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Prosumers and Bottlenecks

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District Heating Development

Prosumers and Bottlenecks

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Abstract
The overarching objective of the studies in this thesis is to solve issues associated with the current district heating development in order to improve the efficiency, and thus the environmental performance, of district heating systems. More specifically, the aim is to solve issues related to prosumers and bottlenecks in district heating networks. Prosumers are consumers who also produce district heating. Prosumers could be used to introduce more renewable and recycled energy into the district heating network. Bottlenecks are areas in which it is difficult to keep a high enough differential pressure, often due to large pressure loss in the pipe leading to the area. Bottlenecks often cause the district heating system to work in a non-optimal way.

The results show that there may be great potential for prosumers to deliver a substantial amount of district heating, especially in areas with mixed building types. Most of the prosumer potential is, however, present during the summer, which is why, for example, large seasonal thermal energy storages would be needed in order to utilise all the prosumer heat. Prosumers are often beneficial environmentally for the district heating network, but the environmental outcome is not obvious. It mainly depends on three factors: if the prosumer needs a substantial amount of electricity to function, if so, how the electricity is regarded, and which type of district heating production is outcompeted. Prosumers may also affect the differential pressure in the district heating network, increase the flow velocity, and decrease the local supply temperature.

Regarding bottlenecks, the results indicate that the existing bottleneck choosing processes in district heating companies are often based on experience and focusing on the distribution system, even if other solutions are also possible to perform. Moreover, the economic calculations often lack a lifecycle perspective. This results in the most effective, both economically and environmentally, solutions often not being chosen. To shed more light on alternative bottlenecks, the results thus highlight alternative solutions, costs, risks, and added values for various bottleneck solutions and finally presents a methodical and comprehensive decision-making process for choosing bottleneck solutions.

District heating developers may use the result to help increase district heating competitiveness and thus increase the possibility of district heating being an important part of a more energy-efficient society.

Key words: District heating, prosumers, bottlenecks, pressure, differential pressure, planning, simulations

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To my family – Magnus, Albert and baby

Abstract

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Populärvetenskaplig sammanfattning

Människor har i alla tider strävat efter att överleva och efter att hitta medel som förenklar överlevnad. På savannen kunde hotet kanske vara ett lejon och medlet för överlevnad vara ett hemmagjort vapen. Ett av de största hoten i dagens samhälle, klimatförändringar, är dock mer komplext än att ett hemmagjort vapen kan hjälpa. Medlen för att förenkla överlevnad måste därmed också de vara mer komplexa. En viktig hörnsten i detta arbete är att arbeta med hur de olika energislagen människor använder genereras samt att verka för att energi används så effektivt som möjligt. Ett sätt att göra det är att använda fjärrvärme för uppvärmnings- och varmvattenbehov. Fjärrvärme kan nämligen ofta använda överskottsvärme, det vill säga värme som annars inte skulle använts, som värmekälla. Därigenom minskar behovet av att generera ny värme. Det är också viktigt att fjärrvärmen är så effektiv och miljövänlig som möjligt. Ett sätt att uppnå detta är att sänka temperaturerna på vattnet i fjärrvärmenäten.

Lägre sådana temperaturer leder till att det blir lättare att införa så kallade prosumenter, kunder som både producerar och konsumerar fjärrvärme, i fjärrvärmenäten. Exempel på prosumenter kan vara solvärme på privata tak eller värme från värmepumpar som tillgodogör sig överskottsvärmen från byggnader med kylbehov, exempelvis kontor, datacentraler eller shoppingcenter. Det finns dock även problem med lägre temperaturer i fjärrvärmesystemen. Ett sådant är att det leder till högre risk för så kallade flaskhalsar i fjärrvärmenät. Flaskhalsar innebär att det blir för lågt differenstryck på vissa ställen i fjärrvärmenätet. Ett för lågt differenstryck innebär att kunder i de drabbade områdena riskerar att inte få tillräckligt med värme.

Miljönyttan för prosumenter är framför allt beroende av tre faktorer. Dels är det viktigt hur mycket el prosumenten behöver för att generera värmen. Exempelvis värmepumpar som använder överskottsvärme från kylagenerering behöver en stor andel el för att fungera. För sådana prosumenter spelar det även stor roll vilken sorts el den använder. Prosumenten blir mer miljövänlig om den använder så kallad grön el än el producerad av kolkraftverk i Polen. Den tredje faktorn som påverkar miljönyttan för prosumenter är hur fjärrvärmen är producerad. Miljönyttan är betydligt högre om fjärrvärme producerad av en oljepanna byts ut än om fjärrvärme producerad av spillvärme byts ut. Resultaten visar också att prosumenter påverkar en mängd olika tekniska faktorer i fjärrvärmenät. Exempelvis kan den lokala framledningstemperaturen påverkas, det vill säga temperaturen på vattnet i röret som leder fram till en byggnad. Detta innebär dels att kunden riskerar att inte få tillräckligt med värme och varmvatten och dels att temperaturen i kundens eget värmesystem kan bli för låg. Det senare kan resultera i potentiellt farliga sjukdomar orsakade av en bakterie kallad Legionella Pneumophila. Prosumenter kan också innebära att hastigheten på vattnet i fjärrvärmerören blir för högt, något som kan göra att ljudnivån i byggnader nära prosumenterna blir hög och störande. Även differenstrycket kan bli påverkat och både bli lägre och högre beroende på prosumentens egenskaper. Prosumenter kan därmed användas som en lösning till flaskhalsproblem men även öka flaskhalsproblem. Resultaten för prosumenter togs fram genom både simuleringar och miljöberäkningar.

Flaskhalsproblem, som redan idag är vanligt i svenska fjärrvärmenät, kan lösas även av en mängd andra åtgärder än prosumenter, som tillhör en av de ovanligare lösningarna. De vanligaste flaskhalslösningarna innebär främst åtgärder kopplade till ledningsnätet. Dock består fjärrvärmesystemet förutom av ledningsnätet även av produktionsanläggningar och av kunder. Möjliga åtgärder kan därmed hittas även i dessa segment. Ofta är det möjligt att dessa alternativa lösningar är bättre både ekonomiskt och för miljön. Besult om vilken flaskhalslösning som ska väljas fattas dock dels baserat på erfarenhet och dels under tidspress. Detta kan leda till att den bästa lösningen inte blir vald. Därför innehåller flaskhalsresultaten en metodik för att välja den bästa flaskhalslösningen, baserad på litteraturstudier, en enkät, intervjuer och simuleringar. Förhoppningen är att denna metodik ska främja mer effektiva flaskhalslösningar. Detta kan, liksom prosumentresultaten, leda till mer effektiva fjärrvärmesystem och därmed mer effektiva energisystem och miljö- och klimatnytta.

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List of publications

Publications included in the thesis

This thesis is based on the following papers, referred to by their roman numbers. Please note that I changed my name from Brand to Brange in 2015.

Paper I **Smart district heating networks – A simulation study of prosumers' impact on technical parameters in distribution networks**

L. Brand, A. Calvén, J. Englund, H. Landersjö and P. Lauenburg, *Applied Energy, vol. 129, pp. 39-48, 2014.*

Paper II **District heating combined with decentralised heat supply in Hyllie, Malmö**

L. Brand, P. Lauenburg and J. Englund, *Conference proceedings from the 14th International Symposium on District Heating and Cooling, Stockholm, 2014.*

Paper III **Prosumers in district heating networks – A Swedish case study**

L. Brange, J. Englund and P. Lauenburg, *Applied Energy, vol. 164, pp. 492-500, 2016.*

Paper IV **Bottlenecks in district heating systems and how to address them**

L. Brange, J. Englund, K. Sernhed, M. Thern, P. Lauenburg, *Energy Procedia, vol. 116, pp. 249-259, 2017.*

Paper V **Bottlenecks in district heating networks and how to eliminate them – A simulation and cost study**

L. Brange, P. Lauenburg, K. Sernhed, M. Thern, *Energy, vol. 137, pp. 607-616, 2017.*

Paper VI **Risks and opportunities for bottleneck measures in Swedish district heating networks**

L. Brange, M. Thern, K. Sernhed, *Energy Procedia, vol. 149, pp. 380-389, 2018.*

Paper VII **Decision-making process for addressing bottleneck problems in district heating networks**

L. Brange, K. Sernhed, M. Thern, *Article in production, accepted manuscript, International Journal of Sustainable Energy Planning and Management, 2019.*

My contributions to the publications

In Paper I, I and Alexandra Calvén gathered the input data, built the model and performed the simulations together. I wrote most of the paper but some parts together with Alexandra Calvén. In Paper II, Paper III and Paper V, I gathered the input data, performed the simulations, the environment and cost calculations and wrote the papers. In Paper IV, I performed the literature study, developed the survey with input from Kerstin Sernhed, sent the survey out, handled and analysed the results and wrote the paper. In Paper VI, I developed the interview questions with input from Kerstin Sernhed, performed interview two to six by myself and the first together with Kerstin Sernhed, documented and compiled the results. I also gathered the simulation input data, performed the simulations and wrote the paper. In Paper VII, I developed and performed the workshops together with Kerstin Sernhed, developed the decision-making processes in their various stages, performed the case study interview and wrote the paper.

Contents

1 Introduction

1.1 Background

District heating is a way to satisfy the heat and hot water demands in buildings in a resource efficient way. The technique is to produce hot water in a heating facility and distribute the hot water in pipes to the buildings, where the heat is delivered to the in-house systems. Cooled water is then transported back to the heating facility where it is once again heated. District heating has many advantages regarding environmental impact and efficiency. For example, the centralised heat production has substantial economies of size and economies of scope. Economies of size means that there are advantages coupled to the industrial size of district heating, such as better opportunities of more efficient flue gas treatment processes or flue gas condensation. More technical competence and expertise regarding heating is also gathered in the same place, leading to a more efficient heating system. Economies of scope means that there are advantages coupled to the very idea of district heating. Examples of such advantages are that excess heat that would otherwise be wasted may be used and that large-scale joint production of heat and power is made possible.

District heating is a well-established heating method in Sweden. The district heating industry, however, faces many challenges. It is, for example, exposed to competition from other heat production techniques. In Sweden, this is often in the shape of local heat pumps. Another challenge is that new requirements regarding building energy efficiency will decrease the future heat demand and thus the district heating market base. Furthermore, district heating customer trust and satisfaction are not always the best. Reasons for this are, for example, discussions regarding the financial situation of district heating and district heating networks, which is to some extent based on the natural monopoly situation of district heating networks. The reason for the latter is in turn that it would not be viable to construct a new district heating network where there is already an existing district heating network, because of the large costs of a district heating distribution network. All these factors force the district heating system to develop. Both the technical systems and the business models are important aspects in this work, in order to increase the efficiency of district heating networks as well as to improve customer relations.

One way to make district heating systems more effective, and thus even more environmentally friendly and more competitive, is to decrease the system temperatures. This would, for example, facilitate more effective heating production, less heat losses, and more possibilities to introduce alternative heat sources. Such heat sources could be solar collectors or excess heat, enabling district heating consumers to also become district heating producers. The latter is called prosumers, a word that is composed of the word producer and the word consumer. The decreased system temperatures could, however, increase pressure losses in district heating systems, leading to more differential pressure bottlenecks. If prosumers are allowed to deliver heat with lower supply temperatures than the rest of the heat production units, the prosumers would hence increase the bottleneck risk.

This thesis thus focuses on two important areas for district heating development: prosumers and bottlenecks. Allowing prosumers in district heating networks may be a way for district heating to improve both customer relations and environmental performance, thus increasing the competitiveness. Prosumers in district heating may, however, pose problems, such as control issues and questions regarding the environmental outcome. One part of the results thus addresses technical parameters that are important to control when connecting prosumers to the district heating network, as well as which parameters that are important for the environmental outcome of the prosumer solution. Regarding bottlenecks in district heating networks, they are presently often solved with traditional solutions associated with the distribution part of the district heating system, even if other solutions may be possible and better from both an economic and environmental perspective. The other part of the results thus addresses bottlenecks and bottleneck solutions.

1.2 Objectives

The overarching objective of the studies in this thesis has been to contribute with knowledge and tools to help improve competitiveness and environmental outcome of district heating. Many issues arise in the wake of the development towards lower system temperatures for district heating. The work in the studies in this thesis has aimed to help solve some of those issues, in order to help district heating developers to increase system efficiency in district heating grids. Within this field, two target areas were studied:

- Prosumers in district heating networks
- Differential pressure bottlenecks in district heating networks

In the first target area, the aim was to investigate some of the issues originating from a distributed heat supply by solar collectors and excess heat upgraded by heat pumps, which are heat sources often used by prosumers. Such installations could either be allowed to supply district heating with lower supply temperature than the conventional district heating or be installed in a district heating network with a lower supply temperature. The lower supply temperature is important for these installations to be viable, as their efficiency decreases with higher supply temperatures. The focus was especially on technical and environmental issues arising from such installations. The technical issues discussed were related to the lower supply temperature and mainly focused on the differential pressure, the flow velocity, and the local supply temperature. These aspects are, for example, coupled to issues like consumer noise problems and difficulties to supply district heating consumers with enough heat. The environmental issues were addressed by considering carbon dioxide emissions and primary energy use for a district heating network with and without prosumers during a year. These questions are discussed in Paper I-Paper III.

Hopefully, these results will help simplify an introduction of prosumers and increase the knowledge about the circumstances in which prosumers lead to a more environmentally friendly district heating network and when they do not.

Lower system temperatures also lead to a higher risk of bottlenecks. In the second target area, the aim was thus to investigate some of the issues associated with bottlenecks and bottleneck solutions. More specifically, the focus was to investigate bottleneck problems and bottleneck solutions in district heating networks in order to help identify the most optimal bottleneck solution in different situations. Issues investigated were what kind of solutions could be used to solve bottleneck problems; the current bottleneck situation in Swedish district heating networks; what the risks, opportunities, and costs related to different bottleneck solutions are; and important aspects when choosing a bottleneck solution. These results were used to create a decision-making process to help choose the most optimal bottleneck solution. These questions are discussed in Paper IV-Paper VII.

Hopefully, these results will lead to more knowledge about different possible bottleneck solutions and a more methodical approach when choosing bottleneck solutions, thereby increasing the efficiency and environmental performance of district heating systems.

1.3 Limitations

The studies are performed from a Swedish perspective. This means that Swedish conditions regarding, for example, technique, economy, and law constitutes the basis for the studies. Furthermore, the focus of the prosumer studies is on district heating as a technical and environmental system. The bottleneck studies, on the other hand, also include other factors, such as economy, law, risks, and opportunities. All the studies are performed from a district heating company perspective; the perspective of consumers is not accounted for. The risks and opportunities for bottleneck solutions are, for example, collected from interviews with district heating companies and the technical issues are coupled to the district heating network.

1.4 Outline of the thesis

Chapter 2 presents a background about the district heating system. Special emphasis is put on concepts important for the analysis in the included papers and on Swedish conditions that may be unknown to the international reader. Chapter 3 presents the factors leading to the current district heating development and what effects this development has on aspects relevant for the included papers. Chapter 4 discusses prosumer background and issues more thoroughly, and Chapter 5 handles bottleneck background and current ways to deal with bottlenecks. Chapter 6 presents the method used in the included studies, including an analysis of the methodology. Chapter 7 presents the most important results and analysis. Finally, Chapter 8 gives a discussion including suggestions on future studies. The included papers are appended at the end of the thesis.

2 District heating

In this chapter, a short overview of district heating is described. More thorough descriptions of technical and regulatory factors specific for Swedish conditions are included as well, in order to put the encompassed studies into context. Furthermore, an explanation of different technical district heating parameters important for the analysis of the results is included.

2.1 Fundamentals of district heating

District heating is a heating method used for satisfying the heat and hot water demands of buildings, facilities and industries. The main idea is to produce heat in one location and use it in another location. The heat is transferred by water or steam in pipes most often buried in the ground. The two main benefits of district heating are the economy of scale and the economy of scope. The economy of scale refers to the advantages of large-scale, centralised heat production. Examples of such are more efficient systems, better emission control and thus environmental benefits, and more accumulated heating expertise. The other benefit, the economy of scope, refers to the resource efficiency that is facilitated by district heating. More specifically, it means that heat sources that could otherwise never have been used, such as waste incineration or waste heat from industries, may be utilised. This creates large environmental benefits. Centralised heating in this context means centrally controlled heat production and not necessarily a large production unit, as district heating today is generated in many ways [1].

An important feature of district heating systems is that they, unlike the gas and electricity system, are local or regional systems. This means that the basic conditions of different district heating systems could differ greatly, leading to, for example, different economic and environmental situations [1].

District heating was historically often produced by an incineration facility, producing heat only. The fuel could, for example, be coal or oil. Later, combined heat and power (CHP) facilities were introduced, which meant that heat and electricity could be produced in the same facility and process. Presently other ways of producing heat are also available, such as waste incineration [2], large heat pumps [3], or using waste heat from industries and heat from prosumers. In Sweden, more than 60 % of district heating is produced from biomass, including organic waste. Other important district heating sources in Swedish systems are heat from heat pumps and waste heat [4]. The most common ways to produce district heating in Sweden are by recycled heat, CHP facilities, and boilers using biomass as fuel [2].

The pipes used to transfer the heat are almost always buried in the ground to decrease heat losses, and the most usual heat transferring medium is water. The most usual types of district heating pipes are pipes with mineral wool insulation, covered by concrete ducts and plastic jacket pipes with cellular polyurethane (PUR) insulation directly buried in the ground. If the supply temperature is lowered, other, cheaper, pipe materials, such as polymers, could be used [1]. In Sweden, a large part of the district heating networks was founded in the 1980s, which means that the two former types of pipes are most common [5].

There are different network structures possible for a district heating network, often typical for the development stage of the district heating network. The simplest structure is the tree structure, containing no interconnections and only one heat production unit. Other structures are a tree structure but with distributed heat production units in addition to the main heat production unit and a district heating structure containing a ring structure. The most advanced structure is the meshed structure, with many ring connections and where the network usually follows the street map [1]. The geographical distribution of the heat demand may be referred to as heat density, where a higher heat density (more geographically concentrated heat outtake) means shorter pipe lengths per heat outtake and thus less heat losses and a more cost-effective system [6], [7], [8]. The cost to distribute district heating is thus lowest in dense urban areas, whereas in more rural areas with lower heat density, other heat and hot water technologies may be more competitive.

Of the district heating in the world, 85 % is used in the European Union, China, and Russia [9]. In Sweden, 57 % of the total heat and hot water demands is supplied by district heating and 90 % of the multifamily buildings are heated by district heating [4]. Also, facilities such as schools and hospitals, single-family houses, and industries use district heating for heating and hot water demands.

The space heating demand is tightly coupled to the outdoor temperature and is thus different for different seasons. In Sweden, this means that the heat outtake is at its maximum during the winter and at its minimum during the summer, when there is often only heat outtake for domestic hot water use (see Figure 1). The district cooling demand is shown in the same figure. The normal balance temperature, i.e., the outdoor temperature where no external heating is demanded, is in Sweden around 17 °C. The domestic hot water demand varies somewhat over the seasons as well, with a dip in the summer due to different degrees of occupancy of buildings over the seasons. This variation is, however, much smaller than for the heating demand [1].

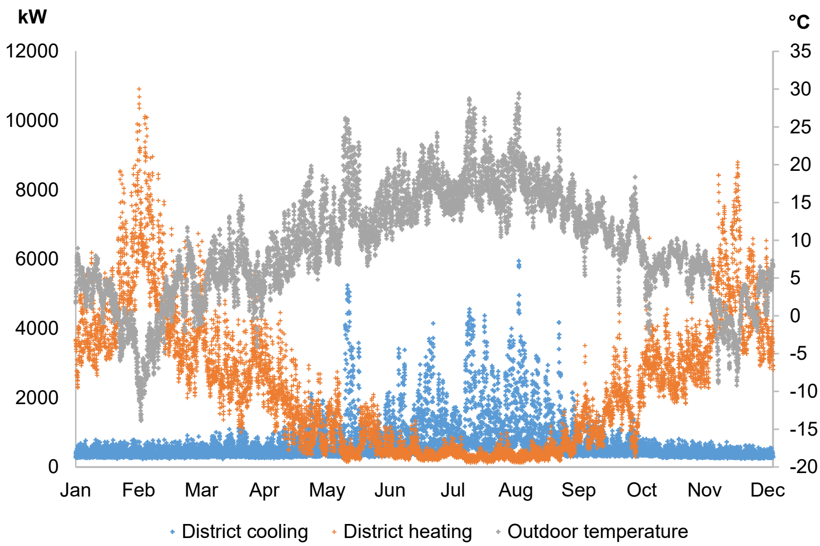

Figure 1
District cooling demand, district heating demand, and outdoor temperature for a district heating area in southern Sweden. Modified from [10].

The district heating consumption also varies over days and weeks as well as over seasons. The daily variation often shows a peak in the morning and one peak in the evening, when plenty of hot water is consumed at the same time. The weekly variation depends on different patterns of heat and domestic hot water use during weekdays and weekends. These patterns vary depending on building type [1], [11].

Hot water circulation is a common method to decrease the time needed for the hot water to arrive at the tapping location in multifamily buildings. Warm water is pumped in a loop in the building, on the building side of the substation. Hot water in the building apartments is drawn from this loop. For buildings with hot water circulation, a large amount of the domestic hot water demand may consist of heat losses from the hot water circulation. In a study by Bøhm, between 23 % and 70 % of the domestic hot water demand in such buildings is due to hot water circulation [12].

The heat power transferred from the district heating network to a building is described by equation (2.1), where P is the consumer heat power (W), $\dot{m}$ is the mass flow rate (kg/s), c_p is the specific heat capacity for water at the average temperature (J/kg/K), t_s is the supply temperature (°C) and t_r is the return temperature (°C). The heat power delivered is dependent on the mass flow rate, the supply and return temperatures, and the specific heat capacity.

$$P = \dot{m} \cdot c_p \cdot (t_s - t_r) \qquad (2.1)$$

2.2 Hydraulic separation

There are different ways to manage the hydraulic separation between the district heating network and the in-house heating and/or hot water system. The most common ways to do this are called indirect and direct connection. These connections are illustrated in Figure 2.

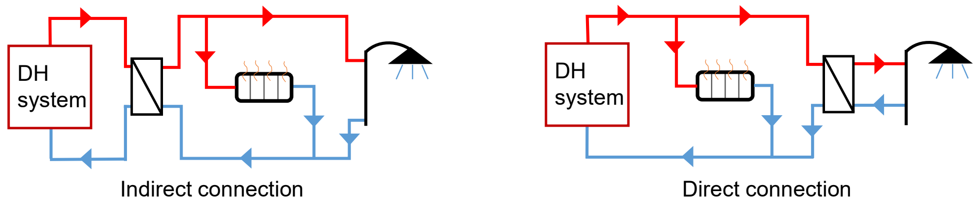

Figure 2
Indirect and direct hydraulic separation. DH denotes district heating. Modified from [10]

In Sweden, an indirect connection is the most common. In this type of hydraulic separation, both the heating and the hot water circuits are separated from the district heating system, via a heat exchanger called a substation. The advantages of this system are many. For example, it makes it easier to keep within the pressure limits in district heating systems with large altitude differences because the radiators designed for a lower maximum pressure belong to a separate hydraulic system. Another advantage is that the volume of water that may leak out inside a building is greatly reduced. If the district heating water contains dissolved oxygen, it furthermore does not affect the radiator systems. The drawbacks are that it entails a higher cost than a direct system and that a few degrees of supply temperature is lost in the heat exchanger. The latter may be a problem if the supply temperature is low because it could be harder to keep a high enough supply temperature in the building.

With the direct connection, the heating system is directly connected to the district heating system but the hot water system is connected to the district heating system via a heat exchanger. The disadvantages of this system are that there is a risk of corrosion in the radiators if the district heating water contains dissolved oxygen and a higher safety risk with higher pressure levels in the radiators and more water in the system if there is a leak in the in-house system [1].

The interface between the distribution system and the in-house system is called a substation and it is often situated in the house of the consumer. In a substation, the different connections and heat exchange procedures are taking place [1]. The substations could either be owned by the district heating company or by the consumers. In Sweden, the most common situation is that the substations are owned by the consumers. According to the results in Paper VI, the advantage of this is that the district heating company does not have any responsibility inside the consumer building. The main disadvantage is that the district heating company does not have full control of and access to the district heating substations, which could be disadvantageous if the substation is faulty.

2.3 Temperature levels and heat losses

The supply temperature is regulated on many factors, such as consumer heat comfort requirements, building requirements and laws, substation performance, and temperature losses. To be able to satisfy consumer heat comfort, different design supply temperatures has been used during different time periods. In Sweden, older radiator design temperatures of 90/70 °C and 80/60 °C were commonly used. The newer radiators have lower design temperatures of around 55-60/40-45 °C [13].

To keep the legislated temperature of at least 50 °C at the tap in Sweden, the local district heating supply temperature needs to be at least 55 °C [14]. The local supply temperature refers to the supply temperature at the consumer. The legislated tap temperature requirements are different in different countries but temperatures between 50 °C and 65 °C are commonly used [15]. This temperature requirement aims to decrease the risk of legionella pneumophila bacteria growth that exists with lower supply temperatures. Legionella pneumophila are present in all fresh water and can, if allowed to grow, cause a serious disease called legionellosis when inhaled. The risk of legionella growth is largest in stationary water with temperatures between 20 °C and 45 °C [16]. There are other ways to avoid legionella bacteria in domestic hot water than temperature requirements; for example, chlorine injection or point-of-use filters. These are, however, not possible to use as single methods today, mainly because legislation focuses almost exclusively on temperature levels [16]. Another solution could be to install individual substations for each apartment, which leads to the volume of water with no circulation inside the apartments could be too small to mean a risk of legionella growth. This means that the supply temperature requirements may be disregarded for such systems [17]. The regulations regarding this solution are, however, different in different countries; it is, for example, allowed in Germany and discussed in Denmark, but not allowed in Sweden [15].

Regarding substation performance, according to Frederiksen and Werner it should be possible to keep an annual average supply temperature of just under 69 °C and an annual return temperature of 34 °C with the current known substation technology, but the national averages in Sweden are an annual supply temperature of 86 °C and an annual return temperature of 47 °C [1]. This indicates, inter alia, that substations are not working optimally, which leads to higher supply temperatures needed [18].

Temperature losses in district heating networks are not the same thing as heat losses, but with the same amount of heat distributed, more heat losses means more temperature losses. Lower temperature levels means lower heat losses in the district heating network according to equation (2.2), where Q_{hl} is the heat loss for a single insulated pipe above ground (W), K is the total heat transmission coefficient with reference to the outer pipe surface ($W/m^2/K$), d_o is the outer pipe diameter (m), L is the pipe length (m), t is the warm fluid temperature inside the pipe (°C) and t_a is the ambient cold temperature (°C).

$$Q_{hl} = K \cdot \pi d_o L \cdot (t - t_a) \tag{2.2}$$

Other parameters affecting the heat losses are the amount of insulation around the pipes, the geographical distribution of the heat demand (heat density), and the pipe dimension, i.e., the inside diameter of the pipe [20].

The amount of insulation around the pipes affects the heat losses because more insulation leads to smaller heat losses. More insulation is, however, more expensive [1]. The pipe dimension affects the heat losses in mainly two ways. Firstly, by changing the heat transferring conditions and secondly by affecting the flow velocity and thus the residence time for the heat transferring media in the pipes. The way that pipe dimension affects the heat transferring conditions is fairly complicated, as it affects many parameters, which in turn affect the heat losses in different directions. A bigger pipe area means an increased heat transfer area leading to increased heat losses. A bigger pipe area, furthermore, causes a lower flow velocity, which means a less turbulent flow and thus a smaller heat transfer coefficient. This effect will decrease the heat losses. The second way is more straightforward where a bigger pipe area induces lower flow velocities in the pipes, a longer residence time of the water in the pipes, and thus increased heat losses. These effects will, together, most often mean that a bigger pipe area leads to larger heat losses [1]. This also means that a lower heat density increases the heat losses, in that a longer pipe length means more heat losses due to a longer residence time of the water in the pipe.

2.4 Pressure

The pressure in the district heating networks is another important parameter, determining the function of the network. The pressure level in the district heating network could be maintained in different ways. The pressure level is set so that the maximum pressure in the pipes is kept under the design pressure level for the pipes (often 1600 kPa) and the minimum pressure is kept above boiling risk limit (200 kPa at 120 °C). This pressurisation of the district heating network could be obtained by, for example, a pump regulating the amount of water in the network or by using static pressurisation systems such as a water column or a steam drum. If it is hard to keep the pressure within the limits, due for example, to altitude differences, distributed circulation pumps may be used [1].

The pressure drop in the district heating network decides the flow direction. An equation for the pressure drop for fully turbulent flow in the flow direction of a circular channel, which is the most usual case for district heating pipes, can be seen in equation (2.3), where Δp is the pressure gradient of a pipe (Pa), λ is the friction factor (-), L is the pipe length (m), d_i is the inner pipe diameter (m), ρ is the fluid density (kg/m^3), v is the flow velocity (m/s), and $\dot{m}$ is the mass flow rate (kg/s). It is obvious that the diameter of the pipe, deciding the flow velocity, is important for the magnitude of the pressure drop. The temperature levels in the district heating network also affect the pressure losses by influencing the flow rate. The higher difference between the supply temperature and the return temperature, the lower the flow rate needs to be to deliver the same amount of heat, according to equation (2.1). This means that less pump work is needed, according to equation (2.4), where P_{el} is the electrical power required to run the circulating pump (W), Δp_{pump} is the pressure difference over the pump (Pa), η_{pump} is the total pump conversion efficiency (-), and $\dot{V}$ is the volume flow rate (m^3/s). A lower flow rate, moreover, means less wear on the pipes [19].

$$\Delta p = -(\lambda L/d_i) \cdot \rho\, v^2/2 = -(8\lambda L/(d_i^5 \pi^2 \rho)) \cdot \dot{m}^2 \tag{2.3}$$

$$P_{el} = \left(\frac{\Delta p_{pump}}{\eta_{pump}}\right) \cdot \dot{V} \tag{2.4}$$

The differential pressure, which is the difference between the supply pipe pressure and the return pipe pressure in the same location, ensures a sufficient heat delivery to consumers. A too large differential pressure, over (600-800) kPa, will exceed the dimension levels for the substations. A too low differential pressure, under 100 kPa, will result in difficulties in delivering enough heat to consumers because the needed internal pressure drop in the substation will not be covered [20]. In Sweden, the substation design advice recommends a differential pressure between 100 kPa and 600 kPa. Often, a single central pump is deciding the initial differential pressure in the district heating system and sometimes additional distributed pumps help with this task. To use several distributed pumps, and thus smaller central pumps, may increase the efficiency of the district heating network as the initial pressure does not need to be as high and the pressure losses thus decrease [21].

A so-called pressure cone can be seen in Figure 3, illustrating a simplified pressure profile in the district heating network. The red line shows the supply pressure and the blue line shows the return pressure. The green lines show the maximum and minimum pressure limits. The difference between the red and the blue line is the differential pressure.

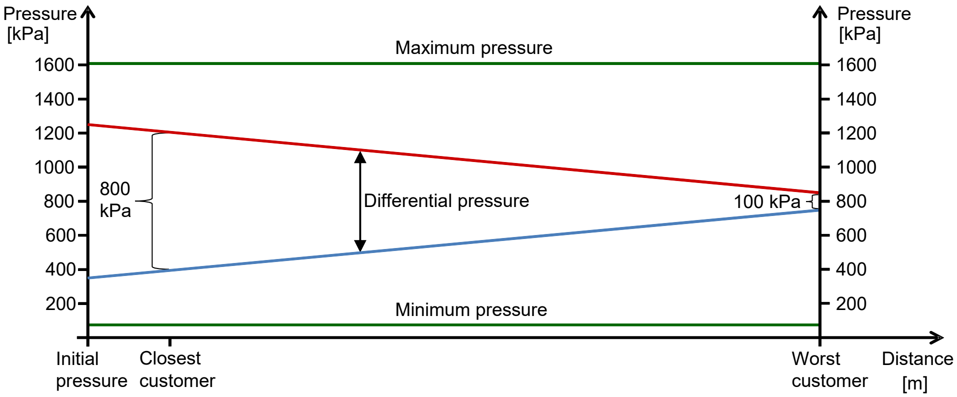

Figure 3
Conceptual pressure cone in a district heating system. Modified from [10].

3 District heating development

In this chapter, the mechanisms behind the current development of district heating is described, as well as some of the issues arising from this development. Some of the effects more important for the analysis of the results in this thesis are also more thoroughly described. This is performed to give the reader a background to understand why the issues handled in the work in this thesis arose and also to explain some of the technical effects due to the development.

3.1 District heating must evolve

In Sweden, the electricity market was deregulated in 1996. At the same time, the district heating market was changed too, in that it was now possible to replace the former cost prices with market-based pricing. The object of the latter was to create more efficient competition between the electricity market and the district heating market. One effect of the deregulation of the district heating price was increasing district heating prices and many previously municipality-owned district heating systems being sold to either private actors or reformed to municipality-owned energy companies [22]. Since then, third-party access has been discussed but not followed through. One of the reasons for this is that third-party access to district heating networks is believed to affect competition only marginally but instead negatively affect the possibilities for district heating systems to remain cost-effective [23]. In the latest change of the Swedish District Heating Act, negotiations between the district heating company and aspiring heat suppliers are, however, decreed and the district heating company is obliged to offer financial compensation for the heat to the heat supplier. Unregulated third-party access is, however, still not enforced [2]. Even if third-party access is not legally enforced, the development of the district heating market in Sweden has led to a larger public awareness about energy questions and more discussions regarding the natural monopoly situation of district heating [22]. Completely unregulated third-party access has not been introduced internationally to the same extent as for the electricity or gas systems either, even if countries have different legal frameworks and regulations [9].

Competition from other heating alternatives is also expected to increase. For example, the heat pump market is increasing in many countries, including Finland [24] and

Sweden [2]. In Sweden, the competitiveness of district heating is further challenged by building regulations, which do not regard the different primary energy factors of different district heating systems, but instead use a default value [25]. This is mirrored in the rest of the European Union, where district heating is denoted rather high default primary energy factors if primary energy factors are at all used [9].

Other important factors leading to district heating development are new regulations, among them the European building regulations designed to promote a reduction of greenhouse gas emissions in the European Union. The directive enforces a transition to less energy intensive buildings called nearly zero-energy buildings and emphasises the importance to use energy from renewable sources [2], [24], [26]. More energy-efficient buildings in turn lead to a lower heat density in district heating networks, resulting in decreased profitability for district heating companies [7].

These factors reduce the heat base for district heating and change the conditions of district heating production and business, which force district heating networks to evolve [27]. One way of increasing efficiency, decreasing heat losses, and thus increasing competitiveness and environmental outcome of district heating networks could be to decrease system temperatures and to introduce more renewables [24], [28], [29]. This transition of district heating networks is commonly denoted as the fourth generation of district heating [28].

3.2 Four generations of district heating

The development of district heating is often described as four generations. In the first generation of district heating, the heat was mainly transferred by steam. A large part of the heat production consisted of heat incineration facilities, mainly burning coal. There are still a few steam systems left, for example in Paris and New York. In the second generation of district heating, the heat transferring medium was changed to water instead of steam. The supply temperatures were still high, around 120 °C. The pipes in the second generation of district heating predominantly consisted of pipes in concrete ducts, and CHP became more common. Oil also became a common fuel in district heating production units. In the third generation of district heating, the average supply temperature was decreased to under 100 °C and the water was transferred in prefabricated pipes buried directly in the ground. The heat production and the fuels both became more diverse, with more distributed production units with different fuels, such as domestic waste and electricity (heat pumps), entering the system [1].

The introduction of the district heating techniques of the fourth generation of district heating is currently taking place, fuelled by the reasons described in section 3.1. The fourth generation of district heating is characterised by even lower supply temperatures and more renewable and reused energy as heat sources [28]. Lower temperature levels are dependent on a low return temperature from the substations. This is important in order to maintain a sufficiently low flow rate. With well-functioning substations and efficient indoor heating systems adapted to lower temperature levels, the temperature levels can be decreased, inducing more efficient district heating systems [18], [30]. This enables both production and distribution benefits [31]. Some examples of production benefits are possibilities to use heat sources with higher efficiencies for lower supply temperatures [32], for example solar collectors or waste heat upgraded with heat pumps. Furthermore, more waste heat sources and renewable heat sources can be utilised and the efficiencies in flue gas condensation [33], CHP utilities, and heat pumps will increase [13]. Commonly discussed levels of the supply and return temperatures are supply temperatures around 55 °C and return temperatures around 30 °C [34], [35]. There is, however, a study showing that the reduction of the supply temperature below 60 °C is sometimes neither environmentally nor economically efficient. The reason is the increased demand of local electricity solutions to increase tap water temperature in order to meet temperature requirements to eliminate legionella bacteria [36].

The lower supply temperatures of the fourth generation of district heating networks will thus simplify and facilitate the introduction of district heating prosumers, as prosumers often generate district heating by excess heat and heat pumps [37] or solar collectors [38]. Lower supply temperatures also benefit the distribution system, in the form of, for example, lower heat losses and the possibility to use cheaper pipe material, such as plastic [32]. Low heat losses in district heating networks are desirable, as this leads to a more efficient and cost-effective district heating network [28]. The discussed levels of the lowered supply and return temperatures will, however, lead to a lower temperature difference in district heating networks compared to the temperature difference in the third generation of district heating (80/40 °C). This decreased temperature difference will lead to higher pressure losses in existing district heating networks, due to an increased mass and volume flow [39], [35]. This can easily be understood when combining equation (2.1) and equation (2.3), see equation (3.1), where Δp is the pressure gradient of a pipe (Pa), λ is the friction factor (-), L is the pipe length (m), d_i is the inner pipe diameter (m), ρ is the fluid density (kg/m^3), P is the consumer heat power (W), c_p is the specific heat capacity for water at the average temperature (J/kg/K), t_s is the supply temperature (°C) and t_r is the return temperature (°C). Increased pressure losses could in turn lead to difficulties to maintain a sufficient differential pressure in weak areas in the district heating network, inducing bottlenecks.

$$\Delta p = -(8\lambda L/(d_i^5\pi^2\rho)) \cdot \left(\frac{P}{c_p \cdot (t_s - t_r)}\right)^2 \qquad (3.1)$$

A summarising picture of the district heating system and which parts need to evolve is shown in Figure 4, where 1 represents production, 2 represents distribution, 3 represents consumption, and 4 represents substations. The production will have to be more flexible and more focused on renewable and reused heat, in order to meet requirements and directions from different sectors. The distribution will have to be more efficient to increase competitiveness. The consumption side will have to be more flexible and more energy efficient. Also, substations will have to be more efficient in order to provide sufficient cooling needed for the supply temperatures to be decreased.

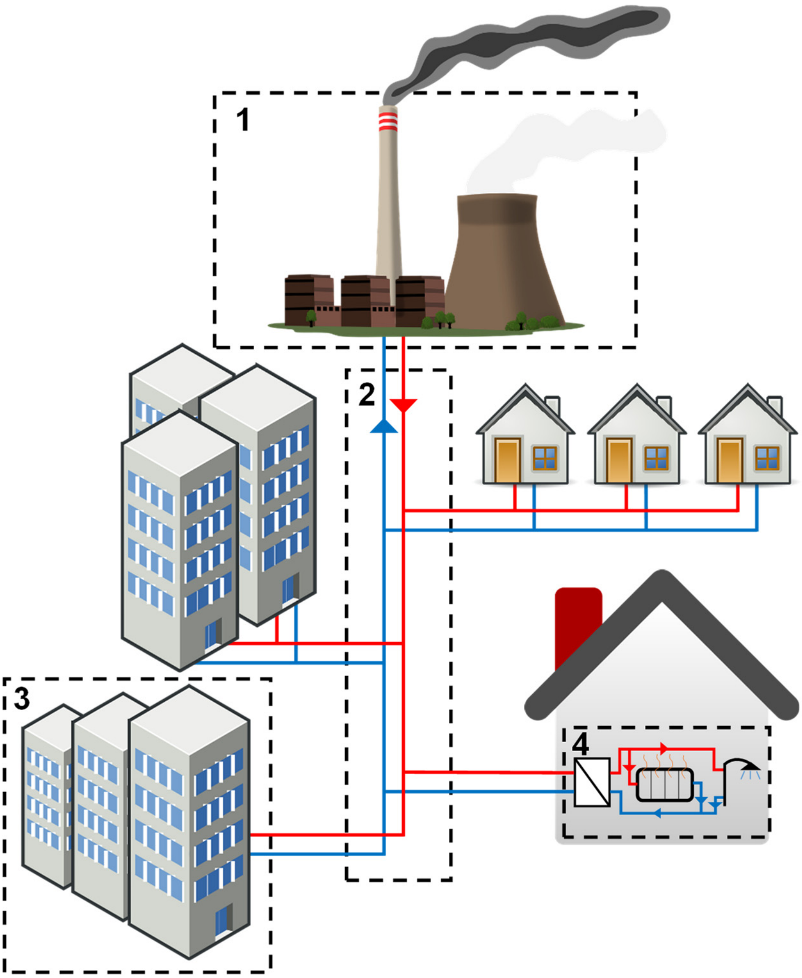

Figure 4
Conceptual picture of the district heating system, where 1 represents production, 2 represents distribution, 3 represents consumption, and 4 represents substations.

3.3 A smart energy system

To be able to develop a renewable energy system, it is important to see the electricity system, the heating and cooling system, industries, buildings, and the transport system as interdependent parts of the energy system and not as separate elements [28]. In that way, the different parts can take advantage of each other and energy can be harvested, used, and stored in a more efficient way. One example is that excess electricity produced by, for example, wind power stations or solar panels when the weather is beneficial can be used as heat in a district heating system or stored in electric cars. This way of seeing the energy system is commonly denoted as a smart energy system [40].

District heating is a necessary part in such a system, in order to completely be able to take advantage of renewable heating alternatives such as geothermal heating and solar heating. Waste-to-energy and excess heat are, furthermore, heating sources with more possibilities to grow in a heating system that includes district heating [41].

4 Prosumers

In this chapter, an explanation of prosumers and examples of prosumer heat production techniques are presented, to give a more thorough background to these concepts. An overview of prosumers issues is thereafter described, in order to put the issues that this thesis discusses into context.

4.1 What is a prosumer?

Prosumer is a word that, in the district heating world, describes a consumer of district heating that is also a producer. The heat production could, for example, take place in solar collectors [38] or in facilities with a large cooling demand, thus having excess heat available [42]. In the latter case, the temperature of the excess heat often must be upgraded, either in a combined heating and cooling machine or in an external heat pump. A district heating system including prosumers is illustrated in Figure 5.

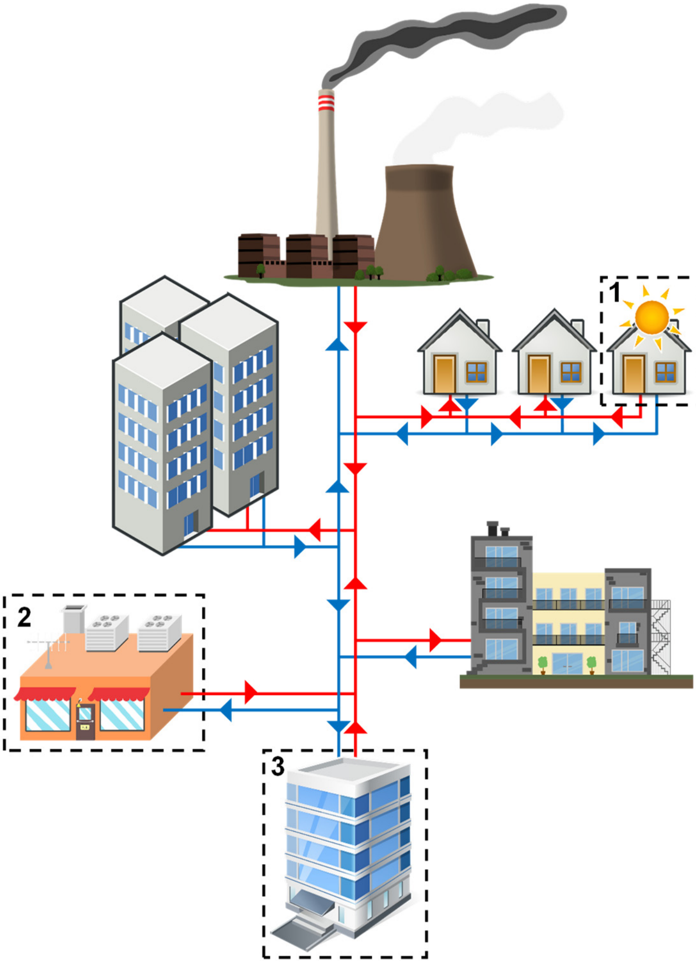

Figure 5
A conceptual district heating system including prosumers. 1 represents a solar heating prosumer, 2 represents a supermarket prosumer, and 3 represents an office prosumer.

4.2 Examples of prosumer techniques

The most often used solar panels for district heating purposes are flat plate collectors and evacuated tube collectors. Both types of solar collectors work by collecting the energy from the sun via an absorber. The heat is then transferred to a liquid, which is pumped from the solar collector to a heat exchanger that is connected to a district heating network.

Flat plate solar collectors have a transparent cover and an isolated back to reduce heat losses. Liquid is pumped through tubes that are in contact with a heat absorbing layer. In evacuated tube collectors, the liquid is pumped through tubes containing the absorbing layer and surrounded by glass tubes containing a vacuum, in order to reduce heat losses resulting from convection and conduction. This kind of solar collector is often more expensive than the flat plate collector but has higher efficiency, especially when the operating temperature is higher and the ambient temperature is lower [43].

Another type of prosumer is the use of waste heat from cooling processes in the district heating network. Available waste heat could, for example, be present in data centres and supermarkets. This heat often has a too-low temperature to be used directly in district heating networks and must therefore be increased, for example with a heat pump.

A cooling machine and a heat pump work in the same way, as both processes take place simultaneously. The function is illustrated in Figure 6.

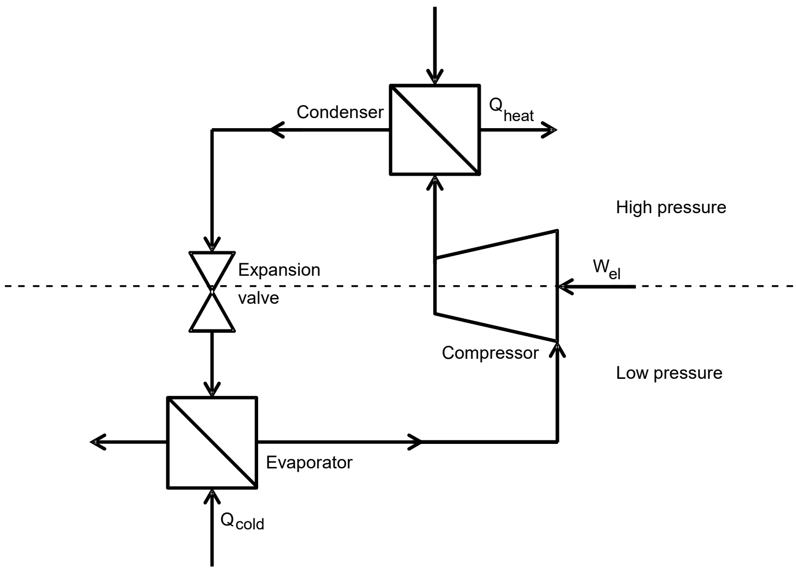

Figure 6
Simplified illustration of the function of a heat pump. Modified from [10].

The machine works by a liquid medium, a refrigerant, absorbing heat from a heat source (Q_{cold}), thus evaporating. The gas is then compressed in a compressor, driven by electricity (W_{el}), causing the refrigerant temperature to increase. The heat in the refrigerant is then delivered to the heat sink via a condenser (Q_{heat}), where the refrigerant condenses to a liquid. Thereafter, the pressure of the refrigerant is decreased in an expansion valve and the process starts over. The energy flows in the heat pump thus relate to each other as in equation (4.1). In equations (4.1)-(4.3), Q_{heat} is the heat delivered to the hot reservoir (kW), Q_{cold} is the heat extracted from the cold reservoir (kW), and W_{el} is the compressor work (kW).

$$Q_{heat} = Q_{cold} + W_{el} \tag{4.1}$$

The efficiency of a heat pump is described by the coefficient of performance (COP) of the heat supplying unit. The COP describes how much electricity is needed in relation to excess heat. The COP can be calculated for both Q_{heat} (COP_{heat} (-)) and Q_{cold} (COP_{cold} (-)) and is calculated as in equation (4.2) and equation (4.3). Because electricity is turned into heat, COP_{heat} and COP_{cold} for a combined heat pump and cooling machine relate to each other as in equation (4.4). The efficiency of a heat pump is dependent on the supply temperature, where a higher supply temperature means a lower heat pump efficiency because more electricity is needed in the process in order to increase the temperature of the refrigerant further [44]. This is evident when rewriting the maximum Carnot efficiency shown in equation (4.5), where $\eta_{heat,\ max}$ is the maximum possible efficiency of a heat pump (-), T_{cold} is the temperature in the cold reservoir (K), and T_{heat} is the temperature in the hot reservoir (K), into equation (4.6), which shows the maximum theoretical COP_{heat}. The COP thus affects the environmental advantage of prosumers needing heat pumps to increase the supply temperature. The COP is in turn dependent on the supply temperature of the district heating network, why the development where the supply temperature is decreased in district heating networks facilitates more efficient prosumers [44].

$$COP_{heat} = Q_{heat}/W_{el} \tag{4.2}$$

$$COP_{cold} = Q_{cold}/W_{el} \tag{4.3}$$

$$COP_{heat} = COP_{cold} + 1 \tag{4.4}$$

$$\eta_{heat,\ max} = 1 - \frac{T_{cold}}{T_{heat}} \tag{4.5}$$

$$COP_{heat,\ max} = \frac{T_{heat}}{T_{heat} - T_{cold}} \tag{4.6}$$

4.3 Different prosumer connections

The heat from prosumers can theoretically be supplied to the district heating network in four different ways: from the supply pipe to the supply pipe, from the return pipe to the supply pipe, from the return pipe to the return pipe, and from the supply pipe to the return pipe. The last one is not used, as the idea of a production unit is to increase the temperature of the water, which would be unnecessary in such a connection. Prosumers using the water from the supply pipe and delivering their excess heat to the supply pipe could, for example, be used to increase the supply temperature in areas distant from the main supply unit. Prosumers using the water from the return pipe and delivering their excess heat to the supply pipe work as a regular supply unit. This is the prosumer connection used in the included papers. An illustration of this type of connection is shown in Figure 7. Prosumers using the water from the return pipe and delivering their excess heat to the return pipe can increase the efficiency of a district heating system with an incineration facility as a production unit but decrease the electric output of a CHP unit [45].

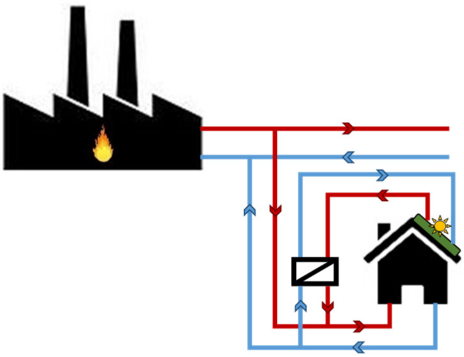

Figure 7
Conceptual illustration showing a prosumer return-supply connection. Modified from [10].

4.4 Prosumer issues

Many issues originate from the introduction of prosumers in district heating networks. Such issues may be related to environmental outcome, control and agreement, and economic concerns.

Regarding the environmental outcome, it is important to not sub-optimise the district heating and energy systems. Prosumers are namely often discussed as a positive and environmentally friendly contribution to district heating networks, regardless of their form and configuration [46]. This is sometimes correct [37], [47], but sometimes conventional district heating production is more environmentally friendly than the heat produced by prosumers. According to the results in Paper III, factors affecting the environmental efficiency of prosumers are, for example, what kind of district heating is replaced, if the prosumers need a substantial amount of electricity to function and if so, which sources are used to produce the electricity.

One part of the control issue is that many prosumers in a district heating network will increase the operation control demand, due to the often intermittent nature of prosumers [38]. The heat production of prosumers based on solar collectors or excess heat from cooling units is, furthermore, often mismatched with the heat demand [48]. The production is largest during the warm summer months when the heat demand mostly consists of domestic hot water. One way to manage the intermittent nature of prosumers' heat production is to install large energy storages [48]. In this way, prosumer output does not have to be matched with heat demand in the district heating network, which means that the prosumer potential could be more fully utilised [49]. Different prosumers, however, have different heat output profilers, where the heat output from, for example, data centres [50] is more stable than the heat output from solar collectors. Also, the pressure control of the district heating network, regarding, for example, differential pressure, must be overseen, as prosumers could alter these conditions [37], [51].

The main issue regarding agreement and economy is the possible difficulty in creating an agreement between the prosumer and the district heating company. For the district heating company, it is, for example, important that the heat supply is of the right quality and in the right location. The duration of the heat supplying contract is also very important to the district heating company, in order to ensure a robust heat supply in the district heating network. The possibility of avoiding investments in other heat production alternatives may, for example, be economically advantageous for the company, but demands long-term, robust agreements [50]. Otherwise, the energy company will still have to make investments to be able to deliver heat to consumers on a long-term basis. The agreement should also favour both the prosumer and the district heating company economically. A district heating market open to all heat suppliers may, for example, be beneficial for both prosumer and district heating owner. This is dependent on which district heating source the prosumer is outcompeting, and the time of year, due to fluctuating heating demand and heat and electricity prices [52]. There is a risk of the prosumer heat production outcompeting other district heat production during times when the latter is more profitable. For example, CHP operation could be outcompeted, which may affect also the electricity profits [50].

5 Bottlenecks

In this chapter, bottlenecks and the origin of bottlenecks is described. Furthermore, a continuation of the discussion regarding why it is important to address bottlenecks, started in section 3.2, is performed, as well as an overview of bottlenecks and bottleneck solutions in the literature. This is described in order to put the issues that this thesis processes into context.

5.1 What is a bottleneck?

In this thesis, bottlenecks mean geographic district heating areas with too-low differential pressure. Bottlenecks affect the control of the rest of the district heating network. The reason for an area to have low differential pressure is technically that the pressure loss between the pump and the area is too high. A common reason for that is that the flow velocity in the pipes is too high, which causes a too-high pressure loss (equation (2.3)). This could, in turn, have many reasons, for example that the pipe is too narrow or that the cooling in the area is poor. Another reason could be that the area is far away from the production units and from the pumps, i.e., that the pipe length is very long (equation (2.3)). A pressure cone showing a bottleneck is illustrated in Figure 8.

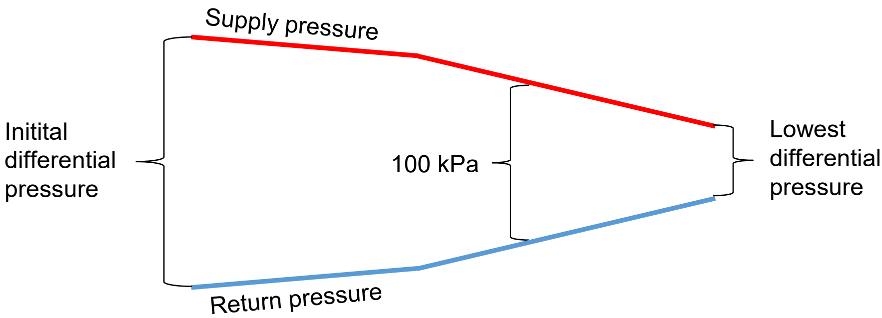

Figure 8
Pressure cone of a bottleneck situation. Presented on a poster in The 16th International Symposium on District Heating and Cooling, HafenCity University Hamburg, September 9th - 12th, 2018 [53], describing the results in [54].

According to the results in Paper VI, Bottlenecks often originate from the difficulties in correctly predicting the future and district heating networks not evolving in the way planned for from the beginning. This results in the piping and pumping system not being optimally dimensioned according to the characteristics and properties of the new network setting. As described in section 3.1, the lower temperature difference of the fourth generation of district heating will also increase the risk of bottlenecks in district heating networks. This is especially an issue in mature district heating systems, as these systems have a higher hydraulic resistance, resulting in even higher pressure losses [55]. The development towards lower system temperatures will thus increase the need for bottleneck solutions.

5.2 Present view of bottlenecks and solutions

There are many possible ways to solve bottlenecks. Except for more pumping, which aims to increase the differential pressure with pump work, they all aim at decreasing the pressure losses in the pipes. It could either be by increasing the pipe area (equation (2.3)) or by decreasing the flow to the affected area (equation (2.3)).

In many studies, lower system temperatures are connected to smaller heat demands in buildings in the future, due to energy directives and renovations of existing buildings, and thus not seen as a problem [32]. The work of renovating and improving the energy performance of existing buildings is, however, time-consuming and resource-intensive work [56], [57]. Therefore, other solutions to the increased flow will probably be needed in the meantime, in order to achieve the other advantages associated with lower system temperatures.

Bottlenecks in literature are sometimes mentioned as something that could have affected the outcome of studies but was not accounted for. This is, for example, the case in a study regarding the introduction of heat pumps and solar collectors as distributed heat sources in district heating networks [58] and in a study dealing with the potential of thermal energy storage [59]. Bottlenecks are also mentioned in studies about simulation programmes, with the feature to be able to discover bottlenecks [60], [61], which indicates the importance of them being discovered.

Pressure losses related to lower system temperatures are discussed somewhat more than bottleneck problems. If pressure losses are accounted for, problems are, however, often thought to be solved by measures in the distribution system. This is probably due to that the problems, and thus the solutions, with too-large pressure losses in the pipes are most apparent in the distribution system, because the differential pressure is a distribution system parameter. Therefore, most often only solutions such as more pumping [62] or larger pipe areas [63] are discussed. Sometimes, lower system temperatures leading to more pump work is discussed, but the risk and effect of bottlenecks and the pressure situation in district heating networks is not mentioned [35]. Tol and Svendsen simulated a network with storage tanks for domestic hot water, which could illustrate a district heating network with distributed thermal energy storages. It was shown that this solution led to the possibility of using smaller pipe dimensions, meaning that such storages could be used to decrease the flow velocity and thus the pressure losses [62]. Li and Wang discussed the importance of having a holistic view of the district heating system in order to achieve the highest system efficiency. The same study also pointed out demand side management (DSM) and thermal energy storages as able to decrease the peak flow [64].

Pressure losses, bottlenecks, and possible bottleneck solutions are thus mentioned in the literature, but not coupled to each other. Bottlenecks may affect the control of the whole district heating network, which is why it is important to address them to be able to, for example, lower the system temperatures and increase the system efficiency. Furthermore, there are many possible flow-reducing actions either not discussed or not used presently as solutions to bottlenecks and increased pressure losses. In many cases, such solutions may be more effective and advantageous for district heating networks than the ones used.

Additionally, bottlenecks could be bottlenecks for optimisation of the district heating network. For example, bottleneck areas could mean a need for a higher supply temperature in the district heating network. If the bottleneck could be eliminated, the network could thus be operated in a more efficient way. In that perspective, the area with the worst differential pressure in the district heating network could also be a bottleneck for optimisation, which gives the work in this thesis a more general field of application.

6 Methodology

In this chapter, first relevant theoretical backgrounds to the used methodologies are presented. Thereafter, an overview of the methodology used in each paper is described and connected to the theoretical background where this is important. An argumentation of why the used methodologies were chosen and a discussion about reliability and validity is also included.

In the papers, many different methodologies were used: simulations, literature studies, a survey, interviews, a cost study, and workshops. Some of these studies were performed in order to obtain proper data for further calculations or simulations, some were used to compile results directly, and some were used as input in order to develop the results. By using this interdisciplinary approach, it was possible to meet the different aims of the studies. This variability and different aims led to a broader picture of the problems related to both prosumer introduction and bottleneck problems and solutions.

The simulations in the papers were performed in NETSIM. In Paper I, Winsun 0709 was also used to develop input data to the NETSIM simulations. Both these programmes are further described in section 6.1.

6.1 Simulation tools

6.1.1 NETSIM

NETSIM is a district heating and cooling simulation programme, used by more than 70 companies all over the world. It is used to simulate thermic networks in order to optimise different parameters in the network, plan changes to the network, and increase knowledge of the network. Examples of specific use of NETSIM could be to find bottleneck pipes and discover cold water stalls during the summer [65]. In NETSIM it is possible to simulate district heating and cooling networks in stationary and quasi-dynamical simulations. The results are achieved via an iteration process, where relaxation and stop criterion are to be decided beforehand. The relaxation is the value of which the calculator needs to adjust the input data of the next iteration. It is normally set to 0.5 but if needed for the calculation to converge, it could be increased to 0.8 or 0.9. The stop criterion is the value of which the calculation is seen as finished and describes the difference in pressure between two consecutive iterations. It is usually set to 0.005 but any value under 0.09 can be seen as a finished calculation. The appearance of a calculation model and of the result from a stationary network simulation can be seen in Figure 9. In both the calculation model and the result model, the pipes are shown as lines and the nodes are shown as circles. In the nodes, for example, production units, consumers, pumps, and bypasses are situated. The colour of the pipes in the result model represents the differential pressure (kPa) in Figure 9, but this could be altered to show the mass flow rate (kg/s), the flow velocity (m/s), the temperature (°C), the pressure (kPa), the pressure level (kPa), and the pressure gradient (Pa/m), for both the supply and the return pipes.

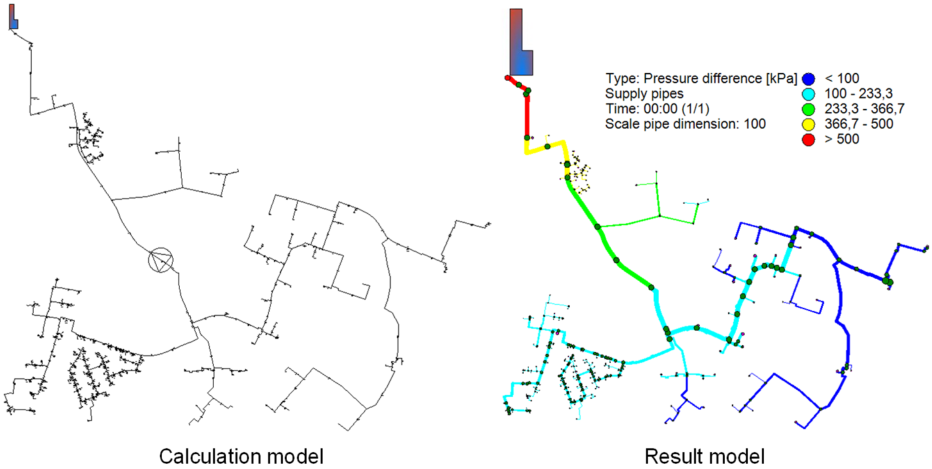

Figure 9
Example of NETSIM calculation model view and result model view.

The pressure losses are in NETSIM calculated according to equation (6.1) (friction pressure loss) and (6.2) (individual pressure loss). The friction factor is calculated as in equation (6.3) for Reynolds numbers larger than 2300 and as in equation (6.4) for Reynolds numbers smaller than 2300. Reynolds number is calculated as in equation (6.5). In equations (6.1)-(6.5), Δp is the pressure loss in a pipe (Pa), K_1 is calibration factor 1 (-), K_2 is calibration factor 2 (m^{-1}), d_i is the pipe inner diameter (m), ρ is the fluid density (kg/m^3), v is the flow velocity (m/s), L is the pipe length (m), λ is the friction factor (-), g is the gravitation constant (m/s^2), z_d is the elevation level upstream (m), z_u is the elevation level downstream (m), ξ is the individual pressure loss coefficient (-), ε is the roughness in the pipe (m), Re is Reynold's number, and μ is the viscosity (kg/m/s) [65].

$$\Delta p = (K_1 + K_2 \cdot d_i) \cdot \rho \cdot \left(\frac{2 \cdot v^2 \cdot L \cdot \lambda}{d_i} + g \cdot (z_d - z_u) \right) \tag{6.1}$$

$$\Delta p = \xi \cdot \rho \cdot \frac{v^2}{2} \tag{6.2}$$

$$\frac{1}{\sqrt{\lambda}} = -4 \cdot log_{10} \cdot \left(\frac{\varepsilon}{3.7 \cdot d_i} + \frac{1.413}{Re \cdot \sqrt{\lambda}}\right) \tag{6.3}$$

$$\lambda = \frac{16}{Re} \tag{6.4}$$

$$Re = \frac{\rho \cdot d_i \cdot v}{\mu} \tag{6.5}$$

The cooling in the substations is calculated according to equation (6.6). The temperature drop in the pipes is calculated as in equation (6.7), where K is calculated as in equation (6.8) and M is calculated as in equation (6.9). C_h is defined for each pipe type and is increasing for increasing pipe size. In equations (6.6)-(6.9), Δt is the cooling at a consumer (°C), P is the consumer heat power (W), $\dot{m}$ is the mass flow rate (kg/s), c_p is the specific heat capacity for water (J/kg/°C), t_d is the temperature downstream in a pipe (°C), t_u is the temperature upstream in a pipe (°C), L is the pipe length (m), c_h is the total heat transfer coefficient (W/m/°C), g is the gravitation constant (m/s^2), z_d is the elevation level upstream (m), z_u is the elevation level downstream (m), and t_γ is the surface temperature of the pipe (°C) [65]. The effect of flow velocity on heat losses is accounted for only in that a larger mass flow means a smaller heat transfer coefficient, which accounts for the decreasing residence time of the water in the pipe and thus smaller heat losses. It can thus be seen that the effect of increasing convection on the heat transfer coefficient due to increased flow velocity is not considered. The results of the simulations are, however, shown to agree with the reality during calibrations, why the results may be seen as reliable, and this effect not very significant in this context.

$$\Delta t = \frac{P}{\dot{m} \cdot c_p} \tag{6.6}$$

$$t_d = \frac{M}{K} + \left(t_u - \frac{M}{K}\right) \cdot e^{-K \cdot L} \tag{6.7}$$

$$K = \frac{c_h}{c_p \cdot \dot{m}} \tag{6.8}$$

$$M = \frac{-g \cdot (z_d - z_u)}{c_p \cdot L} \cdot K \cdot t_\gamma \tag{6.9}$$

6.1.2 Winsun 0709

Winsun 0709 is a TRNSYS based calculation programme used for calculating the theoretical monthly and annual output from solar collectors and solar panels in different locations [66]. TRNSYS stands for Transient System Simulation and is a very widely used software environment used for simulating transient systems, most commonly thermal and electrical energy systems. The types of solar collectors possible to simulate in the programme are standard types of flat plate collectors, evacuated tube collectors, and one type of unglazed collector used for pool heating.

6.2 Environmental data

The environmental calculations were based on national guidelines and values. The environmental data were collected first-hand from *Miljöfaktaboken - Estimated emission factors for fuels, electricity, heat, and transport in Sweden (Miljöfaktaboken)* [67]. If the needed data were not available in *Miljöfaktaboken*, data from *Agreement in the Heating Market Committee 2013* [68] was collected.

The data in *Miljöfaktaboken* are based on examinations, assessments, and compilations of existing life cycle assessments. The total environmental impact, including extraction of raw material, refining of raw material, transport, and incineration, is included in the presented data. The data in *Miljöfaktaboken* is describing Swedish conditions. Data for different types of wood fuels, energy crops, bio oils, waste fuels, fossil fuels, peat, transport biofuels, fossil transport fuels, electricity, and solar heat is presented in the report. All studies that are included in the basis of the presented data meet some requirements: the data must be allowed to be published, data must be presented per emission parameter (for example in carbon dioxide, methane, and nitrous oxide instead of carbon dioxide equivalents), and data must be presented per energy unit or possible to convert to this form.

The data in *Agreement in the Heating Market Committee 2013* describe the emissions in carbon dioxide equivalents and the primary energy factors for many energy sources. The data in this report are mainly collected from *Miljöfaktaboken*, but sometimes complemented with data from other Swedish sources.

For district heating produced in CHP plants, the environmental effect of the input fuel needs to be allocated between district heating and electricity. This allocation was performed according to the efficiency method, and the factors for respective energy type was collected from *Miljöfaktaboken* [67]. The efficiency method is based on calculating the alternative efficiencies if only district heating or only electricity was produced with the same fuel, and then calculating the resulting amount of the input fuel that should be allocated to district heating and electricity, respectively, using equation (6.10) (district heating) and equation (6.11) (electricity), where $\alpha_{heat,i}$ is the allocation factor for the heat for fuel i (-), $\alpha_{p,i}$ is the allocation factor for the electricity for fuel i (-), $Q_{heat,tot}$ is produced heat, excluding heat produced by flue gas condensation (kWh), $Q_{p,tot}$ is the total produced electricity (kWh), $\eta_{heat,i}$ is the reference efficiency for heat-only production for fuel i (-), and $\eta_{p,i}$ is the reference efficiency for electricity-only production for fuel i (-). This is the method used in Directive 2004/8/EC of the European Parliament and of the Council [69] and one of the methods proposed by the greenhouse gas protocol [70].

$$\alpha_{heat,i} = \frac{\frac{Q_{heat,tot}}{\eta_{heat,i}}}{\frac{Q_{heat,tot}}{\eta_{heat,i}} + \frac{Q_{p,tot}}{\eta_{p,i}}} \tag{6.10}$$

$$\alpha_{p,i} = \frac{\frac{Q_{p,tot}}{\eta_{p,i}}}{\frac{Q_{heat,tot}}{\eta_{heat,i}} + \frac{Q_{p,tot}}{\eta_{p,i}}} \tag{6.11}$$

6.3 Interviews, survey, and workshops

There are many ways to define an interview study. Some of the most common ways describe how structured the interview is and if the purpose is to gather qualitative or quantitative data.

When quantitative data is sought, the purpose is often to collect facts from the interviewee, whereas qualitative data instead describes the interviewee's interpretations of a matter [71].

Regarding the interview structure, there are mainly three ways to describe the interview: the structured interview, the unstructured or open interview, and the semi-structured interview [72], [73]. In a structured interview, the questions and the order of the questions are pre-determined and the interview is completely controlled by the interests of the interviewer. The answers are closed-ended. This type of interview yields mostly qualitative data. In a semi-structured interview, the question areas and their order are pre-determined as well, but this format allows for follow-up questions. In this format also, the interview is controlled by the interests of the interviewer. The answers could be both closed-ended and open-ended. This type of interview could produce both qualitative and quantitative data. In an unstructured or open interview, one large question is explored. The questions are determined during the interview in an emphatic way that follows the interests of the interviewee. The answers are open-ended. This type of interview yields qualitative data [74].

A survey could be seen as the most extreme form of the structured interview. There are many ways to collect the facts; for example, by face-to-face surveys, telephone surveys, or computer-based surveys. The objective of the chosen survey form is to collect facts with as high quality and as few faults as possible but not use more resources than necessary. There are mainly four types of error that affect the results in a survey study. The first type of error is the sampling error, which means the difference between the results of the sample and the results of the population, as the sample can never describe the whole population perfectly. The second type of error is the coverage error, which means that some elements of the populations are not represented in the sample. The third type of error is the nonresponse error, which means that not all respondents answer the survey. The fourth type of error is measurement error, which means that the respondents may interpret the survey questions differently and thus not answer in the same way [71].

Workshops can be used for many purposes, including as a research methodology. It is often used to produce data regarding forward-oriented processes, such as organisational change. The group dynamics in workshops can work to reveal issues and solve problems in a way that is not possible in, for example, interviews. There are some issues and important parameters regarding workshops with a research purpose. For example, the researcher in workshops with a research purpose should balance between a clinical and an ethnographic role. A clinical role means that the researcher focuses on the needs of the participants and the ethnographic role means that the researcher focuses on the research output. It is important to keep a balance between these roles, in order to achieve an efficient workshop process. The research workshop style could, moreover, be either collaborative or collegial, where a collaborative workshop means that the researcher is in control of the workshop and a collegiate workshop means that the participants control the process. Issues with workshops are that they could be hard to document and that the participant match is important. It is thus advised that a dedicated person for taking notes or videotaping the workshop is designated and that participants all share the same technical language regarding the content of the workshop [75].

6.4 Methodology used in the papers

The aim of Paper I was to describe technical issues originating from the introduction of prosumers into district heating networks. The results in Paper I were mainly based on simulations in NETSIM. The simulations were performed on an area called the Western harbour in the city of Malmö. The input data came from simulations in Winsun 0709, data from the Malmö district heating network, and measured data. The analysis of the results was mainly based on differential pressure, local supply temperature, and flow velocity. Possible pipe fatigue was analysed to some extent as well. Simulation as a method was chosen because it is easy to try delimited cases and investigate the conceptual outcome by this method. The alternative would have been to test real cases, but it would be more difficult to isolate all cases that were tested and more time consuming as well. This was not possible to perform within the scope of the study. Furthermore, the aim of the study was to achieve conceptual results, which is why simulation was deemed to be the best method. NETSIM was chosen as the simulation programme because this programme was used by the district heating company managing the geographical target area, which meant that the basic input data and models were already validated with real data. The technical factors investigated were important in order to see possible problems and issues that could arise when prosumers are introduced into district heating networks. Heat losses would also have been interesting to include, but heat losses are more thoroughly investigated by other researchers, which is why it was neglected in this study.

The aim of Paper II was to investigate the effects of district heating prosumers in a newly built area called Hyllie, with special emphasis on energy balance and environmental outcome. Different supply temperatures were investigated. The results in Paper II were developed by simulations and calculations. First, simulations on different heat pumps and cooling machines were obtained from a heat pump and cooling machine manufacturer. Other input data to the NETSIM simulations was obtained from measured and simulated values from the Malmö district heating network and from municipal future plans. Data to calculate the environmental outcome were obtained by national values [67], [68]. The analysis of the results was mainly based on energy balance, primary energy, and carbon dioxide emissions. Different types of electricity used in the environmental calculations were investigated and analysed. Technical parameters in the form of differential pressure, local supply temperature, and flow velocity were also slightly included in the analysis. Simulations were chosen as a method in this paper, too, partly due to the same reasons as in Paper I, but additionally because the geographical target area in this study was not yet completed, which is why it would not be possible to perform the study in the real world. Primary energy was chosen as an important factor to study because it gives a good picture of the energy benefit in the form of resource efficiency. Carbon dioxide emission was chosen for analysis because it is an important environmental parameter for climate impact, which is one of the current main issues in the world. Other environmental parameters could have been chosen for investigation, for example water use or biodiversity, but the ones chosen were considered to be most relevant for the target group of the study, which is developers of district heating in any form. Primary energy use and carbon dioxide emissions are often used as quality indicators of energy companies and often used in district heating research.

The aim of Paper III was to investigate the possible prosumer potential and environmental outcome of prosumer introduction in the same district heating area as in Paper II, called Hyllie. Two prosumer cases were investigated, one where the prosumers were allowed to deliver heat outside of the Hyllie area (called extern) and one where the heat production was restrained to keep the prosumer heat within the Hyllie area (called intern). The results in Paper III were developed through simulations in NETSIM and further environmental calculations. The input data were for existing buildings and network parameters obtained from measurements in the Malmö district heating network and consumer agreements. For not yet built buildings, data came from plans and calculations achieved from the individual building contractors, the district heating company, and municipal plans. Environmental data for this paper were also obtained from national values [67], [68]. The analysis of the results was based on heat balance during a year for different output temperatures and cases, COP, carbon dioxide emissions, and primary energy used. Also, different types of electricity and two different methods to keep within the legal domestic hot water temperature boundaries were investigated and analysed. One of the methods was to increase the temperature of the water from prosumers with a heat pump and the other was to increase the local supply temperature of the consumer domestic hot water with an electric boiler. Simulation was chosen as a method for the same reasons as in Paper II. The same environmental factors as in Paper II were chosen to be analysed, and for the same reasons.

The aim of Paper IV was to examine different ways to solve bottleneck problems and to investigate the current state of bottleneck problems in Swedish district heating networks. The results in Paper IV were developed through a literature study and a survey. The literature study was performed in order to see how district heating bottlenecks and bottleneck solutions are handled and described. The survey was sent to all relevant members of the former Swedish District Heating Association, now a part of Swedenergy. These companies account for 98 % of district heating deliveries in Sweden. The survey went to 131 district heating companies and 89 answers were returned. The analysis was based on a compilation of the survey results in combination with input from the literature study. A survey method was chosen because the aim was to collect facts about the bottleneck problems in district heating companies in Sweden. More openly structured interviews would thus be unnecessary to fulfil this objective. A web survey was chosen instead of a telephone or an in-person survey because these alternatives would have been much more time consuming without providing more relevant information. The possible errors for survey studies [71] were handled in several ways. The sampling error was considered to be low, because the survey was sent to almost the whole population (district heating companies in Sweden). The coverage error was probably low, too, for the same reason. It was, nevertheless, a specific group (district heating companies, not members of the District Heating Association) that did not receive the survey, which could have affected the results. The probability of the omitted companies all having similar, specific types of bottleneck problems was, however, considered to be small. The nonresponse error was probably more important, as 32 % of the surveyed companies did not answer the survey. Even if the larger part of the surveyed companies, 68 %, answered the survey, it was hard to know if the companies experiencing or the companies not experiencing bottleneck problems responded to a greater extent. All types of answers were however represented by the respondent companies. An attempt to minimise the measurement error was made partly by developing the questions with a researcher experienced in surveys and partly by having many simple multiple-choice questions. The respondents were, furthermore, often given the opportunity to clarify their answer.

The aim of Paper V was to investigate how different bottleneck solutions work technically in different district heating network configurations and to estimate the cost ranges and parameters that affect the cost of the bottleneck solutions. The results in Paper V were developed through simulations on a fictitious district heating network called the Pasture and cost calculations. The simulations were performed on four different network configurations: one main configuration called 'original', one configuration describing a district heating network with a ring structure, one configuration including larger altitude differences, and one scenario with lower heat density. All the different bottleneck solutions were to increase the lowest differential pressure from 0 kPa to 1 kPa for the dimensioning winter outdoor temperature. The extent of the solution needed and the effect on the district heating network were thereafter analysed. The cost calculations were based on the lowest possible and the highest possible costs for the investigated bottleneck solutions, including investments, service and maintenance costs, and fuel costs. Data regarding costs were obtained from experts on respective bottleneck solution technique. The analysis of the technical results was based on the difference in magnitude of the bottleneck solutions needed in different network configurations, as well as physical flow and pressure prerequisites for different flow situations. The analysis of the economic results was based on the cost order of the different bottleneck solutions, i.e., which solutions were more expensive and which were less expensive. Both the order within the same network configuration and the differences in order between the network configurations were considered. Simulation was chosen as a method partly because it would be very difficult to perform the studies on different network configurations but still achieve comparable results in the real world. In the simulation environment it was possible to test the same district heating network but with slightly different properties. Moreover, it would be very time consuming and expensive to test all the bottleneck solutions in the different network configurations in the real world. Another reason for using simulations was that it was sufficient to fulfil the aim of achieving more conceptual results. NETSIM was chosen as a simulation programme because it was a familiar software and because the basic input data were already available and validated by the cooperating district heating company. The cost study was performed on direct costs from a lifecycle perspective, but indirect costs and possible savings were excluded from the study. The cost picture would have been more complete if these factors had also been included, but the scope and timeframe of the study did not allow the much more extended study this would have led to. A small extra study about possible savings was, however, included in the article, in order to give an extra perspective on the economy issue of bottlenecks.

The aim of Paper VI was to investigate district heating developers' views of bottlenecks and bottleneck solutions, focusing on risks and possibilities for different bottleneck solutions. Another aim was to examine technical effects of bottleneck solutions more clearly. The interview results in Paper VI were developed through semi-structured interviews with district heating companies. Six companies were interviewed. In the later interviews, few new facts emerged, and the interview study was thus seen as saturated. The interviewee companies were chosen according to the survey answers in Paper IV. Companies that had used many types of bottleneck solutions were chosen. Apart from that, emphasis was put on interviewing different types of companies considering, for example, size and management. The interviewees were responsible for the development of the district heating network, both technically/strategically and economically. In some interviews, these features were combined in one person and in some interviews, two or three interviewees participated. The simulation results were developed through simulations in NETSIM. The same network as in Paper V and the original network configuration was used. The solutions were simulated during different seasons: mild winter, spring/autumn, and summer, in order to determine whether some effects were more profound for some seasons and to see which effects the solutions had on the network during a year. The analysis of the interview results was based on a compilation of the interview results and an analysis of differences and similarities between the companies. The analysis of the technical results was based on similarities and differences between the outcomes for different seasons. Technical parameters analysed were heat and temperature losses, local supply temperature, location of the building with the lowest differential pressure, and possibility to reduce the initial supply temperature. Because one part of the aim of the study was to collect the companies' views of risks and opportunities, i.e., qualitative data, a semi-structured interview was chosen as the method. The interviewee or interviewees here represented the view of the entire company. The alternative would have been to conduct a completely unstructured interview, but to achieve the data wanted, the possibility to control the interview was considered important. The possibility to ask follow-up questions to further investigate interesting answers and matter was also considered important, which was another reason a structured interview was rejected as a method. Simulations and the use of NETSIM were chosen for the same reasons as in Paper IV.

The aim of Paper VII was to develop a decision-making process to decide which bottleneck solution is the most optimal to perform in different situations. The results in Paper VII were developed by using knowledge achieved in Paper IV-Paper VI to outline a preliminary bottleneck solution choosing methodology. Thereafter, two workshops were performed in order to evaluate and improve the methodology. One of the workshops was with persons from the same company but with different positions and one workshop was with persons from different companies but with roughly the same position. In the workshops, advantages and disadvantages with different solutions were also discussed, which thereafter was complemented with knowledge from the previous bottleneck papers and presented in table form in the paper. One researcher was dedicated to taking notes during the workshops. An interview with a district heating company regarding a real bottleneck case was also performed and presented, in order to illustrate how the decision-making process could be used. The analysis of the results was based on the final decision-making process and which factors in the mentioned table were important for each process step. Workshop was chosen as a method partly because the decision-making process could be seen as a forward-oriented process and partly to utilise the issue-resolving group dynamics present in the workshop environment. Interviews were not considered to be as effective in this matter. Workshops were thus considered to give the most input to the decision-making process in the most effective way. To get many different perspectives but still uphold the requirement of the same technical language among the participants, two workshops were performed. In the first workshop, the use of participants with different positions within the company provided a broader perspective of the decision-making process. The fact that they came from the same company was their common factor. In the second workshop, the professional position among the participants was, instead, the common factor, but the fact that they were from many different companies from all over the country gave a more varied input to the study. Regarding the researcher role, we leaned towards the ethnographic role in order to achieve better quality of data, but the clinical role was still somewhat upheld as the workshop participants could all make use of the discussions in their professions. The participants would, furthermore, be able to make use of the decision-making process in the future. The workshops were performed in a collaborative way instead of a collegial way, as we had a specific target with the workshops and wanted to be sure to reach that target within the workshop timeframe. The case study interview was considered to be a time efficient way to show how the decision-making process could be used. Another way to obtain these data could, for example, have been to perform simulations and calculations. This would, however, have been a less time efficient way to achieve the same data, as the company had already performed all the necessary calculations, simulations, and background studies.

6.5 Reliability and validity

The reliability of the simulations was considered to be very high because simulations show the same results with the same input data in the same programme. Moreover, the basic input data in the simulations were already validated with real data by the collaborating district heating company, which means that the simulation programme gave a good picture of the reality. Even if it was hard to mirror the real world exactly, simulation was a good way to achieve conceptual results of what happens in district heating networks in different situations. The aims of the simulations in the studies included in this thesis were mostly to achieve conceptual results. More specific results could be harder to obtain with a simulation study.

The reliability of the environmental calculations was mainly affected by the environmental input data, which could change over time. For example, technical development could affect these data. By clearly presenting which input data have been used and why, the frames within which the study is valid is hopefully apparent. The important conditions for the outcome of the environmental studies will, however, not change over time and constitutes generic results that can be used by the target group also in the future.

Regarding the reliability of the survey study in Paper IV, the risk of researcher bias was lessened by letting more experienced researchers, as well as employees of a district heating company, evaluate the survey questions before the surveys were sent out. The questions, however, addressed the present state of the district heating company, which means that the answers would change over time. The knowledge about the district heating network and the bottleneck problems of the respondent person may also affect the results. The answers, however, showed that bottlenecks are a common problem in Swedish district heating networks. The survey also managed to fulfil the aim of investigating various possible bottleneck causes and solutions.

The reliability of the interview study could be affected by, for example, technical issues and the role of the researcher. All the interviews were recorded and in the few cases where the respondent's answers were not clear, the respondent was contacted for clarification. The first interview was conducted together with a more experienced interview researcher to achieve more redundancy in this interview and to obtain valuable advice on how to be a better interviewer. The aim of the interviews was to collect as wide a variety of risks and opportunities as possible for the different bottleneck solutions and for many different bottleneck situations. Another aim was to investigate motivations and important factors leading to the choice of a bottleneck solution. The interview study was continued until almost no new answers were revealed in order to fulfil this purpose.

The reliability of the workshops was affected by the same factors as the interview study. In the workshops, another researcher had the main task of taking notes during the workshops. The workshop was, furthermore, planned with a researcher experienced in interview and workshop techniques. The different backgrounds of the workshop participants was meant to give a more varied input in order to enhance the usability and generalisability of the decision-making process. Additionally, the fact that all workshop participants were somehow experts on district heating and district heating development contributed to a more valid result.

7 Overview of results and analysis

In this chapter, the most important results from the studies are presented. First, the prosumer results and analysis are presented and then the bottleneck results and analysis are presented.

7.1 Prosumers in district heating networks

The prosumer results indicate that there is great potential to introduce prosumers into district heating networks. Buildings with a cooling demand, such as offices, supermarkets, shopping centres, and indoor ice rinks, are potential prosumers due to their available excess heat. The same applies for buildings with solar collectors on the roof. Some factors are, nevertheless, important to take into account in order to be sure that introducing prosumers does not sub-optimise either the technical function, the environmental outcome, or the consumer experience of the district heating network.

The results showed that one important aspect when introducing prosumers was that prosumer summer production (when the heat demand is often lower) could be much higher than the winter production. This can be seen in Figure 10, which shows a duration chart and hourly energy use over a year for Hyllie, with and without prosumers. This may affect both the economy of the prosumer solution, as district heating often is cheaper during the summer, and the possibility to utilise all the prosumer potential. The latter could for example be solved by seasonal thermal energy storages, but the viability of these is not obvious [76], [77], [78]. Another issue with prosumers' high district heating production during the summer is that prosumer production, instead of prosumer consumption, may be decisive for the pipe dimension needed. This could pose a problem, especially when introducing prosumers into an already existing district heating network, where the pipes are dimensioned for heat consumption. Furthermore, prosumers could contribute to an increase of the differential pressure in the area close to the prosumers.

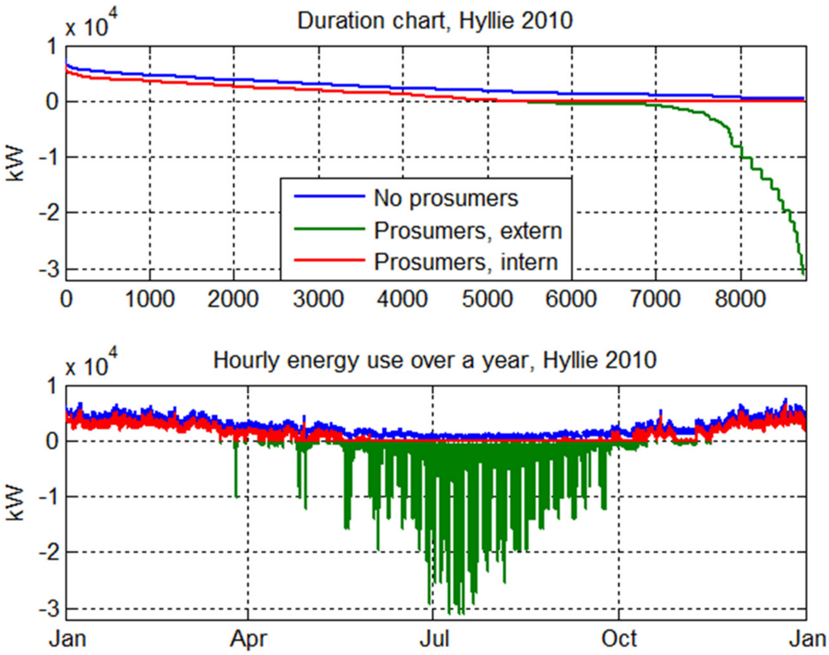

Figure 10
Duration chart and hourly energy use over a year for Hyllie, with and without prosumers [79].

If prosumers were allowed to deliver heat with a lower supply temperature than the rest of the district heating network, some specific technical problems occurred. For example, this sometimes led to lower local supply temperatures for consumers. This could cause difficulties in delivering enough heat to consumers and to an increased risk of legionella growth in consumer heat systems. Due to the lower supply temperature, the flow was affected too, which affected both the differential pressure and the flow velocity in the district heating system. The flow velocity in the pipes increased because a larger flow was required to deliver the same amount of heat, according to equation (2.1). The differential pressure at consumers that were reached by the heat from prosumers both increased and decreased, depending on how much heat the prosumer delivered and the location of the consumer in question. If the prosumer created its own pressure cone, the differential pressure was increased, especially close to the prosumer. If the prosumer heat was, instead, mixed into the flow from the rest of the district heating network, the differential pressure decreased, which could be explained by equation (3.1). The way the differential pressure in the district heating is controlled may also affect what happens with the differential pressure, both close to and far away from the prosumers.

One thing that affected the environmental outcome of a prosumer was if the prosumer needed a large proportion of electricity to function. This was, for example, relevant for heat pumps increasing the temperature of the available excess heat or if electric domestic hot water heaters had to be used. The environmental outcome was then dependent on how the electricity was produced. A lower supply temperature from heat pumps, however, increased the COP, thus giving the type of electricity somewhat less impact. The efficiency of solar panels is also increased by a lower supply temperature, which leads to larger possible environmental benefits. The type of district heating source that was replaced by the prosumer's heat production was also very important when evaluating the total environmental outcome. The results regarding carbon dioxide and primary energy often aligned but sometimes diverged. It mainly differed when the electricity was regarded as stemming from a Nordic residual mix. The reason it diverged was that the district heating exchanged by prosumer heat consisted of waste incineration, which led to very low primary energy use but much larger carbon dioxide emissions. The environmental results for different types of electricity scenarios for the Hyllie intern case when the prosumer heat temperature is increased with heat pumps can be seen in Figure 11.

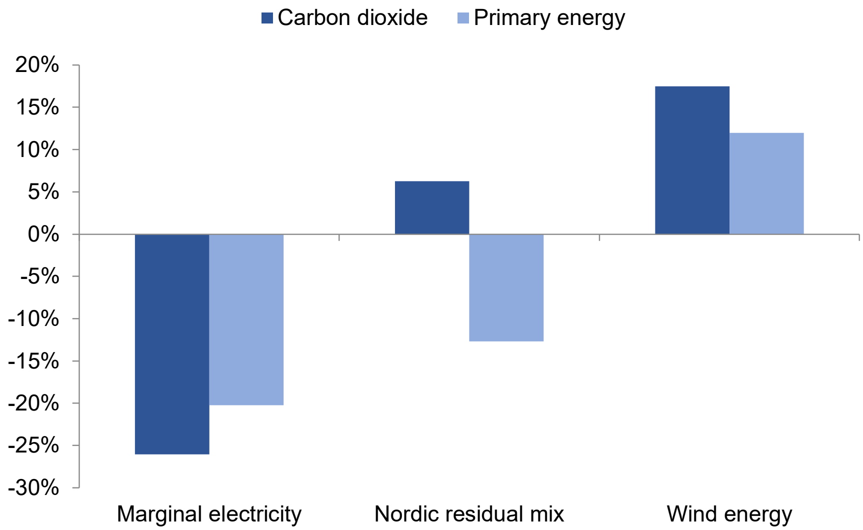

Figure 11
Environmental results for Hyllie with prosumers, intern case, and temperature of the prosumer heat increased with heat pumps. Modified from [79].

The fact that many prosumers often produce more heat during the summer may lead to a better environmental outcome. This depends on the electricity demand in the society being much lower during the summer, meaning that peak electricity units often running on fossil fuels are not running [80]. Moreover, the electricity during summer is more likely to be produced by, for example, solar panels. These effects, together with seasonal thermal energy storages, could render an important synergy effect between the heating system and the electricity system, where excess electricity could be stored as heat in seasonal energy storages and used when there is a larger heat demand, thus outcompeting less sustainable energy sources.

It is thus possible to create a more efficient district heating system and energy system by utilising prosumer heat, even if there are some factors that must be addressed and controlled to achieve this. Regarding the technical aspects, many of the possible problems that may occur can lead to dissatisfied customers, which is not good for either the business or the reputation of either the district heating company or district heating as a heat supply alternative. This may affect both the present and the future competitiveness of district heating. Regarding the environmental aspects, each prosumer situation must be evaluated with respect to environmental values for the district heating production that is replaced, the prosumer heat production, and the electricity demand. For as comprehensive an analysis as possible, prosumer effects on the district heating network in a larger perspective should be considered as well, for example, prosumer effect on the efficiencies of other heat producing facilities and on heat losses.

7.2 Bottlenecks and bottleneck solutions in district heating networks

The results regarding bottlenecks showed that bottleneck problems are common, at least in Swedish district heating networks. The most common causes were expansion or densification of the network, which means that the main problem is difficulty predicting the future development of heat demand and grid expansion. Therefore, it is important to plan for future settlements and expansions to avoid bottlenecks. But it will never be possible to exactly foresee the future, which is why bottlenecks will continue to be present in district heating networks. Moreover, the development towards lower system temperatures will increase the risk of bottlenecks in existing district heating networks, due to a decreased temperature difference and thus more pressure losses, which is explained by equation (3.1).

The most used bottleneck solutions were to install a bigger pipe area, to increase the supply temperature, and to increase pumping power. This indicates that bottlenecks are seen as a distribution problem. The reason for this is probably that the bottleneck is a problem most visible in the distribution system. Local heat supply, most often constituting of heat boilers, and more cooling at consumers were also solutions that were used to some extent. Demand side management was not much used but was often mentioned as a possible solution in the future. The results, however, showed that neither the most efficient nor the best environmental solution was often chosen. Not even the cheapest solutions from a lifecycle perspective was chosen, even if economy was seen as the most important parameter when choosing bottleneck solutions, according to the interviewed companies. An explanation for this is that the companies seemed to lack a lifecycle perspective that includes all costs and savings of bottleneck solutions when performing the economic calculations. There is thus a need for a more systematic decision-making process that sheds light on other factors than investment costs and that views the district heating system in a more holistic way in order to identify the most optimal bottleneck solution for every situation.

Such a decision-making process is suggested by the results in Paper VII (see Figure 12). It includes seven steps: problem description (step 1), inventory of bottleneck solutions (step 2), preconditions (step 3), risks (step 4), added values (step 5), economy (step 6), and basis for decision (step 7). The idea of the decision-making process is to go through all steps, in the order described above. By following this process, solutions are rejected as early as possible in order to decrease time-consuming evaluations and calculations as much as possible.

Coupled to the process, positive and negative important factors for the most used bottleneck solutions in Sweden were evaluated. The bottleneck solutions considered were increased supply temperature, increased pipe area, increased pump work with an existing pump, increased pump work with a new, distributed pump, increased cooling, local heat supply using liquid or gas fuel, local heat supply using solid fuel, local heat supply using prosumers, and DSM. The factors were reliability, simplicity, swiftness, no investment cost, costliness, additional customer interaction, environmental outcome, and no extra maintenance demand. These results are thought to be helpful when going through the decision-making process.

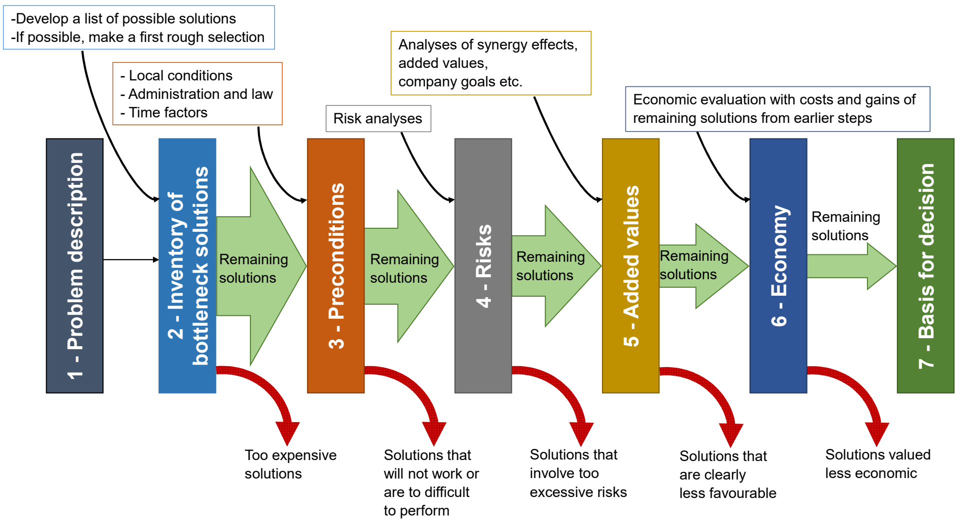

Figure 12
Proposed decision-making process for choosing bottleneck solution (Paper VII).

In step 1, the first decision-making process step, the bottleneck problem is stated. For example, the reasons for the bottleneck problem and the physical features of the area and the consumers are described.

In step 2, a list of available and possible solutions to the bottleneck problem is developed.

In step 3, preconditions are evaluated and solutions not possible to perform are rejected. Important aspects for companies when choosing bottleneck solution were, for example, future plans, time factors such as how urgent the solution is, local conditions, and directives from management. Local conditions are very important because different bottleneck solutions work better in different situations and district heating networks. One factor affecting this could be the pipe configuration; for example, the desired effect of more pumping may be hard to achieve in a ring configuration. The pressure situation and the altitude difference may also affect whether more pumping is a possible solution. Also the flow situation may affect which solutions are possible and which are not, especially when combined with the consumer situation. If there is, for example, a very smooth heat outtake curve for the bottleneck area, it may be hard to achieve enough flow reduction to reach the pressure loss reduction needed with DSM. The same issue may occur if the cooling among the consumers in the area is already satisfactory. Furthermore, legal issues could affect which solutions are possible, as many solutions, such as a new pump station, a new pipe, or a new heat supply unit, often require municipal permit.

In step 4, risks are evaluated for the remaining solutions, and the solutions with too-high risks to accept are rejected. Important aspects regarding risks for companies when choosing bottleneck solution were the robustness of the solution, the redundancy associated with the solution, and the owner situation of substations. The latter may affect the possibility of achieving more cooling among consumers. Other mentioned risks with solutions included personal safety, the solution leading to more heat losses, a decreased local supply temperature, and the effect on the lowest differential pressure location. The effect on local supply temperature was in the results mainly critical during the summer. Regarding robustness, this is a risk of, for example, prosumers as a solution. The uncertainty is whether prosumers will be able to supply heat when it is needed and what happens if the prosumer situation is altered; for example, if the supermarket or indoor ice skating rink closes. Therefore, the contract between the company and the prosumer is very important for the company, in order to increase the robustness of this solution.

Step 5 means a review of added values for the remaining solutions and a rejection of less interesting solutions. Important aspects regarding added values for companies when choosing bottleneck solutions were the robustness of the solution and the redundancy associated with the solution. Other added values included environmental gain, the possibility of the solution leading to better and more efficient control of the district heating network, and the possibility of the solution leading to more consumer contact. The latter is positive for the company-consumer relationship and may lead to more loyal customers and thus a more competitive district heating company. Another example of an added value is if prosumer heat is already available in the area, as that could lead to a simplified installation process. An example of an added value for the increased pipe area solution is if the pipe with a too-small dimension leading to the area needed to be exchanged for other reasons.

In step 6, the economy calculations are performed. This is the last step before the basis for a decision is reached. Economy was, as earlier mentioned, the most important aspect for companies when choosing a bottleneck measure. The reason for economy to be the last step before the basis for a decision is that all the facts revealed in the previous steps should be included in the economy calculation in some way. Solutions too expensive to accept are rejected in this step. Different bottleneck solutions are more or less costly in different situations and district heating networks, and the cost ranges are often large. This can be seen in Figure 13, which shows the maximum and minimum costs of some bottleneck solutions in the Pasture.

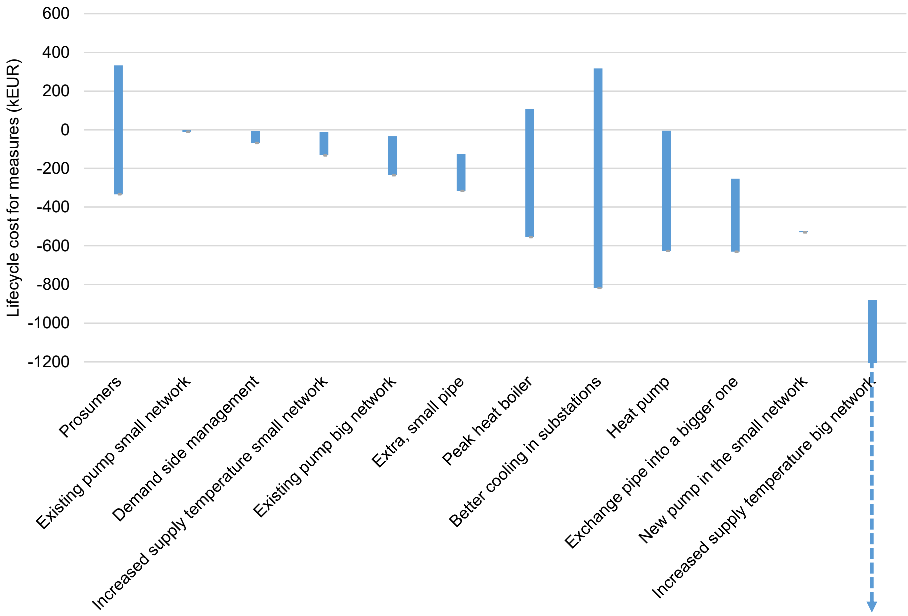

Figure 13
Cost ranges for different bottleneck solutions, if used 1 month per year in the original Pasture scenario. The blue arrow indicates that the maximum cost of 'Increased supply temperature big network' is much larger than shown, but the scale is set to show the other solutions more clearly. Modified from [81].

The blue arrow indicates that the maximum cost of 'Increased supply temperature big network' is much larger than shown (around -11 200 kEUR), but the scale is set to show the other solutions more clearly. It is evident that the most expensive solution was to increase the supply temperature in a large district heating network if not performed for a very short period. The reason for this is that the supply temperature affects many parameters in the district heating network; for example, the efficiency of CHP and heat losses. Factors affecting the economic outcome of a bottleneck solution were the investment cost of the solution, as well as the lifecycle costs and possible savings coupled to the solution.

The investment costs often depended on the situation in the district heating network; for example, how extensive the solution needed to be. For DSM and more cooling for consumers, it was, e.g., more expensive to involve many consumers than only a few. For a larger pipe area, the length and location of the new pipe affected the cost, as did whether some part of the existing pipe could still be used.

Many aspects could affect the saving potential of solutions; for example, technical effects on the district heating network, such as possibilities to decrease the supply temperature and less or more heat losses. More cooling for consumers may, for example, result in large savings because it leads to a more efficient system. Another example is that it may be economically viable to utilise prosumer heat if it is easily available.

Another thing that emerged in the studies was that a well-balanced price model for customers was important for the company revenue flow, especially when choosing the solutions of more cooling for consumers and DSM. The price model should mirror the expensive aspects of district heating production and distribution, in order to encourage the company to develop the district heating network in the most efficient way. The price model should, however, also be easy to understand for the common person [82].

In step 7, the basis for decision, the remaining solutions are evaluated. If only one solution remains, the choice of bottleneck solution is easy. If several solutions remain, the decision maker must compare and evaluate revealed advantages and disadvantages of the solutions in order to reach a decision.

8 Concluding discussion

In this chapter, the answers to the aims and objectives is first briefly outlined, in order to conclude the results covered by this thesis. Thereafter, an outlook of the importance and usability of the results and the effect of the limitations on the results is described. At last, suggestions of future studies are given.

The aim of the studies in this thesis is to contribute to the current body of knowledge regarding issues associated with the development of district heating networks. Hopefully, the results will help increase efficiency and improve both the environmental outcome and the competitiveness of district heating networks. More specifically, the aim is to look at important technical and environmental factors for prosumers in district heating networks and to develop a strategy to cope with bottleneck problems that takes the whole district heating system into account.

The results show that prosumers may cause an increased flow velocity that could cause noise problems. The production – instead of the consumption – of the prosumer could also end up being decisive for the pipe area. If prosumers have a lower system temperature than the rest of the district heating network, this can lead to a too-low supply temperature for consumers. This could lead to dissatisfied consumers and in worst case to a growth of the legionella bacteria, which can cause a serious disease when inhaled. Differential pressure could both increase and decrease depending on the properties of the prosumer. The environmental results show that the environmental outcome of a prosumer depends on whether the prosumer uses a significant amount of electricity and, if so, how the electricity is considered. If only renewable electricity is used, the prosumer is most often better than conventional district heating, but the reverse applies if the electricity is produced by, for example, coal power plants. Additionally, the type of district heating that is exchanged is important for the environmental outcome. If, for example, excess heat is replaced with heat from prosumers, prosumers may instead sub-optimise the system. The prosumer results thus show the importance of a careful evaluation before introduction, in order to not create a less efficient district heating system. If such an evaluation is performed, prosumers may improve the environmental outcome of the district heating network, as well as strengthen areas with a low differential pressure and increase district heating network competitiveness.

The results also show information about various bottleneck solutions in different district heating situations and a decision-making process for choosing a bottleneck solution. The idea of this process is to develop a list of as many possible bottleneck solutions as possible in the beginning of the process and then eliminate solutions that are not possible to perform or that are less advantageous during the course of the process. The last step before the decision is made is to evaluate the economy of the remaining solutions. The reason this step is the last step is that economy is the most important factor to district heating companies when choosing a bottleneck solution. To make a fair evaluation, it is important that all relevant facts, including risks and added values, are included in the economy calculations. The bottleneck results also highlight other solutions than the ones that are presently most used, which are increased pipe area, increased supply temperature, and more pumping. Examples of other bottleneck solutions are demand side management, local heat supply, or more cooling for consumers. The bottleneck results will hopefully lead to more informed choices of bottleneck solutions and thus a development towards more efficient and hence more environmentally advantageous district heating networks.

The results regarding both prosumers and bottlenecks are thought to be used when developing and increasing the efficiency of district heating networks. This is an important work in order to increase competitiveness of district heating, as district heating faces increasing competition, from heat pumps for example [2], [83]. As shown in the results, prosumers may lead to effects that mean more dissatisfied consumers, which leads to poorer competitiveness for the district heating network. Bottlenecks may lead to a less efficient district heating network, which also leads to poorer competitiveness of district heating networks. At the same time, prosumers and bottleneck solutions could be a way to increase the competitiveness of district heating. To open the district heating network to other heat producers may show goodwill and show that the district heating company works to improve environmental outcomes, which is good for customer satisfaction. Some bottleneck solutions may, furthermore, except for optimising the district heating network, increase customer satisfaction due to more customer contact. Two such bottleneck solutions are increased cooling for consumers and demand side management. The use of prosumers as a bottleneck solution may have the same effect. Both prosumers and bottleneck solutions could thus be used to increase the competitiveness of district heating. An increased competitiveness is, however, not a purpose of its own, other than for district heating companies. To preserve the unique advantages of district heating – for example the ability to utilise excess heat – an increased competitiveness is important to society as well. District heating is thus an important cornerstone to making the energy system more efficient [41]. If competitiveness is not increased, district heating may be outcompeted by less environmentally advantageous alternatives. It is, however, important to notice that district heating is not always the most environmentally advantageous heating alternative. In rural areas, for example, heat pumps may be a better alternative [2].

The work in this thesis also strives to contribute to the perception of district heating systems as integrated systems and to extend that perception to include the whole energy system. The former is performed by discussing issues regarding all parts of the system in the prosumer study but is more pronounced in the work about bottlenecks. In this work, an effort is made to illustrate possible solutions in the production segment, the distribution segment, and the consumption segment of district heating, and also to highlight the advantages of other solutions than the conventional. The holistic perspective of one energy system is, instead, mainly illustrated in the prosumer study by highlighting the importance of analysing the electric system when calculating the environmental outcome. In the bottleneck studies, this is mostly mentioned by exemplifying different risks and opportunities for the bottlenecks related to the electricity system.

Common to the results is that they often do not give any definite answers regarding what will happen or what is the most optimal solution. Even if the studies often are performed on case areas, the results only indicate which parameters are important to evaluate and what to investigate. Examples are shown for more understanding. The reason for presenting the results this way is that district heating is not one large unified system, unlike, for example, the electricity system. Instead, district heating systems consist of many local or regional systems with different prerequisites regarding everything from technical aspects and local prerequisites to the political and legal framework the district heating company must relate to. More specific results would then not have been as usable and generic.

The limitations of the studies may have affected the generality of the results. The fact that Swedish conditions and numbers are the basis of all included studies, for example, affects environmental specific results regarding prosumers. The results regarding which parameters affect the environmental outcome of prosumers are more general. Furthermore, the environmental results are dependent on the time factor, as other conditions may apply in the future. For example, the marginal electricity viewed as coal condensing power in Paper II and Paper III may instead consist of solar power in the future. Moreover, many district heating prosumers produce most of their heat during the summer, which further supports this scenario. With a warmer climate due to climate change, there is, however, a possibility that use of air conditioning increases [84], which reduces access to excess electricity during the summer.

The bottleneck results are affected by the national perspective as well. For example, the results regarding costs and risks and opportunities may be different in other countries. Because bottlenecks are often caused by difficulties predicting the future and because the work of decreasing system temperatures is discussed worldwide [85], [86], the general results are applicable also in other countries. For example, the decision-making process should be useful in many district heating systems.

The technical results in both the prosumer and the bottleneck studies are more coloured by the local conditions in the case areas than in which country they are situated, due to district heating systems being local or regional systems. The analysis is, however, based on physical properties of flow in pipes and heat transfer, which is why the general results should be relevant for most district heating systems, even if small justifications sometimes will have to be made. For example, the lowest allowed tap water temperature, affecting the lowest possible supply temperature, differs from country to country [15].

The focus of the studies included in this thesis is on technical, economic, and environmental factors for district heating companies, as they have the largest executive control of district heating development. For a more comprehensive view of issues and advantages of both prosumers and other bottleneck solutions, consumer perspective would have been an important supplement to the results. This is possible to perform in future studies. Other possible future studies may include a more thorough investigation of the economic and legal perspective of both prosumers and of bottleneck solutions. This may contribute to facilitating prosumer introduction and expanding the work about advantages and disadvantages regarding various bottleneck solutions. A validation of the decision-making process would be valuable as well; for example, by a study where companies choose a bottleneck solution first without and then with the help of the decision-making process. The differences between the choices could then be analysed.

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