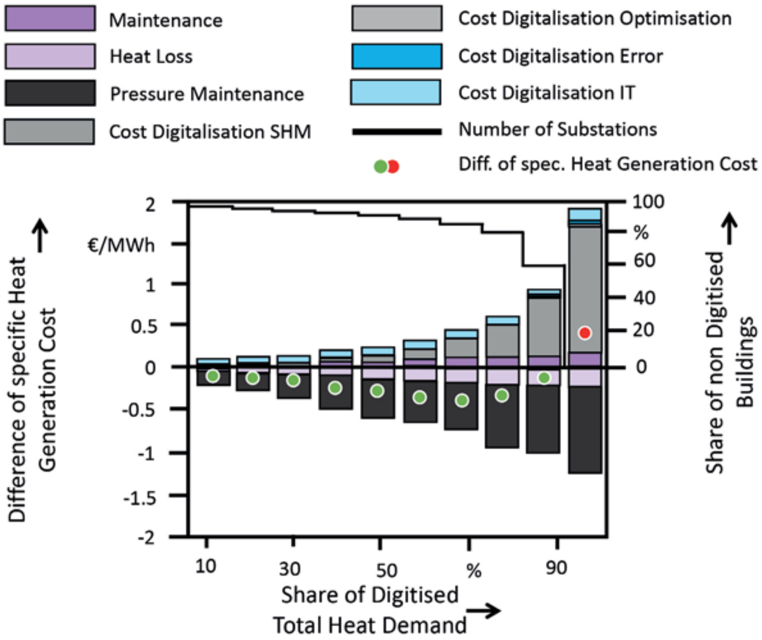

Figure 8.9: Specific heat production costs as a function of the digitalised share of the total heat demand

digitalised share of the total heat demand of all consumers in the balancing area. The consumers still to be digitised after the respective digitalisation stage are shown on the secondary axis.

Because the DHN of the investigated use case is an old one, it was assumed in the analysis that investments in the generation, the network and the substations have already been written off and can therefore be omitted, since the return temperatures of the consumers can be reduced through the identification and elimination of both errors and suboptimal conditions. In some cases, this results in positive effects in the DHN, which lead to savings or increases in efficiency. These must be compared with the costs for digitalisation in order to evaluate their effectiveness. Costs that can be saved through digitalisation are evaluated negatively, additional costs positively. One of these effects is the increased transport capacity of the DHN due to a reduced return temperature as a result of an increase in the maximum usable temperature spread between flow and return. So, the heat demand of the consumers can be served with a lower mass flow, which leads to savings in pressure maintenance. At the same time, the previously mentioned lower return temperature leads to reduced heat losses. However, it should be noted here that the heat losses saved by a reduced return temperature should tend to be higher. As the reduced mass flow ensures a lower flow velocity, the heat transfer medium has a longer residence time in the DHN and is thus subject to additional cooling.

Digitalisation can increase the expenses for the maintenance of the DHN. Temperature fluctuations in the DHN lead to thermally induced length changes in the material, which in turn leads to stresses. If the number of stress changes exceeds the design parameters, damage to the pipe is to be expected. Since the return temperatures of the consumers decrease in the course of digitalisation, but the flow temperature is not necessarily adjusted, the temperature spread in the DHN increases. This means that potential temperature fluctuations are subject to a higher spread, which leads to higher stresses in the material. Without adjusting the flow temperature, the additional costs for the maintenance and servicing of heat pipes can increase in the course of digitalisation, as more and more consumers have reduced return temperatures.

The largest cost component is the equipment of the consumers with smart heat meters (SHM). Since the investment and operating costs do not depend on the size of the sub-station, the total costs are only dependent on the number of consumers to be digitised. The last 30 % of the total heat demand of the balance area is consumed by 80 % of the buildings, which is why the costs for digitalisation with SHM increase exponentially in the course of digitalisation. The elimination of errors and suboptimalities is associated with costs. Since these were distributed randomly over all buildings in the balance area, no clear trend emerges here. The costs for the acquisition and operation of a central server infrastructure (IT) are identical across all levels, as it is assumed that this is already necessary for a few digitised consumers and can be scaled relatively easily.

If all the costs described are added up, the difference in the specific heat production costs results; shown in the figure as red or green dots. If the sum is negative, i.e. costs are actually saved due to digitalisation, the dot is coloured green. If the negative effects exceed the positive effects, the costs for digitalisation must be increased; the colouring is red. At the beginning of digitalisation with shares of less than 30 % of the total heat demand, the advantage of digitalisation is overwhelming, whereby the specific savings are relatively modest. From a digitalised share of 40 % and more, the cost reduction increases successively to reach a maximum at shares of 60 %. With further increasing shares of digitised heat demand, the saved costs decrease again. With a digitised share of 30 % of the heat demand, comparable economic effects can be achieved in the DHN as with a digitalisation of 90 % of the total heat demand. With a share of 100 %, i.e. full digitalisation, the negative effects clearly outweigh the positive effects. Up to this point, digitalisation would be self-sustaining. In the last stage, however, a profitability gap appears that cannot be minimised by the positive effects.

8.4.5.2 Conclusion and Outlook:

During the course of the digitalisation of consumers, collected measured values can contribute to an improvement in the performance of substations. Improved efficiency of substations also has an impact on the operation of DHN. The aim of this analysis was to evaluate the effects of the digitalisation of consumers on the underlying DHN from a techno-economic perspective. This showed that digitalisation can save costs in the operation of the DHN. Although the achievable cost reductions are low compared to the total heat production costs, digitalisation is largely economical in itself. However, the economic efficiency is strongly dependent on the target value of the number of consumers to be digitalised. Depending on the underlying distribution of building sizes, global optima emerge, for which the greatest cost reductions can be expected with digitalisation. Particularly in the case of full digitalisation or the digitalisation of very small consumers, the economic efficiency may turn and additional financial resources may be required.

In the analysis, however, it should be emphasised that not all effects of digitalisation were evaluated in monetary terms. In particular, a simplified billing system, faster and direct fault reporting and generally improved service can lead to further cost reduction potentials. In further analyses, the influence of digitalisation should be expanded to include the effects of an actively controlled demand for space heating and domestic hot water. In addition, the effects of a different generation fleet will be evaluated in the downstream techno-economic analysis.

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9 Legal Issues in the digitalisation of district heating and cooling

9.1 Introduction

This chapter provides an overview of that European legal framework, which applies in all EU member states.

Remote reading of meters in the electricity sector began as early as 2009 with the Electricity Directive (Directive 2009/72/EC of the European Parliament and of the council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC), which called for the introduction of smart metering systems[9-1]. The digitalisation of district heating did not begin until 2018 under Union Law through Article 9c of the Energy Efficiency Directive (Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency), which stipulates that "installed meters (...) must be remotely readable after October 25, 2020" and "already installed meters that are not remotely readable (...) must be retrofitted with this function or replaced by remotely readable devices by January 1, 2027." This directive had to be transposed into national law by the end of 2021; in Germany, this was done by the District Heating or District Cooling Consumption Metering and Billing Ordinance (in German: Fernwärme- oder Fernkälte-Verbrauchserfassungs- und Abrechnungsverordnung, FFVAV).

In the future, data processing is expected to play an increasingly important role in the heating sector including the district heating supply, as it may help increase energy efficiency through digitalisation and to enable the transformation of district heating supply to renewable energies. However, this requires district heating suppliers to pay greater attention to the legal requirements and obligations relating to data protection and data security. The legal requirements are complex and distributed among various EU and national-level rules, with the EU's General Data Protection Regulation (GDPR) playing a dominant role in the European legal framework.

9.2 Legal requirements for data protection

Data protection rules relating to the digitalisation of district heating exist at both European and national levels. In the Federal Republic of Germany, these are the Federal Data Protection Act (in German: Bundesdatenschutzgesetz, BDSG), which supplements the European GDPR, and the Metering Point Operation Act (in German: Messstellenbetriebsgesetz, MsbG), which is more specific to the energy sector. In addition, there are state data protection laws in the federal states. Those laws, national and sub-national, implement the respective European secondary legislation.

However, the GDPR as a regulation is directly applicable in all member states of the EU. Due to the direct applicability of the EU regulations of the GDPR and their outstanding relevance in the field of data protection law: This article focusses on the presentation of the EU regulation of the GDPR.

It serves as the general data protection law at EU level. Thus, the GDPR needs to be respected whenever personal data is processed. In addition to the requirements for processing, the GDPR also contains several additional obligations. The GDPR differentiates the level of protection to be applied based on the quality of the data, i.e., whether it is personal or anonymised data. In order to be considered personal, the data must be related to a natural person. If it is data from non-legal persons or companies, such as a stock corporation or a limited liability company, it is not considered personal and different rules may apply.

Personal data is information of any kind that relates to a natural person that can be identified as such, at least theoretically. The person behind the data must therefore be either directly identifiable or identifiable from other available information or from technical aids. This also applies if persons have not been irreversibly anonymised. In principle, the European legislator has opted for a broad scope of application, which means that in case of doubt, a reference to a person will be assumed and the data thus has to be protected. In the case

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[9-1] The following remarks are based on results of the project “EnEff: heating: FW-Digital – digitalisation of technique and business processes in heating supply systems”; more about this project under https://stiftung-umweltenergie recht. de/en/projekte/eneff-heating-fw-digital-digitalisation-of-technique-and-business-processes-in-heating-supply-systems-eneff-waerme-fw-digital-digitalisierung-der-technik-und-geschaeftsprozesse-in-wae/. The authors thank Jana Nysten, LL.M. for her valuable notes.

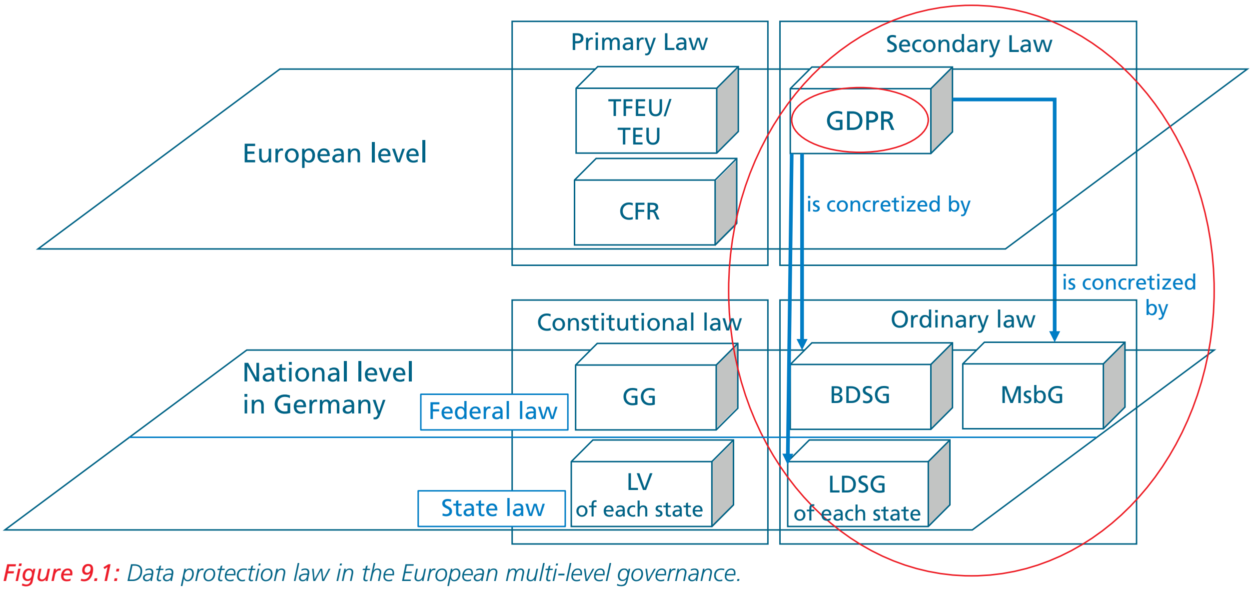

Figure 9.1: Data protection law in the European multi-level governance.

of district heating supply, the question of personal reference arises, in particular in the case of majorities of persons at a house station: How many tenants and residents does a property need to have for their consumption data to not fall under the definition of personal data under the GDPR?

Depending on whether the data is personal or anonymous/anonymised, the legal consequences of processing this data differ. For personal data, the GDPR (and in Germany, the Municipal Data Protection Act) is applicable, which means that data processing is only permitted in the cases regulated by law and, on the other hand, the obligations of the GDPR must be observed. For non-personal data, however, the GDPR does not apply, and the obligations do not have to be observed.

If it is personal data, Article 6 (1) GDPR is the central standard for the question of whether it may be lawfully processed. This is the case if either one of the explicitly listed cases applies or a consent to data processing exists. The cases of application are listed exhaustively in the regulation and include, among other things, the case in which data must be processed for the performance of a contract. These circumstances may also apply to data relating to district heating supply. In addition, the circumstances that allow data processing for the performance of a task carried out in the public interest (Article 6 (1) (e) GDPR) or data processing necessary for the purposes of the legitimate interests pursued by the controller (Article 6 (1) (f) GDPR) may be relevant.

If none of the cases listed in the catalogue of Art. 6 (1) lit. b) to f) GDPR apply, an effective declaration of consent by the data subject is required for data processing in accordance with Article 6 (1) a) GDPR. Consent requires awareness, personality, voluntariness and definiteness. There are no formal requirements for consent, so it can theoretically also be given verbally. However, due to the accountability obligations of the person responsible for processing the data, the written form is recommended. Unlike the cases listed in lit. b) to f), the consent to lit. a) can be revoked at any time. Where a person withdraws such consent, the personal data must be deleted in accordance with Article 17 of the GDPR.

If data is processed based on an explicitly listed case of application or consent, specific obligations according to the GDPR must be complied with. The essential obligations include the following:

- According to the sharing of responsibility (e.g., Article 26 GDPR), there must be a party who is responsible for the fulfilment of the obligations of the GDPR.
- The right to erasure (Article 17 GDPR) requires that personal data must be deleted immediately after revocation of consent or when data is no longer needed – even if it is held by third parties.
- Finally, the so-called data portability (Article 20 GDPR) grants the right to the data subject to have their personal data available in a structured, common and machine-readable format (interoperable format).

If data protection rules are violated, Article 83 of the GDPR introduces fines, which, according to paragraph 1, shall be effective, proportionate and dissuasive in each individual case. According to Article 83 (5) GDPR, these can be fines of up to € 20 million or 4 % of the company's annual global turnover.

9.3 Excursus: Data protection in South Korea

The Korean government recognises the importance of allowing third-party use of personal information and is actively exploring ways to use it to promote new industries, technologies, and services in the era of digitalisation. Personal information is defined as information about a living individual, including name, national identification number, and image that allows the individual to be recognised, even if the information alone cannot identify a specific individual but can be easily combined with other information.

Previously, laws have regulated the provision of information collected from individuals to third parties by requiring explicit consent (opt-in) from the data subject. This is because various personal information collected and managed by the government and companies can be combined with additional information, such as energy usage, to identify individuals in whole or in part. However, the existing excessive regulations have caused controversy over privacy infringement when service providers utilise energy usage information, which has become an obstacle to the vitalisation of new industries utilising information in the energy sector.

Therefore, in 2020, the 'Personal Information Protection Act' was revised by benchmarking the EU's GDPR regulations to expand the use of new businesses. The revision focused on establishing legal definitions for clear terms such as 'Pseudonymized information', 'Pseudonymization', 'Anonymous information', 'Anonymization', and 'Scientific research'. Pseudonymised information is data from which identifying information has been removed or replaced, and pseudonymisation refers to the processing of such information. Anonymous information is data that cannot identify the individual even after combining it with other information, anonymisation refers to the processing of such information. Scientific research refers to research that applies scientific methods, such as technology development and verification, basic research, applied research, and private investment research. In addition, the revised law also includes provisions to strengthen institutional measures, such as the elevation of the Personal Data Protection Commission and the creation of a chapter on exceptions to the processing of pseudonymous information. These changes aim to ensure a balanced approach between the utilisation and protection of personal information.

The Personal Information Protection Act requires that only the minimum necessary information be collected when collecting personal information. When obtaining consent, information on (i) the purpose of collection and use, (ii) the items to be collected, (iii) the period of data use, and (iv) the right to refuse consent and the penalties for refusal should be provided.

When utilising personal information, it may only be provided to a third party within the purpose of utilisation with the consent of the information subject. However, in the case of use or provision without the consent of the information subject, information on (i) whether it is relevant to the original purpose of collection, (ii) whether there is foreseeability of further use or provision of personal information, (iii) whether it unfairly infringes on the interests of the information subject, and (iv) whether necessary measures have been taken to ensure safety, such as pseudonymisation or encryption should be considered. These regulations help to expand the scope of personal information utilisation.

The above personal information refers to general information, and the exact scope of personal relevance of energy usage information of individual households has not yet been determined. However, it is stipulated that the personal information of users can be collected and used without consent if it is necessary for the settlement of bills for the provision of information services. In the electricity sector, the 'Promotion of the Construction and Use of Intelligent Power Grids Act' stipulates that in order to utilise personal information items of the power grid, the information subject must be informed and consented to in advance, and the information must not be provided to a third party or used for purposes other than those for which it was provided. However, in the district heating and gas sector, there are no regulations governing the collection and management of energy data yet (klri 2020).

9.4 Legal requirements for data security

Cybersecurity is not synonymous with data security or information security. Cybersecurity could be described as a generic term for data and information security[9-2]. However, in the European Cybersecurity Act (Regulation (EU) 2019/881) cybersecurity is defined as the "activities necessary to protect network and information systems, the users of such systems and other persons affected by cyber threats". Thus, information security is a part of this definition and helps to protect technical and non-technical systems from dangers and threats. In contrast, data security – like data protection law – is aimed at the personal information seen from the perspective of the person responsible for processing personal data and thus for protecting it.

Cybersecurity law in the European Union in general and in Germany in particular is in constant motion. In 2016, the GDPR established a few – directly applicable – provisions relating to data security in European Law, and the Network and Information Systems Directive (Directive (EU) 2016/1148; in short: "NIS I") established rules aiming at a common level of security for operators of essential services. After the Cybersecurity Act in 2019, which provided a detailed legal framework for the European Union Agency for Cybersecurity (ENISA) und for the establishment of European cybersecurity certification schemes, the European Commission revised the NIS I and the revised Directive (EU) 2022/2555; in short: "NIS II") entered into force at the end of 2022. In the following, first, the NIS II will be discussed, followed by the GDPR.

The NIS II is, compared to the former directive, a legal act of high regulation depth. Nevertheless, the directive contains in principle just two questions for operators of district heating and cooling. First, do they fall under the scope of the directive or not? Second, and provided that this question is answered in the affirmative, are they an "essential entity" or an "important entity" in the terms of the NIS? Being considered an essential entity leads to – at least partially – more severe supervision and enforcement measures than being an important entity.

Regarding the first question, the NIS II covers only entities that belong to one of the specific sectors listed in Annex I or Annex II. Annex I lists sectors considered highly critical, such as the energy sector, as well as subsectors, such as the electricity subsector as part of the energy sector. Beyond the subsector, the type of entity for each subsector are listed, e.g., electricity distribution system operators as part of the electricity subsector. Annex II defines – in the same manner – other critical sectors, which are not considered highly critical, but still critical enough to be part of the directive, such as postal and courier services. If a type of entity is listed in the Annexes, it falls under the scope of the NIS II. Whereas the NIS I defined for the energy sector just three subsectors (electricity, oil and gas), the NIS II now defines five subsectors and especially includes district heating and cooling. This means: District heating and cooling is now – as of 2022 – considered a highly critical subsector in the European Union and, in contrast to the past, operators of district heating and cooling could now fall under the scope of the directive. Thus, NIS II is a novelty for the district heating and cooling industry and the legislation will make an impact on the entrepreneurial activity.

However, in addition to being an entity listed in the Annexes, operators of district heating and cooling have to meet further requirements to fall under the scope of NIS II. Further requirements are defined in Article 2 (1) NIS II, which addresses the specific size of the entity, as well as in Article 2 (2) NIS II, which addresses the specific importance of the entity. It is only necessary to fulfil the criterions of one paragraph. A specific size is reached, if – to summarise – the criterions for medium-sized enterprises are reached or exceeded. A medium-sized enterprise has between 50 and less than 250 employers, an annual turnover of at least 10 million € and not more than 50 million € sas well as an annual balance sheet of at least 10 million € and not more than 43 million €. In many cases operators of district heating and cooling will meet these criterions and thus, they are under the scope of NIS II and have to comply with its requirements.

In some cases, such operators are small enterprises or microenterprises and do not reach these ceilings. In such cases, a close look on the specific importance of the entity according to Article 2 (2) and the following paragraphs should be examined. Specific importance can be obtained in different cases, which are concretised in the

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[9-2] Kipker in: Kipker, Cybersecurity, ch. 1, no. 4.

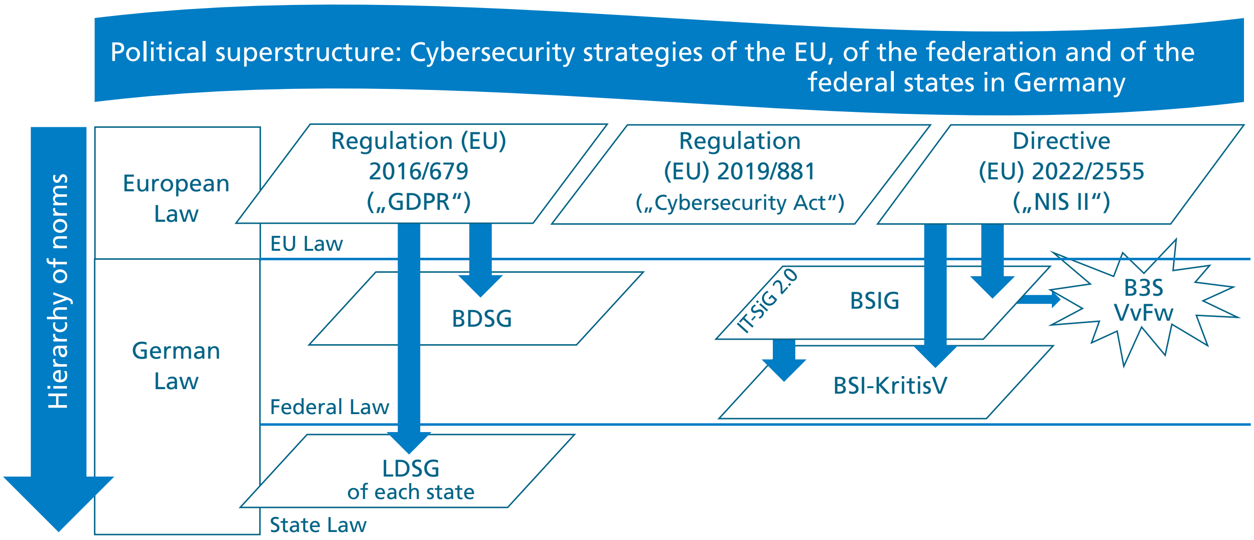

Figure 9.2: Architecture of cybersecurity law in the EU und Germany.

directive in six case groups, four of which may be relevant for district heating and cooling.

The first group includes entities, which, if their services are disrupted, could have a significant impact on public safety, public security or public health. However, the NIS II does not provide examples of types of such entities, and does not define the terms of public safety, public security and public health. Even if the European Court of Justice defines these terms in concretisation of the European (Primary) Law und thus minimises the national margin of appreciation in the transposition and application of the directive, it is indistinct, in which cases a significant impact exists. On the one hand, the formulation ("significant") implicates that a certain threshold of importance has to be exceeded. On the other hand, a potential significant impact on public safety, public security or public health could already be sufficient. This contrast makes it difficult to point out the relevant cases. Whereas, depending on the definition in detail, a disruption of district heating during winter season may lead to a certain impairment of public safety and/or public security, it seems even clearer that it could provoke serious health impairments especially for seniors and young children. Thus, one could argue that even operators of district heating running a small enterprise or microenterprise possess such specific importance. Of course, the exception that proves the rule: If such operators only provide district heating for commercial or industrial purposes, it seems questionable to assume this significant impact on public health. Ultimately, it thus depends on the individual case.

The second group is tailored to entities, which, if their services are disrupted, could induce a significant systemic risk. Although the NIS II does not concretise the nature of such risk and how it could be specified, it specifically focusses on sectors, "where such disruption could have a cross-border impact". District heating and cooling is usually not a service with a cross-border impact, as it normally requires production and consumption to take place in the same area. This category is thus of limited relevance for district heating and cooling.

The third group is designed for entities, which are critical due to their specific importance at national or regional level for the particular sector or type of service or for other independent sectors in the member states. Unfortunately, the formulation is vague and gives little guidance as regard to which types of entities could fall under it. In light of the exceptional nature of Article 2 (2) NIS II, a restrictive reading may be advised. In most cases operators of district heating and cooling are unlikely to fall within this category.

The fourth group includes entities, which are identified as critical entities under Directive (EU) 2022/2557. According to Article 6 of that directive, every member state has to identify these critical entities until 17.07.2026, based on certain criteria. Therefore, member states have the possibility to identify operators of district heating and cooling as such critical entities, even if they are small enterprises or microenterprises.

Thus, not only those operators of district heating and cooling, who are qualified at least as a medium-sized enterprise, may fall under the scope of the NIS II, but also smaller ones; they might have a significant impact on public health and thus have the specific importance, the directive requires.

If an operator of district heating and cooling falls under the scope of NIS II, the operated entity could be qualified as an essential or an important entity. Essential entities are enumerated in Article 3 (1) NIS II: they include especially all entities listed in Annex I, which belong to an at least medium-sized enterprise and thus, fulfil the criterions of Article 2 (1), all entities listed in Annex I and II, which belong to an at least small enterprise or microenterprise and fulfil the criterions of Article 2 (2), and all entities identified as critical entities under Directive (EU) 2022/2557 according to Article 2 (3). Important entities are all those entities listed in Annex I and II, which do not qualify as an essential entity under Article 3 (1). Thus, the term “important entity” has a catch-all function; those entities are subject of less severe supervision and enforcement measures than essential entities. Still, operators of both essential or important entities have to comply with detailed obligations in terms of risk management, reporting and governance. A detailed discussion of those obligations would exceed the scope of this chapter; please refer to Articles 20 et seq. NIS II. One detail, however, still has to be stressed: Failure to comply with said obligations can lead to the imposition of an administrative fine, which has to be “effective, proportionate and dissuasive” and takes the circumstances of each individual case into account. The provision about the application of administrative fees in Article 34 is obviously oriented towards GDPR.

The detailed requirements of the NIS II, including the provisions on sanctions, will now have to be implemented by the member states. In Germany, this will likely happen through an amendment of the laws concerning the Federal Office For Information Security (Bundesamt für Sicherheit in der Informationstechnik; in short: BSI), namely the BSI Act (in German: BSIG) and the derived BSI Critical Infrastructure Regulation (in German: BSI-KritisV). While operators of district heating and cooling, who qualify as at least medium-sized enterprises, in any case fall under the scope of the NIS II, this could arguably also be the case regarding smaller enterprises. Therefore, operators in the district heating and cooling industry have to be prepared for the new legal framework of cybersecurity law.

Data security law in the narrower sense, which originated in particular in Article 17 of Directive 95/46/EC (Directive 95/46/EC of the European Parliament and of the Council of 24 October 1995 on the protection of individuals with regard to the processing of personal data and on the free movement of such data), which has since expired, is thus concerned with what the controller must do to ensure an appropriate level of data protection, and often includes technical and organizational measures. Today, data security law is a cross-sectional matter, and the respective provisions are scattered across many directives and regulations. Still, the GDPR lays down the basic rules, and the ones most relevant for the digitalisation of district heating supply.

The central provisions on data security are found in Articles 5, 25 and 32 of the GDPR. Article 5 (1) f) of the GDPR contains the principle of data security, according to which personal data "shall be processed in a manner that ensures appropriate security of personal data, including protection against unauthorised or unlawful processing and against accidental loss, destruction or damage by appropriate technical and organizational measures ("integrity and confidentiality")". The corresponding obligations of the controller to take appropriate technical and organisational measures (in short "TOM") are then standardised in Article 25 GDPR. This is also referred to as "built-in data protection" or "privacy by design".

The individual criterions for selecting a "TOM" are listed in Article 25 (1) of the GDPR. Accordingly, the selection must consider the state of the art, the implementation costs, the type, scope, circumstances and purpose of the processing, as well as the probability of occurrence and severity of the risk.

Regarding the first criterion of the state of the art, this is a dynamic concept which, according to the case law of the German Federal Constitutional Court, shifts the "legal standard for what is required and permitted (...) to the front of technical development”[9-3]. This means that compliance with the state of the art requires more than best practice, but less than the latest research findings (i.e., the state of science and technology).

[9-3] BVerfGE 49, 89 (135).

Especially in the field of data security, the state of the art can be difficult to determine in individual cases. Technical rules and regulations and other technical publications can provide clues.

The GDPR does not define which implementation costs – as the second criterion – are eligible for consideration in any more detail. For this reason, there is some dispute in the legal literature as to what should be included in such costs. Some argue that operating and follow-up costs are not eligible[9-4]. However, better other arguments argue – as do the European data protection supervisory authorities – in favour of a broad definition of the term "costs" in order to select an appropriate measure in terms of costs as well[9-5].

The third criterion considers the type, scope, circumstances and purpose of the processing, which influence the probability of occurrence and severity of the risk. In terms of the type of processing, the risks in local systems without a network environment are lower than in distributed cloud systems. With regard to the scope of processing, the risks are generally higher for a larger number of personal data than for a smaller number. With regard to the circumstances of the processing, along with the external framework conditions of the processing - i.e., the global cybersecurity situation and the operational framework conditions - must be evaluated. Regarding the purpose of the processing, its scope must be determined in order to distinguish necessary and non-necessary processing operations[9-6]. The purpose of the processing is particularly fraught with risks if it is based on social dependency relationships or involves follow-up measures relevant to fundamental rights.

The fourth criterion relates to the probability of occurrence and the severity of the risk. The risk can be determined using a quantitative or a qualitative method. In the quantitative method, the risk is represented in monetary terms, expressed by the damage i ("impact") and the probability of occurrence p ("probability"): i x p = r[9-7]. The qualitative method would consist of mapping of the risk in a risk matrix expressed in different levels of risk and probability; the data protection supervisory authorities support the qualitative method[9-8].

When selecting the "TOM", the responsible party weigh all criterion. However, Article 25 (1) of the GDPR does not give more guidance on the selection procedure. However, Article 32 (1) of the GDPR expands on the notion of suitable measures, suggesting for example data protection concepts or data protection impact assessments as suitable measures.

Article 32 GDPR generally regulates data security during the processing of data. In contrast to Article 25 of the GDPR, which is (only) addressed to the controller and must be observed prior to the actual data processing, Article 32 of the GDPR addresses the processor and the original processing of collected data. According to paragraph 1, Article 32 GDPR is also intended to "ensure a level of protection appropriate to the risk". Regarding the selection of a "TOM", the same criterion apply as for Article 25 GDPR.

9.5 Interim conclusion

When collecting and processing data during the digitalisation of the district heating supply, the legal rules on data protection and cybersecurity must be observed; respective requirements can be found on EU, national and – not discussed here – sub-national levels.

The European General Data Protection Regulation (GDPR) plays a central role in this context; as a regulation it is directly applicable in all member states and it contains rules that may be relevant for data used in district heating supply. However, the GDPR only applies to personal data. If data is personal, then the lawful processing of the (customer) data requires either a justification under Article 6 (1) GDPR or an explicit consent of the customer with the possibility of revocation at any time. In addition, several legal obligations must be observed, such as the transferability of data in accordance with Article 20 of the GDPR, non-compliance with which can result in high fines or even criminal charges.

[9-4] Keber/Keppler in: Schwartmann/Jaspers/Thüsing/Kugelmann, DS-GVO/BDSG, Art. 25, no. 48.

[9-5] Hansen in: Simitis/Hornung/Spieker gen. Döhmann, Datenschutzrecht, Art. 32, no. 26; Jandt in: Kühling/Buchner, DS-GVO/BDSG, Art. 32, DS-GVO, no. 11; Ritter in: Schwartmann/Jaspers/Thüsing/Kugelmann, DS-GVO/BDSG, Art. 32, no. 97.

[9-6] Ritter in: Schwartmann/Jaspers/Thüsing/Kugelmann, DS-GVO/BDSG, Art. 32, no. 89.

[9-7] Hansen in: Simitis/Hornung/Spieker gen. Döhmann, Datenschutzrecht, Art. 32, no. 28; Ritter in: Schwartmann/Jaspers/Thüsing/Kugelmann, DS-GVO/BDSG, Art. 32, no. 90.

[9-8] Ritter in: Schwartmann/Jaspers/Thüsing/Kugelmann, DS-GVO/BDSG, Art. 32, no. 90.

In addition to the data protection law aimed at individuals, the cybersecurity law must also be observed. Such is required even before the actual processing. Cybersecurity law has a growing importance and is shaped especially in the Network and Information Security Directive (NIS II). This directive contains detailed requirements for operators of district heating and cooling and – as seen – may also address small enterprises and microenterprises. The NIS II is not directly applicable but will be transposed into the law of the member states very soon. Operators in the district heating and cooling industry have to be prepared for the new cybersecurity law. Besides the NIS II, operators already have to observe the requirements of data security in the GDPR. Such requirements concern built-in data protection; which suitable technical and organizational measure(s) (abbreviated to "TOM") the controller selects must be weighed up based on various criterion. However, data security must also be ensured during the actual processing by means of an appropriate level of protection; here, too, the selection of the measure(s) must be weighed up based on various criterion.

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10 Current Challenges and Future Directions

The previous sections presented many results which highlight the benefits related to the digitalisation of DHC systems. However, the real-world adoption of these solutions faces many barriers, some of which are similar to other industrial fields, some others are specific to DHC systems.

In the following sections, we analyse the main barriers we could identify regarding the widespread deployment of digitalisation in DHC systems. We organise the content starting with the challenges most specific to DHC systems and ending with more general barriers related to digitalisation in the industry.

10.1.1 Challenge #1: Heterogeneity of DHC systems

It is well-known that almost every DHC system is unique. This situation is very specific compared to other areas of the energy industry, which have witnessed a progressive homogenisation. This process has not taken place in DHC systems, which by nature are more independent and less connected than power or gas grids. DHC systems also have a longer history of continuous development, spanning over decades or even more than a century (e.g., the Paris and Copenhagen networks). As a result, we can usually observe the following characteristics:

- Various local "traditions" for building substations (direct or indirect connection): depending on countries and even sometimes on cities, the way buildings are connected to the network can vary significantly. While direct connection is widespread in some countries (e.g., Denmark), most DHC system rely on heat exchangers in substations to isolate the main (primary) network from the building (secondary) distribution system. However, these substations themselves are sometimes not off-the-shelf products, assembled on site to accommodate for each specific situation. Nowadays, packaged substations becoming increasingly available, especially for newer buildings and single-family houses. Nevertheless, the architecture and type of substation and heat exchanger can vary significantly, even in a single DHC system.
- Different temperature level requirements: in a given DHC system, the supply temperature is usually dictated by a combination of the temperature requirements of customers and the characteristics of the distribution network (length, pipeline bottlenecks, heat losses…). The consumer requirements can vary significantly, due to both the different types of substations, along with different buildings will requiring different temperature levels (depending on insulation, type of internal heating system…). DHC systems also often deliver heat to local industries, with their own requirements.
- Heat production units depending on local resource availability: sometimes, the choice of a temperature level and the way the network behaves may also be related to the heat production units. For instance, some countries favour biomass boilers (e.g., in France and Austria), which offer a high temperature level. Others tend to favour lower temperature levels, especially when using heat pumps (e.g., Sweden) or solar thermal (e.g., Denmark, Germany). High temperature geothermal resources are also specific to some designated areas (e.g., Iceland).

A consequence of this heterogeneity is that there are relatively few "big players" in the field of DHC systems. Most systems are operated by local operators, with directions often given by public authorities and/or local communities. Only a few companies (Dalkia, Engie, Veolia, E.ON, Vattenfall, Fortum…) operate a significant number of networks, but even in this case they usually do not own the network and have to comply with the rules set by local authorities. This is very different from other fields in the industry, where dominant companies often push for harmonization under their umbrella, imposing de-facto standards on the market. Even when companies come with their own practices, methodologies and tools, they may not be able to fully deploy them in each network they operate.

In this context, digital solutions for DHC systems are often provided by third parties in a fragmented market. They usually address specific parts of the DHC system (e.g., substation monitoring). Although there are some mature products, no obvious "one size fits all" solution exists. Some of the aforementioned "big players" may develop integrated solutions internally but these solutions are not available as commercial products for others to use.

From the R&D perspective, this situation particularly hinders and slows down the deployment of innovative solutions. In particular, each deployment requires a significant amount of engineering for integration in an existing and specific system, and sometimes the required effort outgrows the benefits of the solution.

10.1.2 Challenge #2: Lack of standards for DHC

In other fields (telco, power systems, industry 4.0 …), the availability of standards (e.g., for describing systems, for data formats) facilitates the integration and comparisons of innovative solutions, and drastically speed up the adoption of efficient solutions.

In relation to the heterogeneity described in the previous section, standards are lacking in the DHC field. Notably, there is:

- No unified way of data stream labelling (even the choice of physical units may vary between DHC operators)
- No unified way of identifying/naming components
- No unified way of describing a DHC network

Only concerning data communication protocols, OPC UA (OPC Foundation, n.d.) seems to have become the “de facto” standard, supported by many SCADA system providers. Nevertheless, its deployment is far from being adopted everywhere, especially when older legacy SCADA systems have not been updated for a long time. It should also be noted that OPC UA requires a server with a database. In some cases a lighter architecture with direct communication and transmission is desired, and various protocols are possible.

Other “higher-level” standards may become more widespread in the coming years. In the context of Annex TS4, the working group could identify the following work-in-progress.

Modelica IBPSA library (IBPSA n.d.)
The Modelica IBPSA library is a joint effort between the research centres LBNL Berkeley / KU Leuven / RWTH Aachen / UdK Berlin to build a common base for each of their Modelica library dedicated to modelling district energy systems (including district heating and cooling). It has been funded by IEA-EBC and IBPSA. The developers of this library managed to codify best practices for the implementation of models for building and community energy and control systems.

The Modelica IPBPSA library is available under a 3-clause BSD-license.

Benefits	Limitations
• EA EBC and IBPSA support • De facto standard in the Modelica community	• Requires Modelica knowledge • Relatively detailed level • No link to GIS

CIM extension for DHC
(Common Information Model (CIM) n.d.)
CIM (Common Information Model) is the basis for several standards used in the power system industry in order to describe and model power systems in an interoperable way. It is not only supported by academia but also by most of the industrial players in the field. Although CIM itself is independent of a given field, the IEC (International Electrotechnical Commission) has published at least three standards related to power systems:

- IEC 61970 – For power system modelling and energy utility data exchange including EMS (Energy Management System), topology, wires, SCADA (Supervisory Control and Data Acquisition, etc.
- IEC 61968 – For power system modelling related to DMS (Distribution Management Systems), assets, work, GIS (Geographical Information System), metering and application messaging.
- IEC 62325 – Modelling for energy markets with support for both North American and European markets

CIM has a very active community and a dedicated User Group (CIMUG n.d.)

CIM was also adapted by as Digital Twins Definition Language (DTDL) ontology for Energy Grid in June 2021. See (Azure n.d.) and (Energy grid ontology for digital twins is now available n.d.). However, although some aspects of the IEC standards and the DTDL may cover district heating systems, no extension of CIM for DHC systems is available yet.

Pros	Cons
• Adopted and used in the power industry (not just academia)	• Extension for DHC not available

District Energy Data Model
(District Heating and Cooling n.d.)
District Energy Data Model is an "outside-the-box" template data model ready to manage district cooling, district heating, and steam data within an ESRI geodatabase. This is supported by ESRI, the company behind the leading GIS software ArcGIS, and was released at the end of year 2021.

Although supported by a single company, this model is based on community work among ArcGIS users, some of which are DHC operators who use this software for their internal operation. District Energy Data Model provides a data dictionary, to formally describe elements of a DHC network.

Pros	Cons
• Supported by leading GIS provider & community	• Only used for describing physical network layout (possible to extend?)

10.1.3 Challenge #3: Vendor-lock in and interoperability

Many of the digital solutions currently deployed in DHC systems are coming from the industrial software field (e.g., Control PLCs, SCADA systems …). Even more than mainstream software systems, vendors in this field traditionally enforce a "lock-in" strategy: once you start to use the core system, it is only possible to buy support, maintenance, extensions from them or their partners. For DHC operators, shifting to a different solution after an initial choice has been made almost impossible: it would not be acceptable to shut down DHC operation even for a few hours in order to switch to a new software system. Actually, this kind of change would rather require several days even with thorough preparation, depending on the size and complexity of the DHC system.

As a consequence of this lock-in, making new features available and integrated into existing systems requires long integration times and high costs, if anything, depending on the software provider policy. Some kind of features (especially offline analytics) may still be deployed using gateways to existing systems (e.g., regular CSV exports from a central database), but these solutions tend to be brittle and prone to failure. Operational control solutions can also be demonstrated as prototypes but are difficult to put in operation.

It is nevertheless possible that some industrial software providers propose more open solutions and enable to "plug in" external software packages. The type of "market-place" ecosystem that exists in the mainstream software industry would clearly boost the availability of innovative solutions for DHC systems, with smaller players being able to provide new features as robust "apps" with strong integration with the underlying system.

10.1.4 Challenge #4: Need for robust and resilient control architectures

Similarly, to other infrastructures, DHC systems are considered as relatively critical systems, in which failures of digital control systems could have significant effects. Although criticality is not the same as in transport systems or even power transmission systems, suspending network operation for several hours especially during winter cold spells can have severe consequences.

When deploying new control solutions for operational optimisation, special care should be taken to always define fallback solutions. Solutions in this direction can be found in other industrial domains, especially in the power transmission systems and in some industrial manufacturing industries. In particular, hierarchical (or even decentralised) control solutions can be designed which enable continuous operation even in the case of failure or misbehaviour of some control modules. These architectures often rely on a conceptual layering of control strategies, with lower-level control system applying set points in a conservative way, while supervisory control systems with a higher level of analysis provide set points for optimised operation. In these architectures, low-level control is designed to be as robust as possible and to enforce safe operation in all conditions. It is also designed so that failure of one control system does not impact others, nor the operation of the whole system. Higher-level control is designed with efficient operation in mind but may sometimes recommend actions that are not accurate enough for the set point to be applied "as is". In such cases, corrections should be applied by lower-level control and feedback should be provided to the higher-level so that it corrects its recommendation. Also, since the higher-level is more exposed to programming bugs due to its higher complexity, the system should keep working with consistent set points even in case of higher-level failure. Depending on the system complexity and organisation, several levels of control layers may be required for obtaining the best compromise between robustness and efficiency.

In order to facilitate the deployment of innovative control architectures, the responsibilities and interfaces between typical control layers should probably be standardised, in the same way as the Smart Grid Architecture Model (SGAM) in the power system field (see challenge 3).

10.1.5 Challenge #5: GDPR compliances

As pointed out in section 9, several applications of digitalisation in DHC systems may be impacted by the rules imposed by the General Data Protection Rule (GDPR) in the EU. It can especially be a challenge if each digital solution needs to implement its own framework for complying with the regulation in place, which can also be slightly different between member states.

10.1.6 Challenge #6: Safety and security of IT systems

Security as well as easier IT integration are one of the key arguments in favour of “closed solutions” proposed by industrial software vendors. Especially in the context of DHC systems which are relatively critical, vendors can emphasise the risk caused by facilitating communication with external software.

Several types of risk should be distinguished:

- the risk that an incorrect (flawed) software has a negative impact on the system (e.g., a software sending too many requests to a database could block other systems from working correctly).
- the risk that malicious software (virus) infects the system and blocks it.
- the risk of cybersecurity attacks to steal data or take control of some parts of the system.

The situation is highly similar in other fields where IT systems could be threatened by the same risks, and solutions have been developed to overcome them.

In the context of DHC systems, systems with well-documented APIs and communication standards would make IT integration and maintenance easier and reduce security threats at the same time. Best practices from other industries should be enforced, in order to make the most critical systems well protected from external threats while still enabling the integration of new features. With regard to this, the hierarchical control approaches presented in the previous sections are a good way of providing security as well.

It should be noted that the risk of flawed software is strongly reduced when possibilities for testing it outside operation are available. In this sense, testing sites with hardware-in-the-loop possibilities are essential for verification and validation of solutions before they are put in production. Again, this would be facilitated by standard APIs and communication standards, so that testing can occur in conditions similar to a real operation.

10.1.7 Challenge #7: Lack of (labelled) reference datasets and benchmarks

Reference datasets and benchmarks are a very efficient way to improve efficiency and accelerate the pace of innovation. As an example, innovation in the field of processor design and computing has long been boosted by the availability of benchmarks for comparing processor architectures as well as algorithms. In the field of Machine Learning reference datasets, such as MNIST digits for handwriting recognition (LeCun et al. n.d.) and ImageNet (Howard et al. 2018) for image recognition, have maintained a strong pace of innovation. Also in the power system field, the various IEEE Bus benchmarks are available for different purposes (e.g., planning, reliability, stability, state estimation, control, see for instance (Peyghami 2019)).

No such reference datasets or benchmarks are available in the DHC field. E.g., although load forecasting has undergone major advancements in recent years, widespread adoption by DHC operators has not yet been reached. Practical implementations have faced difficult access to operational data. DHC systems usually have the monitoring infrastructure in place; however, recorded measurements are not necessarily well managed. The data might not be stored in a database or not at the right frequency (every 10 seconds or every 90 minutes, rather than every 5-15 minutes); variables might be associated with improper labelling (e.g., no descriptive names nor associated units); key variables might not be measured, or measured with uncalibrated sensors.

Data sharing for research purposes is also a key challenge: DHC owners might be reluctant to share the data due to potential security, cybersecurity and privacy considerations while they might not be aware of benefits, they could get by sharing the data. While this does not prevent the deployment of new solutions, the availability of benchmarks would help both researchers and DHC operators for evaluating relevant solutions more quickly, and drive focus to the more promising solutions.

10.2 Future directions for research in digitalisation of DHC

In order to overcome the challenges of DHC digitalisation, the following directions are recommended:

- **Standardisation:** develop new or improve existing standards addressing data stream labelling, component naming and DHC network description, especially by leveraging what is available in other fields (e.g., Power Systems, Industry 4.0, Geographical Information Systems, Haystack and Brick schemas for buildings); develop techniques to automate data labelling and to generate descriptive names for variables in existing datasets.
- **Benchmarks with reference datasets and (simulated) use cases:** define and share well-documented datasets and use cases which (i) are representative of existing types of DHC systems, either measured from existing systems or simulated, (ii) enable comparison of control solutions (e.g. FDD, supervisory controls), and (iii) are available for research purposes to DHC researchers and companies.
- **Data analytics:** investigate in-depth and improve the actual operation and performance of DHC systems by leveraging available operational data and state-of-the-art data analytics methods, to maintain high levels of efficiency; tools and software development are required to facilitate this process, which include FDD, predictive maintenance but also the development of key performance indicators (KPI) and virtual sensors and virtual energy meters to calculate key variables that are not measured.
- **Artificial intelligence and digital twins:** develop virtual representations of DHC systems, i.e. digital twins (Definition of a Digital Twin - Digital Twin Consortium, 2022) by leveraging existing modelling capabilities including machine learning and artificial intelligence techniques that are continuously emerging, in order to enable the testing of new robust and efficient low-level control and supervisory control solutions, and a better management of information for DHC built assets; these models could make DHC systems more proactive by anticipating changes in weather, occupancy, energy costs, and grid carbon intensity and adjusting the operation accordingly; generalisation of DHC system models is also a promising direction to explore (archetype models, transfer learning, etc.).

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11 Conclusions

The district heating and cooling sector is facing novel challenges in the energy systems transition. The required decarbonisation of energy supply will not only make the district energy sector more complex but also more important. Furthermore, to maintain a consistent and cost-effective thermal energy supply, district heating and cooling systems must be operated more efficiently and with more diverse thermal supply plants. Increased acceptance of digital technology in the district heating and cooling sector provides an opportunity to make systems smarter, more efficient, flexible, and reliable in this changing climate, hence expediting the necessary integration of more sustainable energy sources into supply systems, as well as supporting the decarbonisation of other energy sectors. District heating and cooling system digitalisation represents a paradigm shift in heat production, delivery, and consumption.

As a result, the DHC Annex TS4 focuses on the digitalisation of district heating and cooling systems. The project's goal is to promote the opportunities for integrating digital processes into district heating and cooling systems, as well as to define the role of digitalisation in various aspects of the operation and maintenance of these supply systems. This research demonstrates how digital technology can make the entire energy system smarter, more efficient, and more reliable, while also increasing efficiency and integrating additional renewables into the system. In the future, digital applications will let district energy systems fully optimise their plant and network operations while also empowering the end user.

Buildings and how end users use thermal energy provide an initial basis for potential improvements, such as decreasing system temperature in district heating systems and forecasting near-future heating demands. Demand side optimisation is regarded as an essential aspect of the project. Historically, buildings were regarded as black boxes due to a lack of operational information from substations and heating/cooling systems. This notion hampered the development of methods for optimally managing and operating these systems, limiting the possibilities for attaining low-temperature operation and transitioning to a CO_2-free district heating supply. Although the extent of demand-side digitalisation differs by country, new rules implemented in recent years have enhanced the availability of new remotely readable devices. This has created new opportunities for monitoring, and managing ensuring low-temperature operation, and providing end-users greater billing transparency. Digitalisation enables new control and monitoring possibilities that were not possible before. Future software development with artificial intelligence and digital twins will increase the potential for enhanced control and flexibility even further. It has been demonstrated that without extensive energy renovation, it is possible to improve the control and operation of space heating systems and comfortably heat existing buildings with supply temperatures ranging from 42 to 58 °C throughout the whole heating season. Furthermore, new methods of managing DHW substations have been developed to assure the required comfort and hygiene of hot water with network supply temperatures in accordance with the 4GDH criteria.

Data-driven automatic screening for fault identification and diagnosis has been demonstrated in mature district heating markets to be an effective tool for monitoring substations and finding outliers with the goal of attaining efficient operation and cost savings. The commercialisation of novel data-driven products is accelerating. However, data processing may be limited by the designation of data as GDPR-sensitive, which means that it must be processed in secure environments, which is determined by national rules. Coordination of a uniform strategy for data security and transparency must be a high priority effort in order to ensure future interoperability and integration of all data sources.

On a system level, the benefits of digitalisation in district heating and cooling systems can be highlighted, despite the fact that the industry's current deployment of digital technology is not uniform. The most common is operation optimisation at the production level, which yields significant savings in comparison to more conventional practises. New advances are aimed at combining more diversified energy sources, as well as merging distribution and consumer-side features. In contrast, distribution-level operational optimisation is still more experimental.

Although it has the potential for generating significant savings by leveraging system thermal inertia, its deployment is centred on larger networks with the largest potential and hence a higher cost/benefit ratio. In implemented cases, operation optimisation at the consumer level has shown promising possibilities, whether for peak reduction or return temperature minimisation. It is projected to become more common in the next years, with a variety of commercial solutions readily available on the market.

With the digitalisation of district heating and cooling networks, analytics for fault and leak detection is an important area of development. It is expected that numerous technology combinations will be used to match the characteristics of each district heating and cooling network. In contrast, predictive maintenance and system improvement analytics have been commercially accessible for several years, assisting system operators through the collecting, organisation, and visualisation of massive amounts of available data. It is still projected to improve, especially as more knowledge is gathered through practical use. Most of the other solutions appear to involve forecasting. In the near future, even greater accuracy and adaptability to local conditions are envisaged.

For the deployment of these digital technologies in the field, the concept of Digital Twins is becoming increasingly popular. Digital Twins enable the integration of digital technologies with existing infrastructure, allowing system operators to seamlessly incorporate digital solutions into their every-day operations. They make use of existing digital tools and make them available online, making it possible to provide real-time services that either support operators or automate activities. The bi-directional, (semi-)automated connection with the district heating and cooling system is made feasible by the integration of remotely controllable assets, facilitating the shift from old passive networks to smart energy systems. As demonstrated, this opens up new possibilities for assisting and/or automating certain aspects of the operation and maintenance of district heating and cooling networks and related infrastructure, particularly monitoring, diagnostics and fault detection, forecasting, and operational optimisation.

It has been demonstrated that digitalisation can reduce operational costs in the heat network. Although, this reduction is small, digitalisation proves cost effective when regarding total heat production costs. However, the economic efficiency is highly dependent on the number of consumers to be digitalised. Depending on the underlying distribution of building sizes, global optima arise for which the biggest cost savings with digitalisation can be envisaged. In the case of full digitalisation or digitalisation of relatively small customers, economic efficiency may suffer and additional financial resources may be necessary to cover the costs. Not all of the effects of digitalisation were assessed in monetary terms in the study. A streamlined billing system, faster and more direct problem reporting, and overall improved service can all lead to additional cost savings. The impact of digitalisation should be increased in future evaluations to include the consequences of actively regulated demand for space heating and domestic hot water. Furthermore, the effects of a different generation fleet will be assessed in the subsequent techno-economic analysis.

When collecting and processing data during the digitalisation of the district heating supply, legal regulations on data protection and cybersecurity must be followed; relevant requirements can be found at the EU, national, and sub-national levels. In this respect, the European General Data Protection Regulation (GDPR) is crucial; as a regulation, it is immediately applicable in all member states and contains provisions that may be important for data used in district heating delivery. It should however be noted, that the GDPR only applies to personal data. If the data is personal identifiable, the law requires either a reason or the customer's explicit consent, which can be revoked at any time, before the data is processed. Furthermore, certain legal obligations must be met, such as data transferability, failure to which can result in large penalties or even criminal charges.

The cybersecurity law must be followed in addition to the data protection law aimed at persons. This is essential even before the process begins. Cybersecurity law is becoming increasingly important, as seen by the Network and Information Security Directive (NIS II). This directive covers precise standards for district heating and cooling operators and, as observed, may also apply to small and microenterprises. The NIS II is not directly applicable, but will be transferred into member-state law. District heating and cooling operators must be prepared for the new cybersecurity law. Aside from the NIS II, operators must already comply with the GDPR's data security obligations. Such standards pertain to built-in data protection; which appropriate technical and organisational measure(s) the controller selects must be considered against numerous criteria. However, data security must also be ensured during processing by employing an adequate level of security.

11.1 Key findings and messages

- One of the primary technological solutions for the needed decarbonisation of the energy system is district heating and cooling. To realise its full potential, however, the district heating and cooling system must evolve and take full advantage of solutions resulting from digitalisation, which are becoming more complex due to a growing mix of production technologies, remote sources, and sector coupling. Digitalisation processes will aid in the operation of these new technologies.
- The increased complexity of the systems can be efficiently managed by leveraging data from the field and other diverse sources, such as market prices, weather forecasts, and so on, through digitalisation measures, such as the incorporation of the Digital Twin concept, resulting in effective design and more efficient operations.
- Maximum performance is realised when the entire value chain is viewed as a whole. Buildings, particularly end-customers, have been underutilised, despite their huge potential for more effective operations.
- When collecting and processing data during the digitalisation of the district heating supply, the legal laws on data protection and cybersecurity must be followed. Requirements are set at the EU, national, and sub-national levels.
- Some degree of standardisation and relevant reference benchmarks would be beneficial for deploying and comparing digital solutions more efficiently. A dedicated effort should be directed to defining shared standards for data stream labelling, component naming and description of DHC network layout. Well-documented datasets and use cases should be made available as reference benchmarks to compare solutions, as it is done in many other fields.
- Regardless of the existing scenario or available technology, we need to advance as soon as feasible and implement digitalisation measures. Utilities can extract actual value from recorded data by enhancing the operational efficiency of their district heating and cooling systems or introducing new business concepts in this manner. Early adopters' experiences demonstrate that integrating these measures is simply a good investment.

Digitalisation of district heating and cooling systems is an essential technology for decarbonising the thermal energy system, and with growing complexity or the demand for system flexibility and a green/renewable heat supply, it is just vital!

12 List of abbreviations

Within this guidebook, the following abbreviations are used:

3GDH	3rd Generation of District Heating
4GDC	4th Generation District Cooling
4GDH	4th Generation of District Heating
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
ANN	Artificial Neural Network
API	Application Programming Interface
ARIMA	Autoregressive Integrated Moving Average Model
ARIMAX	Autoregressive Integrated Moving Average Model with Exogenous Variables
ARMA	Autoregressive Moving Average Model
ARX	Autoregressive Exogenous Model
BACS	Building Automation and Control System
BDSG	Federal Data Protection Act
BEMS	Building Energy Management Systems
BERC	Building Energy Research Centre
BMS	Building Management System
CAPEX	Capital Expenditure
CCMS	Centre Control and Monitoring System
CHP	Combined Heat and Power
CIM	Common Information Model
CNN	Convolutional Neural network
CRG	Cost Reduction Gradient
CRM	Customer Relation Management
CSV	Comma-Separated Values
DDC	Direct Digital Control
DE	District Energy
DEA	Danish Energy Agency
DH	District Heating
DHC	District Heating and Cooling
DHN	District Heating Network
DHW	Domestic Hot Water
DMI	Danish Metrological Institute
DMS	Demand Side Management
DS	Danish Standard
DSO	Distribution System Operator
DT	Decision Tree
DTDL	Digital Twins Definition Language
EBC	Energy in Buildings and Communities Program
EC	European Commission
EED	Energy Efficiency Directive
EMS	Energy Management System
EPBD	Energy Performance of Buildings Directive
ESCO	Energy Service Company
ETR	Extra-Trees Regression
EU	European Union
ExCo	Executive Committee
FDD	Fault Detection and Diagnosis
FFVAV	District Heating and Cooling Consumption Metering and Billing Ordinance
FMU	Functional Mock-Up Unit
GDPR	General Data Protection Regulation
GIS	Geographical Information System
GP	Gaussian Process
IBPSA	International Building Performance Simulation Association
ICT	Information and Communication Technology
IDEA	International District Energy Association
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IT	Information Technology
KDHC	Korean District Heating Company
KIER	Korean Institute of Energy Research
LNG	Liquified Natural Gas
LoRa	Long Range
LR	Linear Regression
LSTM	Long-Short Term Memory Neutral Network
LTDH	Low Temperature District Heating
MAPE	Mean Absolute Percentage Error
MILP	Mixed Integer Linear Program
MPC	Model Predictive Control
MsbG	Metering Point Operation Act
NASA	National Aeronautics and Space Administration
NB	Narrow Band
OECD	Organisation for Economic Co-operation and Development
OPC	Open Platform Communications
OPEX	Operational Expenditure

PCL	Printer Command Language
PDTP	Pressure Drop Time Point
PWA	Piece-Wise Affine
R&D	Research and Development
RD&D	Research, Development and Demonstration
RES	Renewable Energy Source
RF	Random Forecast
RNN	Recurrent Neutral Network
SAM	Smart Asset Management
SC	Space Cooling
SCADA	Supervisory Control and Data Acquisition
SEMS	Sustainable Energy Management System
SGAM	Smart Grid Architecture Model
SH	Space Heating
SHM	Smart Heat Meter
SVM	Support Vector Machine
TCP	Transmission Control Protocol
TCV	Temperature Control Valve
TES	Thermal Energy Storage
TL	Test Leakages
TRL	Technological Readiness Level
TS	Task Shared
TSO	Transmission System Operator
UA	Unified Architecture
ZEB	Zero Energy Building

13 Appendix

13.1 Participants in the Annex TS4

In this section the project participants are presented.

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13.2 Other IEA DHC Projects

To date, the following projects have been initiated by the IEA DHC Executive Committee (completed projects are identified by (*)):

1983-1987 / Annex I (*)

1987-1990 / Annex II (*)

1990-1993 / Annex III (*)

1993-1996 / Annex IV (*)

1996-1999 / Annex V (*)

1999-2002 / Annex VI (*)

2002-2005 / Annex VII (*)

2005-2008 / Annex VIII (*)
- New materials and constructions for improving the quality and lifetime of district heating pipes including joints - thermal, mechanical and environmental performance
- Improved cogeneration and heat utilisation in DH networks
- District heating distribution in areas with low heat demand density
- Assessing the Actual Annual Energy Efficiency of Building-Scale Cooling Systems
- Cost benefits and long-term behaviour of a new all plastic piping systems

2008-2011 / Annex IX (*)
- The Potential for Increased Primary Energy Efficiency and Reduced CO_2 Emissions by DHC
- District Heating for Energy Efficient Building Areas
- Interaction Between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy
- Distributed Solar Systems Interfaced to a District Heating System that has Seasonal Storage
- Policies and Barriers for District Heating and Cooling outside EU Countries

2011-2014 / Annex X (*)
- Improved maintenance strategies for district heating pipelines
- Economic and Design Optimization in Integrating Renewable Energy and Waste Heat with Disrict Energy Systems
- Towards Fourth Generation District Heating: Experiences with and Potential of Low Temperature District Heating
- Development of an Universal Calculation Model and Calculation Tool for Primary Energy Factors and CO_2 Equivalents in District Heating and Cooling including CHP

2012-2016 / Annex TS1 (*)
- Low Temperature District heating for Future Energy Systems

2014-2017 / Annex XI (*)
- Transformation roadmap from high to low temperature district heating system
- Plan4DE: Reducing greenhouse gas emissions and energy consumption by optimizing urban form for district energy
- Smart use as the missing link in district energy development: a user-centred approach to system operation and management
- Structured for success: Governance models and strategic decision-making processes for deploying thermal grids

2017-2020 / Annex XII (*)
- Effects of Loads on Asset Management of the 4th Generation District Heating Networks
- Methodology to evaluate and map the potential of waste heat from industry, service sector and sewage water by using internationally available open data
- Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and Cooling
- Stepwise transition strategy and impact assessment for future district heating systems

2018-2021 / Annex TS2 (*)
- Implementation of Low Temperature District Heating Systems

2017-2021 / Annex TS3 (*)
- Hybrid Energy Networks

2018-2024 / Annex TS4
- Digitalisation of District Heating and Cooling

2019-2024 / Annex TS5
- Integration of Renewable Energy Sources into existing District Heating and Cooling Systems

2020-2023 / Annex XIII

- Leave 2nd generation behind: cost effective solutions for small-to-large scale DH networks
- MEMPHIS 2.0: Advanced algorithm for spatial identification, evaluation of temporary availability and economic assessment of waste heat sources and their local representation
- Artificial Intelligence for Forecasting of Heat Production and Heat demand and Fault Detection in District Heating Networks
- Cost Benefit study on the building secondary network for improving DH performance
- Optimized transition towards low-temperature and low-carbon DH systems (OPTiTRANS)
- The district heating business model 2050
- CASCADE: A comprehensive toolbox for integrating low-temperature sub-networks in existing district heating networks
- District heating scheme for carbon neutrality in Asia

2021-2025 / Annex TS6

- Status Assessment, Ageing, Lifetime Prediction and Asset Management of District Heating Pipes

2021-2025 / Annex TS7

- Industry-DHC Symbiosis - A systemic approach for highly integrated industrial and thermal energy systems

13.3 Additional Information from IEA DHC Annex TS4

All additional information is available via the homepage of IEA DHC: **www.iea-dhc.org**

IEA DHC Annex TS4 Guidebook

A printable .pdf version of the “Guidebook for the Digitalization of District Heating: Transforming Heat Networks for a Sustainable Future”, the final report of the IEA DHC Annex TS4 project, is available for those who prefer to have a good and consistent overview regarding the perspectives on the digitalisation of district heating and its application.

Tool

A tool to estimate the total heat emitter thermal output of a single dwelling or space is provided. The tool is very useful for the determination of the ‘district heating low temperature readiness’ of a building’s heating system. The algorithms are developed based on a large number of radiator catalogues and decades of experience from radiator laboratory. The present tool is adapted and translated to English as part of IEA-DHC Annex TS4 Digitalisation of district heating and cooling and is available on the webpage:
https://www.teknologisk.dk/iea-dhc-annex-ts4-digitalisation-of-district-heating-and-cooling/45243

Material from Workshops

A number of workshops have been organized by the IEA DHC Annex TS4 participants to enhance the exchange with other experts from the industry and science. The documentation, the proceedings from these workshops are available from the indicated homepage:

- Industry and R&D workshop on
  “Digitalization for optimizing integrated district heating systems”
  Online web meeting September 9, 2020
- Industry and R&D workshop on
  “Digitalization for optimizing integrated district heating systems”
  Online web meeting
  November 3, 2021
- Industry and R&D workshop on
  “Testbeds for Digitalization Solution in District Heating”

Online web meeting
April 27, 2022

- Industry and R&D workshop on
  "Demand response and digitalization of demand side in district heating and cooling systems"
  University of Aalborg, Denmark
  September 15, 2022

Video recordings

Video recordings from the above mentioned workshops are available on IEA DHC's YouTube channel:
https://www.youtube.com/channel/UCuYcqLjJi8thrUJCjzLBaow

Conference Sessions

A number of special sessions on the topic of Annex TS4 have been arranged by the working group. More detailed material from the sessions is available from the Task Manager:

- EA DHC Annex TS4 special session on:
  "Digitalization of District Heating"
  at the 8th International Conference on Smart Energy Systems, Aalborg, Denmark
  September 14, 2022
- Special session of Annex TS4 on:
  "Digitalisation in District Heating - with data to optimised systems and new Business Opportunities"
  at CEBC 2023, Graz, Austria
  January 20, 2023
- Special session of Annex TS4 on:
  "Digitalisation of District Heating"
  at 18th International Symposium on District Heating and Cooling (DHC2023),
  Beijing, China
  September 05, 2023
- IEA DHC Annex TS4 special session on:
  "Digitalization of District Heating"
  at the 9th International Conference on Smart Energy Systems, Copenhagen, Denmark
  September 13, 2023
- Special session of Annex TS4 on:
  "Digitalisation of District Heating"
  at Energy Informatics.Academy Conference 2023, São Paulo, Brazil
  December 07, 2023

Published articles

A large number of conference articles and journal papers have been published by the Annex TS4 participants:

Schmidt, D. (2020).
Digitalisation of District Heating Systems. In: 6th International Conference on Smart Energy Systems October 06-07, 2020 / Aalborg, Denmark

Schmidt, D. (2020).
Digitalisation of District Heating. In: EUROHEAT&POWER international, Brussels, Belgium, Vol.2020, no. 2, (2020), pp. 28-30.

Schmidt, D. (2021).
Digitalisation of District Heating Systems. In: 17th International Symposium on District Heating and Cooling, DHC2021, 06–09 September 2021, Nottingham, UK. Energy Reports, Volume 7, September 2021, pp. 458-464. DOI: 10.1016/j.egypro.2021.08.082

Schmidt, D., Tunzi, M., Widl, E., Gölles, M. & Vanhoudt, D. (2022).
Digitalisation in District Heating Supply – with Data to Optimised Systems and new Business Opportunities. In: 8th International Conference on Smart Energy Systems September 13-14, 2022 / Aalborg, Denmark

Schmidt, D. & Gölles, M. (2023).
Digitalisation as the Basis for Efficient and Flexible District Heating Systems. In: 9th International Conference on Smart Energy Systems September 12-13, 2023 / Copenhagen, Denmark

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Technical presentations

A series of technical presentations were prepared for the biannual IEA DHC Executive Committee (ExCo) meetings during the working time of Annex TS4 and are available from the Task Manager.

The Digitalisation of District Heating Systems Research Program

The guidebook offers consolidated and up-to-date information regarding the prospects for broader digitalisation process integration into district heating and cooling networks. It delves into the role of digitalisation in many aspects of district heating and cooling network operation and maintenance. The digitalisation of and its possibilities for the demand side are demonstrated through real-life examples. On the system level, the prospects for greater efficiency of district heating systems are outlined, as are the use and benefits associated with the digital twin concept. The topic of new opportunities coming from new business models and processes for various partners, as well as associated legal aspects, are taken into account. As a result, the guidebook summarises the situation of district heating digitalisation and provides insights through a mix of theoretical background, current solutions, and case studies.

The IEA DHC Annex TS4 is a three-year international partnership initiative including research, scientific, and industry partners.

More information about the program:

Up-to-date information about the participants and the progress of the research program is available on the web page: **www.iea-dhc.org**

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