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Various Aspects of Fourth-generation Systems

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Various Aspects of Fourth-generation Systems

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Various Aspects of Fourth-generation Systems

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Abstract
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In this thesis, aspects of improvements in district heating systems are assessed. Three aspects, in particular, have been analysed. These are integration between energy systems, improvements in heat distribution technology, and economic benefits of low-temperature district heating systems.

An increasing interest in integrating different energy systems has been prompted by the rapid introduction of intermittent renewable electricity supply in the energy system. Large-scale conversion of power to heat in electric boilers and heat pumps is a feasible alternative to achieve the balancing capacities required to maintain system functioning. Analysis of the unique Swedish experience using large heat-pump installations connected to district heating systems shows that, since the 1980s, 1527 MW of heat power has been installed, and about 80% of the capacity was still in use in 2013. Thus, a cumulative value of over three decades of operation and maintenance exists within Swedish district heating systems.

Increased competition prompted by changes in the operation environment necessitates improved heat distribution. This thesis focuses on three system-embedded temperature errors: first, the temperature error that occurs due to recirculation in distribution networks at low heat demands; second, the temperature error that occurs due to hot-water circulation in multi-family buildings; third, the temperature error that occurs due to lower heat transfer than is possible in heat exchangers (i.e. too-short thermal length). To address these temperature errors, three technology changes have been proposed (i) a three-pipe distribution network to separate the recirculation return flow from the delivery return flow, (ii) apartment substations to eliminate hot-water circulation use, and (iii) improved heat exchangers for lower return temperatures. The analysis of the proposed changes indicates annual average return temperatures between 17°C and 21°C.

The final analysed aspect is the economic benefits of low-temperature district heating. It was identified that strong economic motives for lower operating temperatures in future heat supply exist, whereas the economic motives are significantly weaker for the traditional heat supply.

The five papers presented in this thesis are related to future district heating systems through the five abilities of fourth-generation district heating (4GDH), which are documented in the definition paper on 4GDH.

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MADE IN SWEDEN

To Vilgot, Alrik, and Harumi

Abstract

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I would like to thank my supervisor Professor Emeritus Sven Werner for his active engagement, enthusiastic interest, and continuous support in this work and for being a commendable and respectable supervisor role model with the adept ability to convey clarity in a variety of situations. I aspire to obtain the ability to one day supervise students with similar quality, and I am sincerely grateful that you decided to slightly postpone retirement to supervise one final doctoral student.

It has been a blessed opportunity to carry out this doctoral research project at Halmstad University, and it has much to do with the great colleagues at the Department of Energy Engineering. It is and has been inspirational to meet and collaborate with you; I would like to thank my co-supervisors, Urban Persson and Mei Gong, in addition to Erik Möllerström, Fredric Ottermo, Göran Sidén, Jonny Hylander, Kristina Lygnerud, Heidi Norrström, Henrik Gadd, and Ingemar Josefsson. Thank you for adding interesting aspects to the everyday work situation and for facilitating a work environment that enabled creative development.

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Second, funding has been obtained from the European Union (EU) through the three following projects STRATEGO[1], ReUseHeat[2] under grant agreement number 767429, and TEMPO[3] under grant agreement number 768936. Using the same method as in the previous paragraph, funding from these EU projects has collectively contributed to 13% of this research (*equivalent to 23% of total research funding*).

Third, funding has also been obtained through the International Energy Agency (IEA) technology collaboration programme on District Heating and Cooling (DHC) including Combined Heat and Power (CHP). The funding was obtained partly by the project Transformation Roadmap from High to Low Temperature District Heating, (reference number XI-01) and by the Task Sharing Annex 2 Implementation of Low Temperature District Heating Systems. The collective funding from IEA DHC|CHP corresponds to 7% of this research, according to the previous method (*equivalent to 12% of total research funding*).

Fourth, national funding through the Swedish district heating research programme that was funded in collaboration with the Swedish Energy Agency and Swedish District Heating Association. Recently, the previously mentioned research programme has been consolidated with other energy-related research organisations into Energiforsk – The Swedish Energy Research Centre. Funding has been obtained from four individual activities, and the most prominent of these four has been the project Future District Heating Technology (in Swedish, Framtida Fjärrvärmeteknik), as it laid the foundation for appended Paper [2] and Paper [3]. Similarly to the previous paragraphs, the national funding obtained corresponds to 15% of the research in this doctoral thesis (*equivalent to 26% of total research funding*).

The remainder of the time (43%), during the period 2014-2019, has been allocated towards educational activities, other off-topic related academic assignments, and paternity leave. These activities are of less importance regarding the acknowledgement and are thus not detailed any further here.

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[1] Full project name Multi-level Actions for Enhanced Heating & Cooling Plans and contract number IEE/13/650/SI2.675851.

[2] Full project name Recovery of Urban Excess Heat, call H2020-EE-2017-RIA-IA, and topic EE-01-2017 Waste heat recovery from urban facilities and reuse to increase energy efficiency of district or individual heating and cooling systems.

[3] Full project name Temperature Optimisation for Low Temperature District Heating across Europe, call H2020-EE-2017-RIA-IA, and topic EE-04-2016-2017 New heating and cooling solutions using low-grade sources of thermal energy.

List of publications

This thesis is based on the following five papers. These papers are appended at the end of this thesis.

[1] Averfalk, H., Ingvarsson, P., Persson, U., Gong, M., & Werner, S.,
Large heat pumps in Swedish district heating systems.
Renewable and Sustainable Energy Reviews, 2017;79:1275-1284.

[2] Averfalk, H. & Werner, S.,
Novel low temperature heat distribution technology.
Energy. 2018;145:526-39.

[3] Averfalk, H., Ottermo, F., & Werner, S.,
Pipe sizing for novel heat distribution technology.
Energies. 2019;12(7):1276.

[4] Averfalk, H. & Werner, S.,
Economic benefits of fourth generation district heating.
(*submitted for publication and revised after first review*). 2019.

[5] Averfalk, H. & Persson, U.,
Low-temperature excess heat recovery in district heating systems: The potential of European Union metro stations.
(*submitted for publication*). 2019.

The authors' contributions to the publications

[1] I was responsible for drafting the manuscript, collecting data, and preparing data for visualisation. The methodology development was a collaborative effort with Sven Werner, who also supervised the process. Paul Ingvarsson contributed with data from the private sector as well as with personal experience with the introduction of the large heat pumps in Swedish district heating systems. Urban Persson and Mei Gong were engaged in the supervision of the project including the review and editing of the final draft.

[2] The conceptualisation of the novel heat distribution technology was a continuous collaboration. I developed the methodology, executed the analysis, prepared the visualisation, and wrote the manuscript. The process was supervised by Sven Werner, who was also responsible for the funding acquisition and project management.

[3] I was responsible for drafting the manuscript, collecting data, and preparing data for visualisation. The methodology development was a collaborative effort with Fredric Ottermo. Sven Werner supervised the process. The finalisation of the manuscript was a collaborative effort. I was responsible for project administration and fund acquisition.

[4] I was responsible for drafting the manuscript, performing the analysis, and preparing the visualisations. Methodology development and the finalisation of the manuscript was a collaborative effort. Sven Werner supervised the process.

[5] I performed the geocoding, developed the methodology, and prepared the analysis. Urban Persson performed the integration of the data and analysis to map the projection. The finalisation of the manuscript was a collaborative effort.

Other publications related to the doctoral studies

During the work on this doctoral study, additional materials have been prepared. Such materials consist of conference papers, both national and international reports, and collaboration on one international journal paper. These publications are relevant to the overall project execution but are not appended at the end of the thesis.

[6] Averfalk, H., Ingvarsson, P., Persson, U., & Werner, S.,
On the use of surplus electricity in district heating systems.
In *The 14th International Symposium on District Heating and Cooling,* Stockholm, 7-9 September (2014) 469-474.
Swedish District Heating Association.

[7] David, A., Mathiesen, B.V., Averfalk, H., Werner, S., & Lund, H.,
Heat Roadmap Europe: Large-scale electric heat pumps in district heating systems.
Energies, 2017;10(4):578.

[8] Averfalk, H., & Werner, S.,
Essential improvements in future district heating systems.
Energy Procedia, 2017;116:217-225.

[9] Averfalk, H., & Werner, S.
Framtida Fjärrvärmeteknik – Möjligheter med en fjärde teknikgeneration (Future district heating technology – Possibilities of a fourth generation technology).
Energiforsk - the Swedish Energy Research Centre & *Fjärrsyn* – the Swedish District Heating Research Programme, (2017) Report 2017:419.

[10] Averfalk, H., Werner, S., Felsmann, C., Rühling, K., Wiltshire, R., Svendsen, S., Li, H., Faessler, J., Mermoud, F., & Quiquerez, L.
Transformation roadmap from high to low temperature district heating systems:
IEA DHC|CHP. Annex XI final report (2017).

[11] Averfalk, H. & Werner, S.,
Efficient heat distribution in solar district heating systems.
In *The 5th International Solar District Heating Conference*, Graz, 11-12 April 2018.

[12] Averfalk, H., Dalman, B.-G., Kilersjö, C., Lygnerud, K., & Welling, S., Analys av 4e generationens fjärrvärmeteknik jämfört med 3e generationens (Analysis of 4th generation district heating technology compared to 3rd generation).
Energiforsk - the Swedish Energy Research Centre & *Fjärrsyn* – the Swedish District Heating Research Programme, (2017) Report 2018:547.

[13] Persson, U. & Averfalk, H.,
Accessible urban waste heat: Deliverable 1.4. 2018:116.
EU Horizon2020 project: ReUseHeat.

Populärvetenskaplig sammanfattning

Denna doktorsavhandling handlar om aspekter för att förbättra förutsättningarna för fjärrvärmesystem att konkurrera på värmemarknaden i framtiden.

I framtiden förväntas värmemarknaden påverkas av delvis lägre värmebehov som en följd av mer energieffektiva byggnader, men även av större användning av förnybar och återvunnen värmetillförsel som en följd av behovet att reducera koldioxidutsläppen.

Lägre energianvändning och mer förnybar energitillförsel är förändringar som är nödvändiga för att uppnå större grad av hållbarhet i framtidens samhälle. Dessa förändringar utmanar dock den nuvarande tekniken av fjärrvärmesystem. Dagens teknik har utvecklats under förhållanden där kunderna har haft höga värmebehov och där huvudsakligen fossila bränslen, som kunnat generera höga temperaturer, använts för att tillgodose värmebehoven.

Lägre värmebehov leder till ökade distributionskostnader, medan förnybar och återvunnen energitillförsel ofta är förknippade med begränsningar i hur höga temperaturer som kan uppnås.

För att hantera förändrade framtida förutsättningar kan fjärrvärmesystem drivas med lägre temperaturnivåer. Inom detta teknikområde benämns denna förändring fjärde generationens fjärrvärme och är förknippad med lägre temperaturnivåer för distribution, i jämförelse med tidigare systemkarakteristik.

Det finns många fördelar med att driva fjärrvärmesystem med lägre temperaturer. Bland annat så motverkas de ökade distributionskostnaderna genom lägre värmeförluster och dessutom förbättras förutsättningarna för att ta tillvara på förnybar och återvunnen värmeenergi.

De två utmaningarna nämnda ovan har sitt ursprung i början (värmetillförsel) och i slutet (värmebehov) av systemet. Men, vilka är förutsättningarna däremellan som tillåter det framtida fjärrvärmesystemet att drivas med lägre temperaturnivåer? Det är en av aspekterna som undersökts i denna avhandling. Lägre returtemperaturer är den i särklass mest intressanta variabeln i detta avseende, eftersom sänkta returtemperaturer är styrvariabeln till lägre temperaturnivåer.

Tre lämpliga teknikförändringar har identifierats för att nå lägre temperaturnivåer. Dessa är trerörssystem, lägenhetscentraler och förbättrade värmeväxlare.

I dagens fjärrvärmesystem finns ett inbyggt temperaturfel som beror på behov av varmhållning i distributionsnätet för att säkerställa komfortkrav fram till kund. Sådan varmhållning förekommer mest under sommaren då värmebehoven är låga. Eftersom dagens system endast består av två ledningar, en fram och en retur, måste varmt vatten blandas med avkylt returvatten. Detta kan ses som ett inbyggt kortslutningsflöde, vilket leder till förhöjda returtemperaturer. Genom att introducera ett litet extra tredjerör i distributionsnätet kan varmhållningen separeras vid behov och därmed undviks förhöjda returtemperaturer.

Varmvattencirkulation som finns i flerbostadshus har identifierats som ett potentiellt problem med avseende på att nå låga temperaturer. Eftersom temperaturen på varmvattencirkulation inte får understiga 50°C kan fjärrvärmereturen aldrig komma under 50°C, vilket är direkt olämpligt om fjärde generationens temperaturer ska nås. För att eliminera behovet av varmvattencirkulation i flerbostadshus föreslås lägenhetscentraler. Den nuvarande arbetshypotesen är att styrning av separation för varmhållning till tredjeröret underlättas när ingen varmvattencirkulation förekommer. Dessutom (i) minimeras risken för Legionella i tappvarmvattensystem som inte använder varmvattencirkulation och lokala värmelager, (ii) behovet av kostsam injustering minimeras då lokala uppvärmningssystem introduceras på lägenhetsnivå, (iii) kunden kan i större utsträckning välja innetemperatur, (iv) kunden kan debiteras på individuell nivå och (v) möjligheten att identifiera olika temperaturfel förbättras.

Funktionen på värmeöverförande ytor kan beskrivas med det dimensionslösa talet termisk längd (NTU, Number of Transfer Units), där ett högt värde är bättre. Genom att kräva längre termisk längd i värmeöverförande komponenter kan likvärdig värmeöverföring uppnås med lägre temperaturnivåer. Förutsättningarna för tillverkare av exempelvis värmeväxlare specificeras av i detta fall vilka förväntningar som tidigare angavs av branschorganisationen Svensk Fjärrvärme. Under 1960-talet resulterade temperaturkraven för värmeväxlare i en termisk längd på 2, idag är resulterar motsvarande temperaturkrav i en termisk längd på 4. I framtiden kan temperaturkrav anges så att en termisk längd på 8 erhålls. Det viktiga är att branschorganisationen sätter nya krav på längre termisk längd, så att samtliga tillverkare verkar på en marknad under lika villkor.

Genom analys av föreslagna förändringar har returtemperaturer på årsmedelbasis i storleksordningen 17-21 °C påvisats. Idag finns det ännu inget existerande system som nått under 30 °C i årsmedelreturtemperatur.

Under senare år har introduktionen av förnybar elomvandling, huvudsakligen från vindkraft lett till pressade elpriser på den nordiska elhandelsmarknaden. Detta har resulterat i ett ökat intresse att använda stora värmepumpar och direktverkande elpannor för att leverera värme i fjärrvärmesystem, internationellt benämnt power-to-heat. Delvis beroende på kostnadseffektivitet, men även som ett sätt att balansera elsystemet för att på så sätt möjliggöra ytterligare introduktion av förnybar elomvandling. En del av detta avhandlingsarbete har handlat om att sammanställa information om den unika erfarenhet som Sverige har sedan 1980-talet av att använda stora värmepumpar och elpannor kopplade till fjärrvärmesystem. I samband med utbyggnad av kärnkraftverk i Sverige översteg den potentiella tillförseln marknadens efterfrågan med stora marginaler. För att få avkastning på investeringen infördes gynnsamma förutsättningar för expansion av värmepumpar och elpannor, vilket ledde till att några av världens största värmepumpar kopplade till fjärrvärmesystem byggdes i Sverige. Dessa har varit i kontinuerlig drift under tre decennier och används fortfarande. Arbetshypotesen har varit att driftserfarenheten kan komma till intresse med avseende på samtida utvecklingstendenser.

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1 Introduction

Regardless of the price of a commodity or the looming uncertainty of high future societal costs due to anthropogenic climate change, efficient resource management should always be an aim in itself. Humankind has almost always historically been dependent on efficient resource management for its survival, especially regarding the accessibility to nutrients in off-growing seasons, to water, and to heat and shelter. Following the Second World War, many nations have experienced thriving economies fuelled by globalisation (and fossil fuels) and, along with this, thriving populations. In these prosperous times, many types of technological infrastructure and hardware, such as easy access to fresh water, convenient access to central heating in buildings, and introduction of improved electric appliances (e.g. refrigerators and freezers) have improved living conditions for millions of people. All these improvements have made us a little less dependent on the resource-efficient mindsets that were imperative for our very survival just a few decades prior. This unparalleled change in our living conditions can be presumed to have affected the methods applied regarding resource-efficient behaviours. This change in society can casually be linked to the developments that sometimes are referred to as a wear-and-tear or throwaway society.

This thesis covers various improvement aspects of a technology that is fundamentally connected to resource-efficient management: district heating. Under local conditions, district heating supplies heat to customers by circulating hot water in pipes between supply and demand, which is heat that is commonly recovered residual heat from society and has little to no other practical use because it is difficult to use low-temperature heat in any other meaningful way. In a scenario without district heating systems, residual heat from society is dissipated into the environment. Hence, heat is being recovered and used one more time, which is considered efficient resource management that is in a development direction opposite to the throwaway society.

Thus, district heating connects to the nature of a rational mindset regarding efficient resource management, or in other words, does more with less. Hence, district heating systems have a very important recycling function in our current energy system.

In concrete terms, use of district heating primarily offers a decrease in the primary energy supply in the overall energy system. As an extension to the previous statement, the dependency on energy import decreases, which results in lower system costs. Furthermore, the strain on available energy resources decreases. Finally, less environmental impact is achieved.

Contemporary work with research and development for future district heating systems is referred to as the fourth-generation district heating (4GDH) systems (see definition Paper [14]). One of the proponents for this research topic is Professor Henrik Lund at Aalborg University in Denmark, who came up with the proverb regarding district heating and future developments, which is '*District heating is here to stay, but district heating has to change*'. This proverb rests upon layers of extensive modelling

conducted throughout different research projects, perhaps most prominently the Heat Roadmap Europe projects.

Lund's proverb constitutes a major cornerstone of this thesis and the overarching PhD project in general, specifically; the part about district heating needs to change. However, in what way is this change supposed to materialise, and why? These are knowledge areas covered in this thesis.

During the PhD project, a trend has become apparent: the work towards change often limits itself to a conventional framework of technology. In this thesis, it is argued that residing inside conventional frameworks will be insufficient; thus, less-conventional solutions have been analysed.

1.1 Purpose and Scope

The purpose of the work presented in this thesis is to explore various aspects of low-temperature district heating systems. The knowledge framework for work that considers low-temperature district heating is referred to as 4GDH, which was defined in 2014 by Lund et al. [14]. The work carried out within the concept of 4GDH has since been revised in a status paper (2018) by Lund et al. [15]. By exploring various aspects of low-temperature district heating, there is a possibility that new ideas of improvement for future 4GDH heat distribution can be identified.

The scope of the research activities in this thesis is framed mostly within the field of 4GDH [14] but is also within the field of smart energy systems [16], which is closely related to 4GDH. The definitions for the smart electricity grids, smart thermal grids (district heating and cooling), and smart gas grids are reviewed [17]. Although implicitly included in the three previous areas, it is also possible to add a fourth part referred to as smart end-use. An elaborate description of smart energy systems is given in the following quote:

> Smart energy systems are defined as an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system [17].

The research in this thesis can be broadly separated into three categories. The first part considers aspects of the integration of electricity and heat. The second part considers technical enhancements of heat distribution to achieve lower system temperature levels in 4GDH. The third part considers the economic benefits of 4GDH.

1.2 Integration of Electricity and Heat

This part about the integration of electricity and heat relates to appended Paper [1] and appended Paper [5] as well as [6, 7]. The chronological order of this part is that Publication [6] was written first as an initial step towards Paper [1], and Publication

[7] was then a collaboration with Aalborg University in Denmark, wherein the results from Paper [1] were integrated. The final appended Paper [5] also relates to this topic.

From a historical perspective, a significant proportion of electric energy has been generated through steam-driven processes, wherein boiling water using fuels has been common. In the modern power system, this paradigm has become somewhat challenged from electricity generation where mechanical energy is converted immediately to electricity, as is the case of wind turbines for instance. Such electricity generation does not give rise to residual heat generation, as steam processes do. Furthermore, there has been a rapid introduction of intermittent renewable power sources (wind and solar power) in recent years. Because the price of electricity as a commodity is market driven, large and rapid introduction of intermittent renewable power supply has had a dampening effect on electricity market prices. In certain regions, according to statistics from Nord Pool, which is Europe's leading power market that operates across nine European countries, there have been a few hours with a negative hourly average electric price due to a high supply in relation to low demand.

In certain areas (e.g. Denmark), the rapid introduction of intermittent renewable power generation has started to compete with combined heat and power (CHP) plants, which has led to less annual operation time for CHP plants for electricity generation in certain regions and thus less heat as well. As current district heating systems are dependent on heat recovery from CHP plants (i.e. more operational hours equal more heat recovery opportunity), a tricky situation arises when the CHP plants are operated for fewer hours throughout a year. Simultaneously, overall electricity prices in such areas have been lower due to the increase of wind and solar power expansion. This has led to increased use of large electric boilers and large heat pumps connected to district heating systems among heat distribution utilities. This interaction between different energy systems is referred to as power to heat and is one of the three aspects considered in this thesis.

The idea of integration between different sectors, such as power and heat, is that it will allow the system to be more intermittent but still reliable and, thus, allow higher shares of renewable energy supply in a cost-efficient manner. This integration is a fundamental part of the concept of smart energy systems as described by Lund et al. in [17].

Some of the research work conducted in this part can be characterised as being of a historical nature. Sweden has a unique relationship with power-to-heat solutions in that such solutions have been used for a long period and this experience is largely unparalleled compared to all other countries. The reason behind this is the surplus of power generation capabilities introduced through the construction of Swedish nuclear power plants in the 1970s and 1980s. In the work presented for this part, Publication [6] focuses on the use of large electric boilers in Sweden. Appended Paper [1] focuses on the use of large heat pumps in Swedish district heating systems. Previously, no literature covering the overall unique Swedish situation of power to heat has existed. Now it does. The results from this study may become useful in relation to policy and

decision making regarding future power-to-heat installations. Publication [7] was a collaborative work focusing on power-to-heat installations in Europe.

1.3 Technology Improvement in Heat Distribution

This part about technology improvement in heat distribution relates to appended Papers [2] and [3] as well as Publications [8] and [9]. The chronological order of this part is that work on Publication [9] was initiated with funding from the Swedish district heating research programme (Fjärrsyn). As a part of this work, Publication [8] was a deliverable to disseminate the early results and has since been further developed into appended Paper [2]. Appended Paper [3] was then a continuation to establish additional details about the novel heat distribution technology. Publication [10] is parallel to the other work presented in this part and is about the transition between different generations of district heating technology; thus, it fits into this part.

Lower temperature levels are identified as a core feature of the 4GDH technology. The envisioned temperatures are around 50°C for supply and 20°C for return, without requiring any local auxiliary heating source to ensure comfort requirements. A brief discussion regarding achieving lower temperature levels regarding system functioning is elaborated in section 2.1. From this discussion, it is understood that the return temperatures are the major independent variable when the aim is to achieve lower temperature levels. In the present research, according to this part, the initially proposed research question was the following: 'If the conventional framework of heat distribution construction design were to be ignored to allow a greater degree of freedom when constructing a new district heating system in a new residential area, which improvements of current technology would be desirable to achieve lower temperature levels?'. In other words, if anything could be changed to obtain lower temperatures, what would it be?

This is the first attempt, to the author's knowledge, to conceptualise a comprehensive technological solution to achieve 4GDH temperature levels in new district heating systems for new residential areas. The enhancement of the technology as proposed consists of three major components. These are (i) three-pipe systems, (ii) apartment substations, and (iii) longer thermal lengths, which are further discussed in Chapter 4.

1.4 Economic Benefits

This part is about aspects of economic benefits with 4GDH heat distribution and relates to appended Paper [4] and Publication [11]. The chronological order of this part is that work on Publication [11] was written as an initial analysis that was later integrated with the analysis in appended Paper [4].

By improving and thus increasing the cost of certain system components in heat distribution, the overall total costs can be decreased. This has been identified in this research. Additional costs to improve distribution network, substations, energy

performance, and internal systems in buildings to reduce operating temperature levels can significantly reduce heat supply costs. The rate of this reduction has been identified for different heat supply sources in appended Paper [4].

The strongest economic benefits are found from heat supply with small or no variable costs, such as geothermal heat, solar heat, or heat pumps. These results are in contradiction to what seems to be a common misconception: that the economic benefits are derived from lower infrastructure investment costs and from reduced costs in less heat loss.

The value of reduced temperature levels is given by the temperature cost reduction gradient. This variable is described in the literature with the units [currency/(unit energy, °C)], commonly in the Swedish literature as [SEK/(MWh, °C)]. In this research, it is €/(TJ, °C)]. The composition of these units reveals a monetary value that depends on annual heat delivery and the difference in temperature levels. As each district heating system operates under local and individual conditions, the monetary benefit differs between systems.

For instance, if the value of lower temperature levels is low, then there is a low-temperature dependency from the heat supply, and in this case, benefits may come from reduced heat loss. However, if the value of lower temperature levels is high, then there is a greater temperature dependency from the heat supply, and in this case, the change in temperature levels may dictate the use of either a high-temperature fossil heat supply (high variable cost) or a low-temperature renewable or recycled heat supply (low variable cost). In this research, individual heat supply sources have been compared separately.

2 District Heating

District heating is a societal infrastructure that connects local heat sources with local heat demand. In a resource management perspective, this is a splendid construct because there is more heat loss in the world's total primary energy supply than there is in the final end-use [18]. It would not be possible to recover all this heat, but it is clear that there is heat available to recycle. For instance, in a city, municipal waste is being incinerated as a management method to handle waste. In this process, power generation can occur, shaving off the high-exergy content of the heating value of the waste. In addition, it is also possible to shave off the low-exergy content (the part that cannot be converted to electricity) as heat, if there is a means to distribute this heat to customers; thus, an opportunity for using the energy occurs twice. If the energy content is used twice (power and heat), the total demand for natural resources for energy purposes is lowered. This is beneficial for society for different reasons, such as less pollution, less extraction of natural resources, and less demand for import of energy.

A major drawback with district heating is related to its local nature and that heat distribution systems tend to end up in a natural monopoly situation, hindering competition and requiring functional pricing control legislation to ensure just customer conditions.

The overall system control function for district heating is described in [18] and consists of four different and independent control systems. The heat demand and flow control systems are located in each customer's substation and heating systems, while the heat suppliers are responsible for the centralised differential pressure and supply temperature control. A broad system classification for district heating is a division into four components: (i) supply, (ii) distribution, (iii) customer interface (substation), and (iv) demand side.

In addition, because district heating operates under local conditions, the technology has historically often been omitted from various types of comprehensive system analyses because reliable information simply has not been available. Prior to the Heat Roadmap Europe projects [19], the major focus in the assessment reports for the future energy system was based on energy demand reduction and electrification. However, through the Heat Roadmap Europe projects, it has been determined that equivalent reductions of greenhouse gases can be achieved at a lower system cost by also introducing district heating.

Since then, increasing interest among policymakers has been observed, partly through the engagement of the United Nations Environment Programme [20] and through the EU Strategy for Heating and Cooling [21, 22]. Introduction of district heating benefits greatly from dense city areas that allow more heat sales per unit of infrastructure required. This is referred to as linear heat density (heat delivery per trench length) [18]. The competitiveness for high heat density areas (cities) has been assessed by Persson and Werner [23], with results that indicate a relatively constant capital

distribution cost up to 60% to 70% of the market share in major European cities, and more recently, it has been assessed in a study with increased resolution [24]. In areas with lower heat densities, outside the competitiveness range of district heating, it is generally agreed upon that heat pumps constitute one of the more feasible heat supply technologies.

Today, about 13% of the EU heat demand is satisfied through district heating [19]. A substantial part of the heat supply is and has been satisfied through individual natural gas boilers. However, as pre-emptive steps are taken to reduce anthropogenic climate change and minimise dependency of energy imports, less use of fossil fuels is expected. Hence, district heating may be a suitable substitute to reduce the primary energy supply through heat recovery.

An intriguing aspect of district heating systems is their individual characteristics; each system operates under individual conditions. Significant variation exists in resources for heat supply, customer conditions, and distribution networks, which may have been expanded over several decades and are examples of individual variables that vary between systems. Hence, each system must be analysed individually.

One measure of such individualism is expressed in the pricing of heat delivery. Werner [25] compiled and analysed the price series for 23 different European countries with value-added tax excluded. These time series are presented as annual average district heating prices from 1980 to 2013. When the standard deviation is considered, the national variation becomes apparent. Furthermore, for Sweden, each system has its own price variation [26] due to the local nature of district heating businesses. Thus, it is probable that such national price variation occurs in each nation's district systems.

2.1 Fourth-Generation District Heating (4GDH)

In 2014, a definition paper for the 4GDH systems was published [14]. This paper defines five major abilities of 4GDH systems. These will be described further in this section. The major conceptual idea behind 4GDH is to operate systems with lower temperature levels.

As the title heading suggests, there are three preceding technology generations. These are partly connected to temperature levels and to the type of technology hardware. For instance, the first generation of district heating is defined as using high-temperature steam for heat distribution. The second generation uses hot pressurised water (>100°C). The third generation uses medium-temperature water (<100°C), whereas the fourth generation is expected to operate at temperature levels of 50°C supply and 20°C return, when no additional heat delivery appears in substations. Even lower supply temperatures are a possibility, but that would require local auxiliary heating to satisfy temperature requirements of domestic hot-water preparation. These systems are referred to as cold district heating systems. For further information about cold district heating systems, the reader is advised to read a review of such systems within Europe

[27]. This thesis does not consider this type of system configuration any further. The five identified abilities for 4GDH are supposed to do the following:

1. supply low-temperature district heating for space heating and hot-water preparation,
2. distribute heat with low grid loss,
3. recycle heat from low-temperature sources,
4. integrate thermal grids into a smart energy system, and
5. ensure suitable planning, cost, and motivation structures.

The first part of this thesis, which was presented in Section 1.2, relates to ability number four. The second part, which was presented in Section 1.3, relates to abilities one, two, and three, whereas the third part, which was presented in Section 1.4, relates primarily to ability five. A summary of the connection between the abilities of 4GDH and appended papers is shown in Table 1. The interconnection between the studied aspects of 4GDH and the abilities of 4GDH ties the thesis together.

Table 1. Summary of how appended papers in this thesis tie into the five abilities of 4GDH, abilites according to [14].

		Appended paper no.				
		1	2	3	4	5
Ability no.	**1. Supply low-temperature district heating to buildings.**		X	X		
	2. Heat distribution with low network grid loss.		X	X		
	3. Recycle heat from low-temperature sources and integrate renewable heat sources.		X			X
	4. Integration between electricity, gas, fluid, and thermal grids to obtain smart energy systems.	X				X
	5. Ensure suitable planning, cost, and motivation structures.				X	

2.2 Energy System Benefits of 4GDH

The energy system benefits of 4GDH reside within the opportunity to use heat supply sources that are limited or hindered by the requirements of high supply temperatures. If the system is operated with low temperature, these heat sources may be used or the level of use may be improved. Some of these heat supply sources are discussed in this section.

Lower system temperature requirements bring about more opportunities for heat recovery from industrial processes that are typically limited by an upper temperature, given by the industrial process. Similar conditions apply to geothermal heat sources, which are limited in temperature at different locations, and which can be used to a greater extent at lower supply temperature demands. At lower supply temperature requirements, the conversion efficiency is improved for solar thermal collectors. Lower supply temperature requirements also allow heat pumps to use ambient heat with less

electricity input. With lower return temperatures, heat recovery from flue gas condensation from combustion of moist fuels is improved, and at CHP plants, if steam is withdrawn at lower temperatures, a higher proportion of electricity can be generated. Furthermore, the overall distribution heat loss decreases [28].

2.3 Temperature Levels

In Section 2.2, a brief summary of the reasons for low-temperature operation is stated. The next step is to assess in what ways to achieve temperature reductions. One potential method is to initiate the assessment at the beginning of the system, represented in this case by heat supply, and move along to the end at the customer's heat demand. Let the amount of heat be represented by Q [J], the mass by m [kg], the specific heat capacity by c [J/(kg K)], and the temperature difference by Δt [°C] constituting a supply temperature t_s [°C] and a return temperature t_r [°C]. With these variables, the well-known basic expression for heat energy can be written as follows in Eq. (1).

$$Q = m \times c \times (t_s - t_r) \tag{1}$$

From the heat supplier's perspective, the supply temperature in Eq. (1) is the only variable accessible to manipulate the heat energy (Q) delivered because the central distribution pump managed by the heat supplier does not control the flow but the differential pressure in the system. Hence, heat suppliers have few options to influence variables other than the supply temperature. It would certainly be possible to lower the supply temperature at the cost of, among others, increased system mass flow rates. The extent to which experimentation with lowering supply temperatures occurs in heat distribution utilities has not been identified. However, it seems reasonable that good safety margins regarding the choice of supply temperature are put into place to ensure good public relations with customers and to follow legislation put in place to protect customers regarding the security of the supply.

Historically, the supply of high-temperature heat has been readily available and the use of high temperatures has eased network operation, as high supply temperatures generally mean lower network flow velocities and thus less distribution pressure drops, which ultimately result in less difficult differential pressure control. In this case, mathematical optimisation to minimise supply temperatures without compromising differential pressure control can be used. Such activities would lower supply temperatures, however, not in a way that would decrease the overall temperature levels, but rather in a way that would minimise supply temperatures because the choice of supply temperature has little to no influence on the level of return temperatures.

In a district heating system, the second component after supply is heat distribution. Temperature levels in distribution networks vary because of heat loss. This variation is typically in the range of a few degrees Celsius between the location of heat supply and a customer located in the periphery of the distribution network. The heat loss is related

to a temperature drop in both the supply and return pipes. This results in a supply temperature at the heat production facilities that is slightly higher than what the customer's request. The rate of heat loss depends on the temperature difference between the distribution pipes and the environment. Thus, lower temperature levels generate less distribution pipe temperature drop. Hence, there is a self-adjusting mechanism involved in this regard, which decreases the difference between temperatures at central supply and at customers' substations.

Furthermore, distribution networks use bypasses in the network. This should typically be the supply to return connections with a thermostatic valve (in ideal cases). This solution is put into place to maintain sufficient flow velocities when heat demands are low (summer nights mostly). These bypasses increase return temperatures and can occur unintentionally and intentionally. Intentional bypasses (also referred to as embedded temperature errors) have constituted a major part of Paper [2] and will be discussed further in Section 4.1.1.

The two last parts of the system consist of the customer interface (substation) and demand side (customer heating system), sequentially. These are treated simultaneously because these two parts of the system generate the resulting return temperatures. Because the two parts, in essence, yield the resulting return temperatures, it is of utmost importance that these operate with impeccable functioning, if 4GDH operating conditions are to be obtained. If the return temperatures can be lowered, then the supply temperature can follow while still maintaining equilibrium in heat supply according to Eq. (1). Thus, the key to lower temperature levels is found in lowering the return temperature because return temperatures are generated regarding the functioning in substations and customer heating systems. This issue has been further addressed by Gadd and Werner [29]. Within that paper, data on the annual average temperature levels from 2004 to 2010 for 142 Swedish district heating systems are presented. The average supply temperature for Swedish district heating systems is 86.0°C, whereas the average return temperature is 47.2°C. The ideal temperature levels of the third generation district heating systems have been analysed to supply 69°C and return 34°C [30].

A representation of return temperatures from substations in single-family buildings can be seen in Figure 1, and for multi-family buildings, it is shown in Figure 2. Both are based on annual averages and are from the district heating network in Helsingborg, Sweden. It is interesting to note that no major difference in the return temperature, which is close to 40°C, between single-family and multi-family buildings occurs. Furthermore, it is clear that a significant variation occurs between the substations with the highest and lowest annual average return temperatures. The annual average return temperatures of the whole system are generated mostly by substations, but some of the return temperature increases are generated due to bypasses in the distribution network, both intentional and unintentional.

Because of future new buildings (as well as renovated existing ones) with lower heat demands, design temperature requirements for space heating can be decreased. In this

sense, new energy-efficient buildings constitute a self-adjusting mechanism for lower temperature levels.

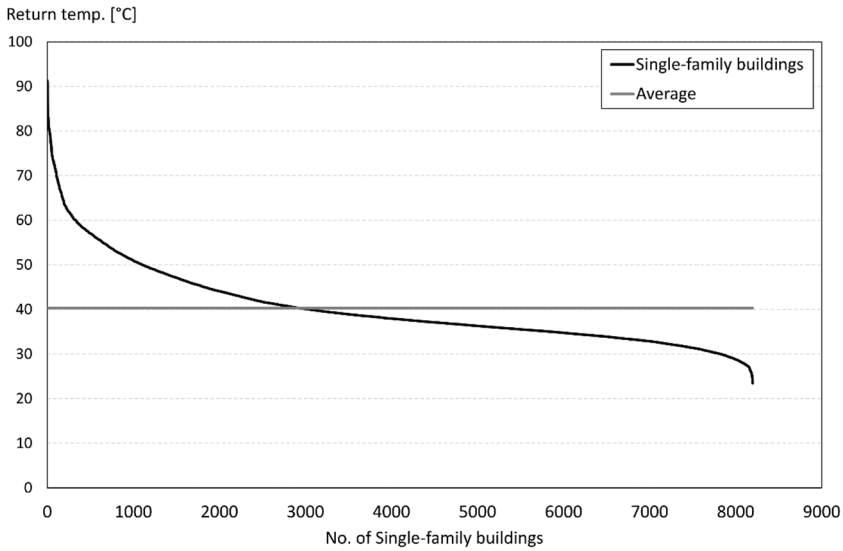

Figure 1. Annual average return temperatures from single-family buildings in Helsingborg, 2016. Source: Henrik Gadd, Öresundskraft, Helsingborg, reproduced with permission.

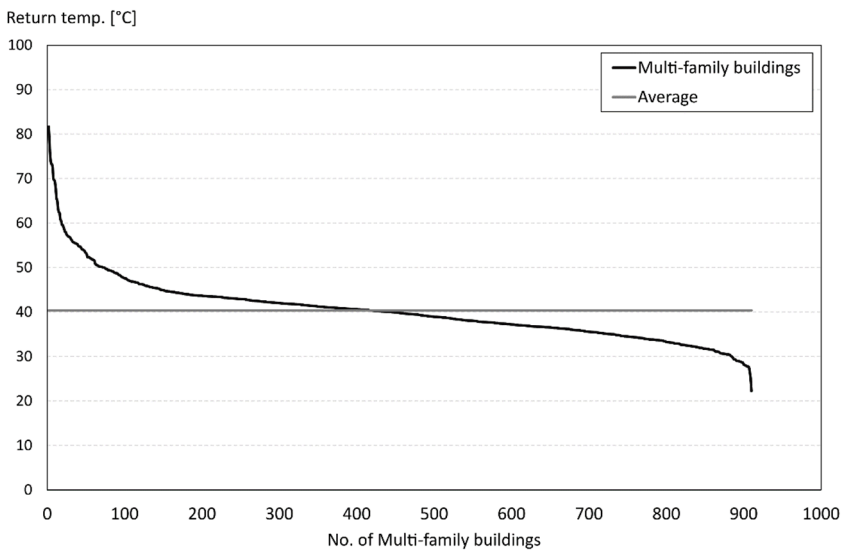

Figure 2. Annual average return temperatures from multi-family buildings in Helsingborg, 2016. Source: Henrik Gadd, Öresundskraft, Helsingborg, reproduced with permission.

3 Future Challenges

3.1 Less High-Temperature Heat Supply

The design of the current district heating systems relies heavily on heat supply from sources that can generate high temperatures with ease. In this section, three energy sources of high-temperature heat supply are discussed. These are fossil fuels, societal waste, and biomass. In addition, why these heat sources may be less available in the future is discussed, indicating that a new design of district heating systems is required to facilitate this change.

Ever since 1992, when the United Nations Framework Convention on Climate Change (UNFCCC) was established, a scientific consensus has prevailed regarding (i) climate change taking place and (ii) the likelihood that anthropogenic emissions of greenhouse gases are the cause. The work within the UNFCCC has led up to the international treaty of the Kyoto Protocol in 1997, in which state parties have ratified and committed to reducing greenhouse gas emissions [31]. With the risk of unprecedented societal costs [32], it seems only reasonable that our current energy systems aim to shy away from the use of fossil fuels. In the current energy systems, fossil fuels constitute a significant source of high-temperature energy supply. If this component is removed, fewer high-temperature sources remain.

Today, societal waste is treated differently between countries with respect to the amount and method of management (i.e. landfilling, incinerating, composting, or recycling). A representation of data regarding this was presented by Persson and Münster [33], from which it is identified that there has been an increase in the generation of municipal solid waste during the previous decades and that the future projection indicates a further increase up to 2030 within in the EU. However, in Directive 2008/98/EC on waste [34], the EU waste hierarchy is defined, and the hierarchy is divided into five categories where energy recovery through incineration is the second-least favoured option. The least favoured option is the landfill, and if this option were to be banned, then energy recovery through waste incineration would be the least preferred alternative, second after recycling, reuse, and reduction of waste generation. When observed from an ideal long-term perspective, one can presume that the policy of the waste directive will resolve with noticeable effect. If this turns out to be the case, then less availability of high-temperature heat recovery from waste incineration is expected because heat recovery through incineration is a prominent source of potential high-temperature heat supply.

In addition to the two previous high-temperature heat sources that are fossil and semi-fossil (societal waste) in origin, the option of renewable high-temperature heat supply originating from biomass incineration also exists. Biomass is a renewable heat source because the carbon cycle is considered to be about a century (which is a considerably shorter time perspective compared to the formation of fossil fuels).

Availability of biomass varies between countries; for instance, Sweden and Finland have good forest biomass natural resources, while other countries might have significantly fewer such natural resources [35]. Ericsson and Werner have authored a paper that introduces the aggregated Swedish use of biomass within the district heating sector [36].

Increased competition for biomass feedstock is expected. This competition is anticipated to be composed of actors with greater ability to pay for the biomass resources compared to the district heating utilities. Examples of competing activities may include conversion of biomass into renewable fuel for the transport sector and manufacturing of new composite materials to replace fossil components in contemporary plastics [37]. An analysis in this regard has been performed for the Swedish energy system with a time perspective of 2030 and 2050 [38]. Use of biomass within the heating sector may become less economically viable due to the increased market competition of feedstock in the future, resulting in less high-temperature heat supply originating from biomass. However, the possibility of industrial excess heat recovery from the industrial activities that compete for biomass feedstock could facilitate this transition.

In all likelihood, the availability of a high-temperature heat supply may be limited in a future scenario. Therefore, it is practical for other system components (distribution, customer interface, and demand) to also adapt to the changing conditions. This is especially important to ensure, as new infrastructure and distribution networks will remain in operation several decades into the future.

3.2 Lower End-use Heat Demands

Lower heat demands are anticipated from future new buildings and from existing renovated buildings within the EU. Due to the Energy Efficiency Directive (EED), Directive 2012/27/EU of the European Parliament and of the Council [39], a common framework of measures has been established to promote energy efficiency within the EU to ensure that the target efficiency increase is met. The EED has since been revised by Directive (EU) 2018/2002 of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency, increasing the temporality of the efficiency target from 2020 to 2030. Organisationally subordinated to the prior directive is the energy performance of buildings directive (EPBD), Directive 2010/31/EU of the European Parliament and of the Council [40], which further aims at introducing policy frameworks to achieve target efficiency increase. The policy framework can be broadly summarised as being comprised of the following six components:

i. a common framework for calculating energy performance in buildings,
ii. minimum requirements for the energy performance in buildings,
iii. national plans to increase nearly zero-energy buildings,
iv. energy certification,

v. inspection of heating and air conditioning systems in buildings, and
vi. independent control systems for energy performance certificates and inspection reports.

The EPBD has also recently been revised by Directive (EU) 2018/844 of the European Parliament and of the Council on 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Further details regarding the amendments for both directives are not covered in this context but can instead be found at the European Commission's webpage about the Energy – Clean Energy Package.

With such strong policy measures, it appears safe to assume that there will be improved energy performance in future buildings, resulting in lower customer heat demands for space heating. This change has been conceptually illustrated in Figure 3, where specific space heating demands [W/m^2] can be observed for a contemporary, energy-inefficient building and for a future energy-efficient building. There are two matters to observe: (i) the specific space heating demand becomes much lower at colder outdoor temperatures for future energy-efficient buildings compared to contemporary buildings and (ii) the intersection at which the space heating operates shifts to a colder outdoor temperature. This intersection is commonly referred to as the building balance point temperature; at this point, the internal heat gain is equal to the building heat loss.

A lower building balance point temperature increases the hours of a year that intentional bypasses may occur and thus energy-efficient buildings magnify the problem of increased return temperatures due to more bypasses. This is an important aspect covered in Paper [2]. Hence, improved energy efficiency is anticipated to worsen the issue of distribution network circulation and thus increase the importance of a strategy to manage the distribution network circulation.

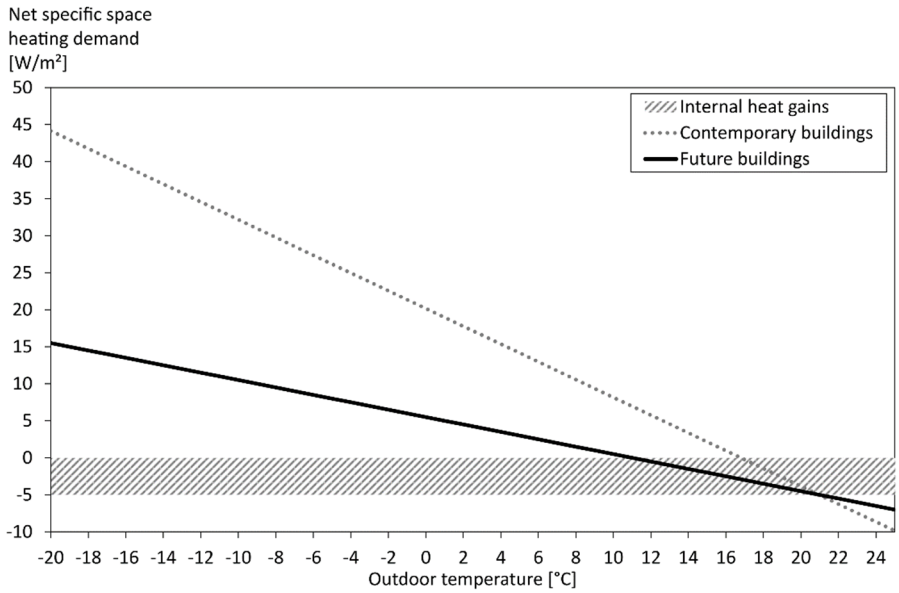

Figure 3. Specifications of thermal performance for a building's specific space heating power demand (W/m²), according to the analysis in Paper [2] for both the contemporary case and the future case. The internal heat gain is added as a negative value because it does not contribute to the net specific heating demand due to the lower slope coefficient in buildings with higher thermal performance. From the slope coefficient, it is clear that the balance point temperature is different because the internal heat gain is sufficient at lower outdoor temperatures. Specific heating demand for domestic hot preparation is omitted in the figure.

3.3 Higher Share of Intermittent Renewable Electricity

As a future challenge for the overall energy system, focusing power systems is the ability to manage the integration of a new renewable energy supply without compromising grid stability. Renewable electricity supply from wind and solar power is unpredictable due to weather dependency. Hence, the large-scale integration of wind and solar power, results in greater challenges for transmission system operators to keep the power system grid-frequency within ±0.1 Hz.

This issue occurs both in times of the surplus and deficit of power. One solution for grid management is to use energy storage. If the power system is integrated with the heating system, then a cost-effective method for managing oversupply in power systems emerges. Power-to-heat integration through large heat pumps, electric boilers, and heat storage may advantageously be used to manage the introduction of a more intermittent renewable electricity supply (e.g. see ref. [41]). For a more comprehensive literature collection, the reader is advised to look in the literature review of Paper [1].

3.4 Temperature Errors

It is common knowledge within the district heating industry that lower temperature levels are beneficial. Yet, achieving low-temperature operation has proven elusive. No known documentation of a system with an annual average return temperature below 30°C has been identified. Some new district heating areas have almost achieved an annual average return temperature of 30°C in the IEA report on 4GDH information for seven district heating areas that have been analysed [28].

The perceived major causes of difficulties in achieving lower temperature levels are the different kinds of temperature errors. During 1992 to 2002, the inventories of 246 substations yielded 520 temperature errors of various kinds [18]. This historical knowledge of temperature errors has also been further elaborated in [10].

In addition to the previous knowledge of temperature errors, more recently, PhD Henrik Gadd at Halmstad University has performed research on hourly measurement data from substations [42] to acquire knowledge about methods to identify temperature errors. In his analyses, he concluded that three-quarters of heat deliveries occur with some form of temperature error [43] and that, to quickly identify temperature errors, it is necessary to learn more about individual customer heat demands in combination with introducing continuous commissioning by increased use of information and communication technology. Work in this field is ongoing, such as working on methods to analyse large datasets. One such method is the data-driven approach for discovering heat-load patterns in district heating [44]; another is the work performed by NODA Intelligent systems on trend analysis to automatically identify heat program changes [45], and a third is a work on smart energy grids [46] by Utilifeed, just to name a few. Furthermore, an interview and survey study among Swedish district heating utilities has identified that obtaining low return temperatures in existing systems is feasible by, for instance, having physical access to customer installations [47].

3.4.1 Embedded temperature errors

Aspects analysed in this research do not have a major focus on actual temperature errors but instead emphasise the embedded temperature errors that exist within a system, the technical system improvements, and the potential methods to address system-embedded temperature errors. In this thesis, three system-embedded temperature errors are identified.

First, district heating distribution networks circulate water when heat demand is low due to comfort requirements, resulting in increased return temperatures, which is therefore considered an embedded temperature error. Second, domestic hot-water circulation in multi-family buildings is used for comfort and hygiene. Since hot-water circulation is regulated by a minimum allowed temperature (50°C according to building regulations in Sweden [48]) this is considered an embedded temperature error because the primary return temperature during heat transfer never can be less than 50°C

in the case of Sweden. Third, the temperature difference between two flows in a heat exchanger reaches a certain level. This is considered an embedded temperature error because this temperature difference could be halved if the industry manufacturing requirements for heat exchangers were stricter, which would cut system temperature level requirements correspondingly.

3.4.2 Characteristic return temperature

In Figure 4, the data points concerning the daily average return temperatures from a Swedish district heating system are plotted. The time-weighted annual average return temperature, in this case, corresponds to 47°C, which is about the same as the Swedish annual average [18]. In addition, when plotting a second-order polynomial trendline, a very characteristic trait of district heating return temperature is displayed. This trait is increasing return temperatures at higher outdoor temperatures, indicating either temperature errors or embedded temperature errors.

Even in new systems that aspire to obtain the 4GDH temperature characteristics, the issues of increasing return temperatures at higher outdoor temperatures should prevail. This issue is illustrated in Figure 4 by the dashed line referred to as the without (w/o) circulation management, where information about seven relatively new installations of district heating systems has been compiled and analysed [28]. In these systems, the annual average return temperature was 36°C, with a span between 32°C and 44°C. Hence, the polynomial curve has been lowered to obtain a time-weighted annual average return temperature of 36°C. This temperature level is to be considered quite good performance.

Finally, an estimation of what the real return temperature curve may look like is drawn in Figure 4. In this case, no temperature errors nor embedded temperature errors are presumed to be in place. Based on the estimation, the time-weighted annual average return temperatures yield a value of 26°C. This indicates that an annual average return temperature below 30°C should be attainable and that reaching the 4GDH target return temperature of 20°C might continue to prove elusive for quite some time to come.

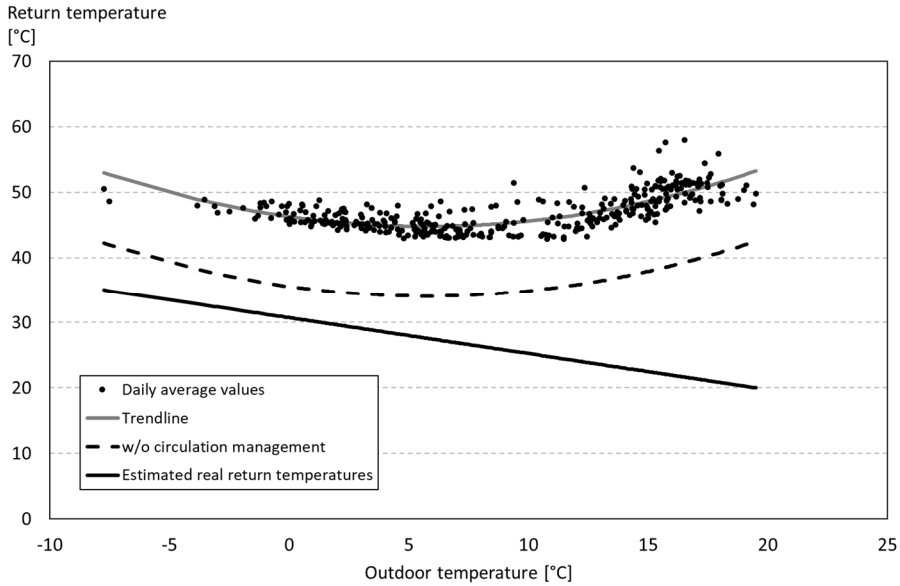

Figure 4. Typical daily average return temperature values in a Swedish district heating system (including the trendline) along with an approximate trendline for new heat distribution systems without (w/o) any strategy to manage network circulation, and an estimated value of the real system return temperature. The final step of longer thermal lenghts in heat exchangers is not included for the estimated real retun temperature. Source data obtained from Henrik Gadd, Öresundskraft, Helsingborg, Sweden.

4 Components of Change

4.1 Three Technical Improvements

The research presented in the second component of this thesis has taken the approach of examining potential technical improvements by observing the system from a perspective beyond the conventional framework of the technology. Considerable interesting research about low-temperature district heating exists. However, most of this research attempts to reach low-temperature operation within the existing technology framework. For instance, in a guideline document on low-temperature district heating, the main focus is on existing buildings [49]. By assessing conceivable potential improvements, three major components of technical enhancement have been assessed as important to achieving low-temperature operation in future district heating systems. These are (i) three-pipe systems, (ii) apartment substations, and (iii) longer thermal lengths. These are described further in the three following subsections. This work is the first occasion of a collective attempt to assess the overall approach to achieving future low-temperature district heating systems consisting of less-conventional technology. Furthermore, the perceived risks of introducing the three technical improvements in future systems are small.

4.1.1 Three-pipe systems

Three-pipe systems address the issue of embedded temperature errors that exist in the current heat distribution design. Today, the supply temperature drop is counteracted by intentional recirculation of supply temperature flow into return temperature flow to maintain system functioning. When this occurs, it increases return temperatures. A supply temperature drop occurs when there is no flow rate in the distribution network, which occurs when there are no heat demands. As space heating demands are continuous, a recirculation situation is most likely to occur when the outdoor temperature exceeds the level required for comfort reasons with respect to the indoor temperature. In old buildings with poor energy performance, this has only been an issue during a small number of hours throughout the year. However, as buildings have higher energy performance, the required outdoor temperature at which space heating occurs becomes lower (Figure 3); therefore, the issue of recirculation occurs for more hours during a year.

4.1.2 Apartment substations

Apartment substations address the issue of embedded temperature errors that exist in the current heat distribution design. Today, return temperatures from buildings with domestic hot-water circulation are high due to the temperature requirements for hygienic reasons. The elimination of secondary domestic hot-water circulation through

apartment substations allows lower return temperatures to be achieved. Using apartment substations allows an improved option for customers to choose the indoor temperature individually and allows better possibilities to charge customers on an individual basis, which is in line with the legislative text from the EU Energy Efficiency Directive [39].

4.1.3 Increased thermal length

Increased thermal length in heat exchangers addresses the issue of embedded temperature errors that exist in the current heat distribution design. Today, the logarithmic mean temperature difference between two flows of a heat exchanger is higher than necessary. Heat transfer is dependent on flow resistance. If the distance between the plates in a heat exchanger were to be narrower, then a larger pressure drop and thus a better heat transfer would be achieved. However, to avoid a large pressure drop over the component, additional plates should be installed. This makes the heat exchanger wider. Additionally, it is argued that this change needs to be prompted by the national recommendations for temperature requirements of heat exchangers for new installations because it is unreasonable to expect the manufacturing industry to ensure component improvements at the risk of impaired market competition. Still, the company Danfoss, for instance, are actively engaging in this development towards low-temperature district heating [50]. This change is also deemed feasible because the counter-flow plate heat exchangers used today are very compact and the manufacturing process is automated. Hence, from a space limitation perspective (within the substation), the cost increase from the use of additional material should not be a major barrier. Finally, the design recommendations in Sweden for thermal length have been improved in intervals since the 1960s [10]. However, the last time the recommendations for the thermal length were revised was during the mid-1990s. These recommendations consider heat exchangers in substations. Perhaps there should be new policies that encourage recommendations of a similar nature to apply when selecting the design for customer heating systems in the future to ensure that, in that part of the system, the heat transfer areas result in smaller temperature differences.

4.2 Additional Aspects of Changes

In addition to the three major changes discussed in Section 4.1, some additional aspects of change are regarded as synergistic add-on benefits from the three major changes.

4.2.1 Legionella

Ever since the first recorded outbreak of Legionnaires' disease in 1976, the introduction of various legislative guides and recommendations has been introduced to prevent outbreaks [51]. The design of the current heat distribution systems relies on high-temperature heat supply. Indirectly, this characteristic has been transferred to

installations for domestic hot-water preparation and is in legislation. Regulation for domestic hot-water preparation is applied on the national level. In Sweden, for instance, the legislative text reads that domestic hot-water circulation temperature never should be less than 50°C and in case of local heat storage temperatures should not be less than 60°C [48].

Thus, to reduce temperature requirements from future system design, the use of domestic hot-water circulation and local heat storage should be eliminated. A document on technical recommendations for the prevention of Legionella growth in installations inside buildings conveying water for human consumption was published by the European Committee for Standardization (CEN) [52], which defines a specification for a domestic hot-water preparation installation without any temperature requirements. This installation excludes domestic hot-water circulation and local secondary energy storage. Within this context, another common regulative text is German legislation by the Deutscher Verein des Gas- und Wasserfaches (DVGW) on domestic hot-water consumption and installations, which defines the three-litre 'rule' for small installations (implicitly understood as no use of domestic hot-water circulation) [53].

Different methods for Legionella management exist [54]. Different treatment methods typically increase system complexity, while the elimination of domestic hot-water circulation should keep the system complexity relatively constant. Furthermore, the idea to reduce Legionella through the elimination of secondary domestic hot-water circulation has been explored by Yang et al. [55]. The method to achieve domestic hot-water installations without circulation and local storage is through directly connected apartment substations.

4.2.2 Hydronic balancing

Balancing of hydronic space heating in multi-family buildings (i.e. manually ensuring that every valve setting is correct) to avoid overflows is a nearly impossible task to achieve or at least to maintain over longer periods. Today, overflows in radiators are presumed to occur frequently. However, this is typically considered a small problem because it does not have any meaningful effect on customer comfort because increased return temperatures are the only effect. In a survey collecting actual temperature levels from 109 radiator systems in the Gothenburg district heating system, at a design outdoor temperature of -16°C, the average values for supply and return temperatures were 64°C and 42°C [56].

The introduction of apartment substations should minimise temperature errors caused by overflows in space heating systems, as the formerly building-wide hydronic systems are divided into apartment-wide subsections instead. In addition, most radiators should be equipped with thermostatic radiator valves. Such valves function (hopefully) as an on/off switch for radiator flows but do not necessarily maintain a sufficient volume flow rate at the minimum required. A component that would alleviate

the issue of overflows would be a flow limiter at the outlets of the individual radiators, limiting flow as a function of the actual outlet temperature.

In research performed by Østergaard and Svendsen, it has been shown that radiator systems in existing buildings often have been oversized and, thus, are able to supply heat at low temperatures, as is the case of the analysed existing single-family buildings in Denmark constructed around the 1900s [57], 1930s [58], and 1980s [59].

4.2.3 Improved temperature error identification

Due to the requirements of hourly measurements in metering and the remote collection of metering data, large quantities of metering data are available. A possibility to analyse metering data to determine heat-load patterns arose, and such data have been analysed by Gadd and Werner [60] to determine (i) what is an expected heat-load pattern from a given customer category and (ii) where the outliers are regarding what is to be expected (i.e. which metering data give an indication of temperature errors).

If apartment substations were used in multi-family buildings, then metering data could be collected at an individual level. This would increase the resolution at which temperature errors could be identified, but also would increase the amount of collected data. Acting upon such a dataset could be done in collaboration with colleagues from the computer science discipline, as is exemplified by work with online machine-learning algorithms [61], for instance, or by the development of a controller based on self-learning algorithms [62].

5 Appended Papers: A Brief Summary

5.1 Appended Paper [1]

Paper [1] is about the unique experience of power-to-heat systems in Swedish district heating systems since the 1980s. Due to the rapid introduction of intermittent renewable electricity supply in the energy system, an increased necessity for power-system balancing capacities has appeared, and large-scale conversion of power to heat in electric boilers and heat pumps is a feasible alternative to achieve such balancing capacities.

The analysis of this unique Swedish experience with large heat-pump installations connected to district heating systems shows that, since the 1980s, 1527 MW of heat power has been installed, and about 80% of the capacity was still in use in 2013. Thus, a cumulative value of over three decades of operation and maintenance with large power-to-heat installations exists within Swedish district heating systems.

5.2 Appended Paper [2]

Paper [2] is about the analysis of the temperature situation in future new district heating systems constructed in new residential areas using the proposed technical solution, which consists of three components: (i) three-pipe distribution networks, (ii) apartment substations, and (iii) longer thermal lengths for heat exchangers.

First, intentional bypasses (temperature contamination) are identified as a growing issue in buildings with high-energy performance. A technical solution to address this issue is proposed. In the current system technology, the supply temperature water is mixed with return temperature water (common return). The strategy consists of the separation of flow rates caused by intentional bypasses (recirculation return) and flow rates that are heat delivery to the customer (delivery return). Second, hot-water circulation in buildings is considered to constitute a small but continuous source of delivery flow that occurs throughout the year and that generates much higher primary side return temperatures in relation to that aimed for by 4GDH. To alleviate the control of separation between recirculation and delivery return, the elimination of hot-water circulation is desirable. This is achieved by apartment substations in multi-family buildings. This is the natural connection between the two first parts of the proposed technical solution. Third, an increased length in heat exchangers, both in substations and in secondary heating systems, is essential to further decrease the temperature levels because it would increase the heat transfer and, thus, the temperature difference in the heat exchanger, allowing lower supply temperatures with equal heat transfer.

The results of the annual average return temperatures for the analysed case areas show significant potential in the return flow separation. The common return temperature situation is analysed under 4GDH supply temperature conditions and is

thus referred to as the two-pipe 4GDH (4GDH-2P). In this case, the annual average return temperature for the contemporary case is 28°C to 30°C, whereas, for the future case, it is 38°C. The corresponding range for the three-pipe 4GDH (4GDH-3P) for the contemporary case is 21°C to 24°C, and for the future case, it is 15°C to 22°C.

This concludes that (i) without a strategy for temperature contamination (i.e. common return), the annual average return temperatures will increase with improved building energy performance. Moreover, (ii) the temperature benefit of improved heat exchangers decreases in the case in which no strategy for temperature contamination is introduced because a significant proportion of the flow volume will flow through as a by-pass. Finally, (iii) with a strategy against temperature contamination, the annual average return temperatures might be as low as 20°C in buildings with improved energy performance.

5.3 Appended Paper [3]

Paper [3] is a continuation of the novel heat distribution technology that focuses on sizing assessment of the third pipe for recirculation purposes. The sizing assessment considers heat loss, which benefits from smaller pipes and pressure loss, which is limiting concerning smaller pipes. Hence, there is a semi-optimal choice of pipe size for the third pipe related to the standard sizes of pipes. The problem was assessed with standard dimensions of steel pipes and with the third pipe being co-located within the same casing as the supply pipe and return pipe.

For the single-family housing area that was the basis for the study, it was found that a third pipe for recirculation purposes can be two to three standard sizes smaller than the supply and return pipes without compromising the system concerning increasing pressure loss. This is due to the considerably small flow rate required to maintain quality in heat delivery. Meanwhile, heat loss is found to remain at a level that is within the same order of magnitude related to ordinary twin pipes.

Using the smallest pipe possible is beneficial regarding minimising heat loss. However, the third pipe for recirculation could also facilitate heat deliveries from prosumers; such heat delivery could then vary in temperature without major negative consequences because the third pipe does not influence the main supply and return functioning of the system. Such a configuration has not been assessed and would most likely benefit from using larger third pipes than what is recommended in this paper.

5.4 Appended Paper [4]

Paper [4] is about assessing the economic benefits of 4GDH systems. The assessment compares a figurative district heating system in a medium-to-large city, using climate data corresponding to a location in central Europe (Strasbourg).

Heat supply costs have been modelled individually for various heat supply sources at both 3GDH and 4GDH temperatures. Hence, the change in heat supply costs for each

analysed heat supply source was identified. With information about heat supply costs at two different temperature levels in addition to a predetermined annual heat delivery and the annual average temperature difference, the cost reduction gradient [€/(TJ, °C)] was determined.

It was identified that the heat supply sources that can be considered feasible future options for heat supply (this includes geothermal heat, industrial excess heat, and heat pumps) have a high cost sensitivity, indicating significant monetary values when moving towards lower operating temperatures in district heating systems. In contrast, the heat supply sources that are considered traditional and are commonly in practice today (this includes waste and biomass combined heat and power) have a low cost sensitivity, indicating much less significant monetary values with reduced operating temperatures.

With this information established, it is observed that an odd situation arises, where the motives of the current traditional district heating systems to strive towards lower operation temperatures are weak due to the heat supply sources in place. Alternatively, the future heat supply sources rely heavily on lower operation temperatures resulting in a contradictory situation, where the change to lower heat supply costs is attractive, but the transitional phase is less so.

5.5 Appended Paper [5]

Paper [5] is about assessing the potential low-temperature excess heat recovery from the ventilation in underground metro stations within the EU. This can be considered a small-scale application of heat recovery in urban areas from an unconventional heat source. Heat recovery from ventilation shafts requires a temperature increase, in this assessment, heat-pump technology is applied. The analysis is performed at 3GDH and 4GDH temperature levels.

Some benefits of 4GDH operation are less variation between seasonal temporality, yielding a smaller absolute variation of power capacity to accommodate the entire potential of sensible and latent heat, and lower annual heat deliveries at an improved conversion rate. It is also realised that the entire potential constitutes only a small fraction of the annual end-use energy demands for space heating and domestic hot-water preparation in the residential and service sectors of the EU.

6 Concluding Remarks

6.1 Contributions

When contemplating this research in retrospective, three parts emerge concerning the contribution of knowledge to the scientific community and to the industry at large. First, information about the unique experience of using large electric boilers [6] and large heat pumps [1] in Sweden has been collected and compiled. This information might prove valuable to other actors in situations where the implementation of heat pumps is under consideration. This work also spurred collaboration with David et al. [7], concerning the use of heat pumps in a broader international perspective within district heating systems. In addition, on a similar theme, the work in appended Paper [5] continues along the lines of further integration between electricity and heat systems.

Second, a novel heat distribution technology for 4GDH systems has been established with the conceptualisation and temperature analysis [2] and the heat loss and pressure loss analysis [3]. This work was iteratively based on the previous publications [8, 9]. This work focuses on the issue of circulation in distribution networks, which results in increased return temperatures. A solution to this issue is proposed and analysed. It was found that by implementing a third smaller pipe used as a second return pipe to circulate supply water when required, the annual average distribution temperatures were lowered by 10°C, compared to an ideally functioning system without any strategy to manage recirculation flows in distribution networks. In addition, the benefits of apartment substations and the potential of improved performance in heat exchangers were detailed.

Third, the economic benefits of 4GDH have been detailed in appended Paper [4]. Strong economic incentives for a reduction in operational temperatures were observed for the future heat supply, whereas the current traditional heat supply has weaker economic incentives. It was also identified that the economic benefits originating from heat loss reduction were small in comparison to other cost reduction components. Paper [4] constitutes the first aggregated summary analysis of the economic analysis for 4GDH. Increasing profit abilities from temperature error identification and establishment of low-temperature operation is the main driving force for 4GDH. Hence, it becomes very important to elaborate methods to find temperature errors and methods to implement low-temperature operation.

6.2 Activities for Continued Work

Having performed the research that led to this thesis and being in a position that is still incomplete, the impression is of being half-way finished and that there is still so much more work to be done to achieve district heating systems with operational conditions matching the ideal of 4GDH systems. Being in such a position is, of course, very

inspirational because it raises the question: How can we go on with the second half of the initiated work?

The continuation of tasks involves a few different topic areas. One such task is to implement the proposed novel heat distribution technology in a case area to collect data in a real setting to verify the functioning of the proposed technology. Another task involves collaboration with the industry regarding the manufacturing of triple pipes and triple-pipe accessories in addition to manufacturing substations that are designed in a way that any form of leak flow between the supply and return is impossible and with the implementation of a feasible control function to accommodate recirculation in a third pipe.

A third anticipated task is policy-related and is separated into two subtasks. The first policy-related subtask is regarding the legislation of domestic hot-water systems and Legionella and aims for the promotion (and assurance) of implementing policies that no temperature requirement exists as long as apartment substations without heat storage are used in national legislation. The second policy-related subtask is regarding the performance requirements of manufacturing heat exchangers with policies that infer improved temperature performance as a standard.

Finally, system benchmarking among newly constructed district heating systems is a planned activity to carry out. This will be done according to the methods developed and employed, according to [28].

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