EVALUATING SYSTEM CONSEQUENCES OF ENERGY CO-OPERATION BETWEEN INDUSTRIES AND UTILITIES

INGER-LISE SVENSSON

Linköping University
INSTITUTE OF TECHNOLOGY

Division of Energy Systems
Department of Management and Engineering
Linköping Institute of Technology
SE-581 83 Linköping, Sweden
This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyzes processes for the conversion, transmission and utilization of energy, combined together in order to fulfill specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg, and the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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Abstract

Energy conservation, energy efficiency measures, and energy carrier conversion within the industry are extremely important issues in order to deal with energy resource depletion and the threats from global warming. In Swedish industry there is potential for reductions of carbon dioxide emissions and resource use through utilization of excess heat and conversion of compression cooling to other cooling technologies using less electricity. Co-operation between industries and utilities can be obtained concerning both heating and cooling, but the choice of technologies and the profitability of co-operation are influenced by a number of factors such as the type of industry, policy instruments, the size and design of the district heating and cooling systems, and energy market prices.

In this thesis, energy co-operation has been studied on two levels: a techno-economic level and a socio-technical level. On the techno-economic level the possibilities for co-operation in two industrial cases have been studied, Scandinavian kraft pulp mills and manufacturing industry in the municipality of Södertälje:

The pulp and paper industry is one of the major energy users in Sweden, and 2.2 TWh of heat was delivered from pulp mills in 2007, mainly to district heating systems. At kraft pulp mills the excess heat can be used either internally or externally. Internally, excess heat can be used in the production process and/or to replace steam and thereby increase the production of electricity, depending on the quality of the excess heat. Externally, excess heat can be used as district heating. The trade-off between internal and external use of excess heat depends on numerous factors. The economic profitability of possible investments is influenced not only by investment costs and fuel costs; several policy instruments, including the electricity certificate system and the carbon dioxide trading scheme, also influence the choice of technology as well as the willingness to co-operate.

In the municipality of Södertälje two large industries use large amounts of electricity, district heating and cooling. The cooling demand in Södertälje is currently covered by free cooling from lake water and compression chillers; but in order to reduce the use of electricity, conversion to heat-driven cooling or increased lake water cooling can be considered. The large CHP plant in Södertälje is today not used to its full potential, but investment in heat-driven cooling and/or a cold condenser unit integrated with the CHP plant could increase the plant’s operation hours. New investments in district cooling could increase the level of co-operation between the two industries and the local utility, but depending on policy instruments, energy market prices and the possible exchange of heat between Södertälje and Stockholm, the profitability of such investments will vary.

On the socio-technical level, co-operation between utilities and industries has been studied through interviews and surveys to further analyze factors concerning co-operation beyond the techno-economic level. Results from the studies show that communication between the parties, the willingness to take risks, and trust between the co-operating parties are key factors that are as vitally important for a co-operation to take place as technical and economic factors.
Sammanfattning

Energibesparingar, energieffektivitet och konvertering av energibärare i industrin är oerhört viktiga frågor att hantera med tanke på det hot vi står inför med uttömning av resurser och global uppvärmning. I svensk industri finns det potential för reducering av koldioxidemissioner och resursanvändning genom utnyttjande av industriell överskottsvärme och konvertering av kompressionskyla till andra kyltekniker som använder mindre el. Samarbete mellan industrier och energibolag kan uppnås både för värme och kyla, men valet av teknik och lönsamheten i samarbete påverkas av ett flertal faktorer som typen av industri, styrmedel, storleken och produktionsmixen i fjärrvärme- och fjärrkylanäten samt energimarknadspriser.

I den här avhandlingen har energisamarbeten studerats på två olika nivåer: en teknologisk-nivå och en socio-teknisk nivå. På den teknologiska nivån har möjligheter till samarbete undersökts i två industriella fall, skandinaviska kemiska massabruk och tillverkningsindustri i Södertälje.


På den socio-tekniska nivån har samarbeten mellan industrier och energibolag undersöks genom intervjuer och enkäter. Resultaten från studierna visar att kommunikationen mellan parterna, vilja att ta risker och förtroende mellan parterna är faktorer som är lika viktiga för att uppnå ett samarbete som tekniska möjligheter och ekonomisk lönsamhet.
List of appended papers

Paper I

Paper II

Paper III

Paper IV

Paper V

Paper VI

Paper VII
To Matteo
Acknowledgement

I first wish to thank my supervisor Professor Bahram Moshfegh for his invaluable support and guidance during my PhD studies. I would also like to thank Professor Thore Berntsson at Chalmers University of Technology who was my co-supervisor during the first years of my PhD studies, Professor Simon Harvey at the same university who provided valuable comments on a draft of the thesis, and Associate Professor Mats Söderström who helped me with an early draft of the thesis.

The work has been carried out under the auspices of the Energy Systems Programme, which is primarily financed by the Swedish Energy Agency.

Thanks are due to the Swedish Energy Agency which funded the SEAST project (System design for Energy efficiency – AstraZeneca and Scania in Södertälje in co-operation with Telge Nät). I would also like to thank Mr Per Erik Johansson (DynaMate AB, Sweden), Mr Karl Pontenius (Scania AB, Sweden), Mr Johan Jürss (AstraZeneca AB, Sweden), Mr Göran Jansson (Telge Nät AB, Sweden) and their staff for their support in this project.

Thank you to all my colleagues at the Division of Energy Systems in Linköping and in the Energy Systems Programme, and especially thank you to Elisabeth Wetterlund for making my workdays much more fun, to Patrik Thollander and Louise Trygg for good co-operation and helpful comments on my work, to Magnus Karlsson for his help in the SEAST project, to Elisabeth Larsson for her invaluable help with all the little details that are needed to complete a PhD thesis, and to Johanna Jönsson and Mikael Ottosson for lots of fun and good co-operation.

I would like to thank my parents, my brothers and my grandparents who have always believed that I am capable of doing anything I set my mind to.

Thank you to all my friends who help me think about other things than work!

Finally, I want to thank my husband Matteo for his support and encouragement during the stressful months that preceded the completion of my thesis, and for always being there for me.
Thesis outline

The thesis gives an introduction to, and background to the seven appended papers.

Chapter 1 includes a short introduction to the research field. The chapter includes the aim and research questions of the thesis which is followed by paper overview, co-author statement and short description of the research journey that influenced the choice of topics in the papers.

Chapter 2 gives an introduction to the research field of energy co-operations. The chapter includes an overview of excess heat co-operations, cooling co-operations and TPA.

Chapter 3 presents some of the most important policy instruments that influence the Swedish energy sector.

Chapter 4 presents the Swedish district heating and cooling sector and gives an introduction to the influence of heat-driven cooling in CHP systems.

Chapter 5 gives an overview of models for CO2 valuation of electricity and use of biomass.

Chapter 6 presents the methods used in the thesis and how they have been applied.

Chapter 7 provides a description of the two cases that have been analyzed in the optimization studies.

Chapter 8 presents selected results from the appended papers in relation to the research questions.

Chapter 9 presents the conclusions of the thesis and a short overview of potential future work.
Abbreviations

BP turbine  Back Pressure turbine
CCS  Carbon Capture and Storage
CHP  Combined Heat and Power
CO₂  Carbon Dioxide
Convap  Conventional Evaporation
DC  District Cooling
DH  District Heating
ECO  Energy Company
ENPAC  Energy Price and Carbon Balance Scenarios
EU ETS  EU Emissions Trading Scheme
FGHR  Flue Gas Heat Recovery
FRAM  Future Resource Adapted Pulp Mill
HWWS  Hot and Warm Water System
MILP  Mixed Integer Linear Programming
MIND  Method for analysis of INDustrial energy systems
NGCC  Natural Gas Combined Cycle
PFE  Program For Energy Efficiency
PIvap  Process Integrated Evaporation
SEAST  System design for Energy efficiency – Astra Zeneca and Scania in co-operation with Telge Nät
TPA  Third Party Access
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1 Introduction

In this chapter the background of the thesis is described together with the aim and research questions addressed in the thesis. An overview of the appended papers is presented as well as co-author statements and a list of publications not included in the thesis.

Increased carbon dioxide emissions from fossil fuels are posing a threat to the global environment. The acknowledgement of the threat from global carbon dioxide emissions has resulted in national and international policy measures in order to decrease the rate of the global warming, and as a consequence both industries and energy utilities need to take measures to decrease the emissions. Policy measures such as the European carbon dioxide emissions trading scheme (EU ETS) could result in increased prices of fuel and electricity and thus increase the need for energy and resource efficiency.

Reduction of the use of fuel and electricity through introduction of industrial excess heat in district heating (DH) systems is one possible solution to decrease the use of fuel resources through industrial collaboration between industries and energy utilities. The use of industrial excess heat in a DH system can provide a possibility to reduce the use of fossil fuels in the utility and is often proposed as an environmentally friendly option. However, depending on the source of the excess heat and possible alternative uses of the heat, external use as DH may not always be the most economically profitable or environmentally friendly option. In some cases the best option may be to use the excess heat for internal energy efficiency measures, depending on external factors such as energy market prices, policy measures and the mix of heat production technologies in the surrounding DH system.

Another possibility for collaboration is district cooling (DC). A DC system can prove to be a means to reduce carbon dioxide emissions if investments are made to replace compression chillers with heat-driven cooling or cooling from nearby lakes. Heat-driven cooling, such as absorption chillers, has been proven in several
studies to increase the operation time of CHP plants (Maidment and Prosser, 2000; Maidment and Tozer, 2002; Trygg and Amiri, 2007). Lake water cooling on the other hand has very low operation costs and can provide a cheap cooling option for both industries and energy utilities. The choice of technology has a great impact on the local energy system, especially when large industries with a substantial cooling demand are considering conversion of their cooling supply.

From the industrial point of view, co-operation can be a new source of income and a possibility for both increased energy efficiency and lower costs. Co-operation can however also mean an increased dependence on another party. Disruptions in heat deliveries can pose a threat to possible excess heat co-operation, since the utility may find the collaboration too much of a risk. The same risk applies to cooling co-operations, since depending on another party for cooling deliveries could be considered risky in comparison to having one’s own cooling production on site.

1.1 Aim and research questions

The aim of this thesis is to analyze co-operation between industries and utilities concerning DH and DC. The thesis is based on seven papers that investigate different aspects of co-operation between industries and utilities.

The aim has been addressed in the thesis on two levels; a techno-economic level and a socio-technical level. The techno-economic level deals with the economic profitability and technical potential for collaborations. The socio-technical level deals with the human factors that influence potential collaborations and implementation of energy efficiency measures in industries and utilities. Papers I-V are all conducted on the techno-economic level but while papers I-III focus on the possible trade-offs between internal and external use of excess heat from kraft pulp mills, papers IV and V are based on a case study of co-operation concerning DH and DC in the energy system of Södertälje. The two cases reflect the differences between co-operation with the energy-intensive industries and the non-energy-intensive manufacturing industries. Papers VI and VII have been conducted on the socio-technical level. Paper VII focuses on the same type of system as papers I-III, namely kraft pulp mills, while paper VI has a broader scope and interviews have been carried out concerning other types of co-operation than excess heat sales from industries. The two research levels and the two energy system cases of the thesis can be summarized in the following research questions:
Research question 1:

How do factors such as policy measures, structure of the district heating systems, and energy market prices influence the potential for excess heat co-operations between kraft pulp mills and utilities? How does the choice of use of excess heat influence the system’s carbon dioxide emissions?

Research question 2:

How will investments in increased district cooling co-operation between industries and a utility influence the heat production, electricity use, carbon dioxide emissions and resource use of a large CHP system?

Research question 3:

What socio-technical factors influence the potential for co-operation between industries and utilities?

The connection between the papers and the research questions is summarized in Figure 1.

![Figure 1 The relation between the research questions and the papers](image)

1.2 Paper overview

Paper I

Inger-Lise Svensson, Johanna Jönsson, Thore Berntsson, Bahram Moshfegh

*Excess Heat from Kraft Pulp Mills: Trade-offs between Internal and External Use in the Case of Sweden – Part 1: Methodology*

Energy Policy, 36, Issue 11, (2008), 4178-4185

This paper presents an approach for investigating the economic trade-off between internal and external use of industrial excess heat. The approach includes a developed methodology and a model of an energy system, where both the generation and utilization of excess heat are considered. The model and methodology are evaluated using energy market prices from 2006.
Paper II

Johanna Jönsson, Inger-Lise Svensson, Thore Berntsson, Bahram Moshfegh
Excess Heat from Kraft Pulp Mills: Trade-offs between Internal and External use in the Case of Sweden – Part 2: Results for Future Energy Market Scenarios
Energy Policy, 36, Issue 11, (2008), 4186-4197

Based on the approach suggested in Paper I this paper investigates the trade-offs between internal and external use of kraft pulp mill excess heat. The trade-off, in terms of economics and CO\textsubscript{2} emissions, is analyzed for different future energy market scenarios. Questions discussed in the paper are: how the use of excess heat influences electricity production and biomass use, how CO\textsubscript{2} emissions are affected by the choice of technology, and whether some technology options are more robust than others when analyzed under different energy market scenarios.

Paper III

Inger-Lise Svensson, Bahram Moshfegh
Absorption cooling – An analysis of the competition between industrial excess heat, waste incineration, bio-fuelled CHP and NGCC

Paper III is based on the same case study as papers I and II. The objective of the paper was to investigate how the trade-off between internal and external use of kraft pulp mill excess heat would be influenced by the introduction of absorption cooling in an integrated district heating and cooling system. Questions addressed were: how the economic potential for external use of excess heat would be influenced by absorption cooling, and how the CO\textsubscript{2} emissions of the system would change.

Paper IV

Inger-Lise Svensson, Bahram Moshfegh
System analysis in a European perspective of new industrial cooling supply in a CHP system.

This paper analyzes new investments in new industrial cooling supply in the case of Södertälje. Optimizations of the joint system including both the utility Telge Nät and two companies in different industries, Astra Zeneca and Scania, are made to investigate how the new investments will influence heat production, electricity use, electricity production, CO\textsubscript{2} emissions, use of primary energy resources, and the total system cost.
Paper V

Inger-Lise Svensson, Magnus Karlsson, Bahram Moshfegh
Integrated energy systems analysis of industries and utilities – Potential for co-operation concerning district cooling and industrial excess heat
Submitted to International Journal of Energy Research

Paper V explores the potential for reduction of CO₂ and primary energy resources through investments in either free cooling or heat-driven cooling, such as absorption cooling or adsorption cooling, in the energy system of Södertälje. The investment scenarios are compared through optimizations using the energy system optimization tool reMIND.

Paper VI

Patrik Thollander, Inger-Lise Svensson, Louise Trygg
Analyzing variables for district heating collaborations between energy utilities and industries

Paper VI examines different factors that either promote or inhibit district heating co-operations between industries and utilities. The paper focuses on both successful and non-successful co-operations, and 12 in-depth interviews were conducted with six industries and six energy utilities.

Paper VII

Inger-Lise Svensson, Mikael Ottosson, Johanna Jönsson, Bahram Moshfegh, Jonas Anshelm, Thore Berntsson
Socio-technical aspects of potential future use of excess heat from kraft pulp mills

This paper aims to gain a broader understanding of the socio-technical factors that influence the use of kraft pulp mill excess heat. The paper brings together the results from previous research in papers I and II with socio-technical studies concerning barriers to, and driving forces for the implementation of cost-efficient energy investments. Four interviews were conducted with representatives from two kraft pulp mills and two energy utilities.

1.3 Co-author statement

Papers I and II are a joint effort by Johanna Jönsson and the author. Jönsson was responsible for the input data and calculations related to the pulp mill whereas the author of this thesis was responsible for the input data and calculations for the district heating system. The system modeling and optimization in the energy system modeling tool reMIND were a joint effort of Jönsson and the author of this thesis. Berntsson and Moshfegh helped with the analysis of the results.
Paper III was based on the same model as papers I and II, but the paper was planned and written by the author of this thesis. Moshfegh helped with the analysis of the results.

In Paper IV the collection of data, the modeling and the optimizations were conducted by the author of this thesis and the paper was planned and written by the same. Moshfegh helped with the analysis of the results.

Paper V was based on the same data as Paper IV and the modeling and optimization were conducted by the author of this thesis. Karlsson and Moshfegh helped with the analysis of the results.

Paper VI was a joint effort by Patrik Thollander, Louise Trygg and the author of this thesis. The interviews and surveys were conducted by Patrik Thollander and all authors contributed comments and discussion concerning the paper.

Paper VII was written with Mikael Ottosson and Johanna Jönsson. The author of this thesis wrote most of the sections in the paper but the interviews were planned and conducted by Mikael Ottosson. All authors helped with the analysis and discussion of the results.

1.4 Other publications not included in the thesis

Inger-Lise Svensson, Magnus Karlsson, Bahram Moshfegh, Göran Jansson, Per-Erik Johansson, Johan Jürss, Karl Pontenius
Integrated energy systems analysis between industries and energy companies - Potential for collaboration on industrial excess heat and cooling.

Inger-Lise Svensson, Bahram Moshfegh

1.5 Research journey

When starting my PhD studies my research project was initially oriented towards excess heat co-operations from energy-intensive industries. Through my participation in the Energy Systems Programme, I was part of a group consisting of Johanna Jönsson, Mikael Ottosson and myself. As a part of the Energy Systems Programme’s PhD course package, the final course was an interdisciplinary project in which our group conducted a study of energy efficiency and use of excess heat in kraft pulp mills. The project resulted in papers I, II, III and VII.
In 2007 I became involved in the SEAST (System design for Energy efficiency – Astra Zeneca and Scania in co-operation with Telge Nät) project, which was a project based in Södertälje, south of Stockholm. Initially the focus of my work was intended to be the use of industrial excess heat and conversion of industrial cooling. However, as the project progressed, it became clear that the amount of excess heat in Södertälje was limited and the direction of my project changed. Instead, the use of industrial cooling turned out to be a significant part of the energy system co-operation in Södertälje. Papers IV and V are based on the SEAST project.

Paper VI deals with socio-technical aspects of co-operation, and was written with Patrik Thollander and Louise Trygg. The paper was based on the results from interviews conducted for a project concerning district heating co-operation funded by the Swedish District Heating Association. Being a part of the Energy Systems Programme, interdisciplinary research has been encouraged during my time as a PhD student. As a result of the interdisciplinary project in one of the courses, the socio-technical aspects of energy efficiency and use of kraft pulp mill excess heat were analyzed in paper VII.
2 Co-operations between industries and utilities

This chapter describes the different types of co-operations between industries and utilities that have been analyzed in the thesis and discusses the effects of third party access.

There are numerous examples of Swedish municipalities where co-operations have been established between local utilities and one or several industries. In 2009 there were 61 municipalities with excess heat co-operations between industries and utilities in Sweden (see Table 1) and about 7% (in 2008) of the district heating (DH) deliveries originated from industrial excess heat (SDHA, 2011b). In addition to the excess heat co-operation, there are also other types of energy co-operations such as co-owned boilers and CHP plants, delivery of DH for industrial processes, district cooling (DC) co-operation, and out-sourcing of energy services. In this thesis the focus has been on excess heat and cooling co-operation and these are the types of collaboration that will be discussed further.

2.1 Excess heat co-operations

Excess heat co-operations are attractive from a resource use perspective, since the use of industrial excess heat can result in reduced use of fuel resources. However, this is only true if the heat sold by the industries is indeed not useful for any other purpose. There are examples of industries that have designed their processes in order to able to supply excess heat, which means that the process is intentionally inefficient (Klugman, 2008; Klugman et al., 2007). If an industry sells heat that would not be present if the industrial processes were more efficient, it is questionable whether it can be considered as excess heat.
Table 1 Excess heat co-operations in Sweden 2009 [Source: The Swedish District Heating Association]

<table>
<thead>
<tr>
<th>Kommun</th>
<th>Industrier</th>
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<tr>
<td>Arvika</td>
<td>Arvoka Ljutens AB, Schott Termofrost AB, Volvo Wheel Loaders AB o</td>
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<td>Bjur</td>
<td>Findus, Höganäs Bju AB</td>
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<td>Borlänge</td>
<td>Stora Enso Kvarnsveden AB, SSAB Tunnplåt</td>
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<td>Bromstilla</td>
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There is no clear definition of what can be considered as excess heat. Some generally accepted definitions are however “heat that cannot be directly used in the industrial processes” or “excess heat that cannot be used internally and the option is to release the heat to the environment” (SEA, 2008a). These definitions imply that for heat to be considered as excess heat, it should not be technically and/or economically feasible to use the heat in the industry’s own processes. The problem with this is that it is very difficult to determine whether a process is thermodynamically optimized and whether heat sold by industries to utilities is in fact true excess heat.

As a consequence of this, it is difficult to determine the energy and fuel resource efficiency of excess heat co-operations in general. Depending on the type of industry and the level of energy efficiency achieved in the industrial processes, the excess heat could be valued quite differently both environmentally and economically. The issue of allocation of carbon dioxide emissions to excess heat is complicated. Since excess heat is considered as a by-product, it is often argued that it should be considered to have no carbon dioxide emissions at all. However, most industrial processes are not fully optimized and the excess heat could have alternative uses (Axelsson et al., 2006a; Axelsson et al., 2006b; Bengtsson et al., 2002; Grönkvist and Sandberg, 2006; Olsson et al., 2006). In addition, depending on the production mix in the DH system to which the heat is sold, the alternative heat production might result in even lower carbon dioxide emissions, and therefore it could be questioned whether excess heat should really be considered as carbon dioxide-free (Holmgren, 2006).

In order for both industries and utilities to benefit equally from co-operation, the issue of pricing of the excess heat must be addressed. There is no well-recognized principle for valuation of excess heat, and the price that the utility has to pay for the heat is negotiated for each specific co-operation (Profu, 2005; Werner and Sköldberg, 2007). A study by Jönsson and Algehed (2008) showed that the price that a utility is willing to pay for industrial excess heat varies greatly depending on energy market prices, while the price at which an industry is willing to sell heat is less sensitive to energy market prices. Jönsson and Algehed (2008) thus concludes that if a co-operation occurs, the utility takes a larger price risk than the industry, although it also has the possibility of making the largest profit. This circumstance has the result that the utilities, being profit-making organizations, might consider a co-operation too big a risk in comparison to producing heat in their own boilers and CHP plants.

### 2.2 Cooling co-operations

DC co-operations between industries and utilities are not as common in Sweden as DH co-operations, since DC systems are still less frequent than DH systems. However, there is an increasing demand for comfort cooling, especially in e.g. shopping malls, hospitals and public buildings, which could result in a growing interest in DC solutions in the future. In 2009 more than 800 GWh of cooling were delivered through DC which is a considerable increase compared to 1996 when
less than 100 GWh were delivered (SDHA, 2011b). Apart from DC in the sense of
distribution of chilled water, DC (or district energy) could also mean that an
existing DH system is used to supply cooling through e.g. absorption chillers at the
sites where cooling is needed (Rezaie and Rosen, 2011). Absorption cooling is
further discussed in Chapter 4.

The temperature level in DC systems is about 5 °C (SDHA, 2011b) which mainly makes it suitable for comfort cooling, but there are also industrial process applications where the DC can be useful. For more extreme cooling needs, it is however often more practical to use a local solution.

Most industries have a need for comfort cooling as well as cooling in the production processes, and currently most industries supply their cooling demand with local cooling solutions. There are, however, examples of industries that supply their cooling demand through DC supplied by a utility. E.g. in Lund the local utility Lunds Energi supplies several local industrial sites with cooling (Lunds Energi, 2011) and in Norrköping, Kungsbacka and Malmö, E.ON. delivers DC to both industrial and residential applications (E.ON, 2011). In Gothenburg the local utility Göteborg Energi delivers DC from both lake water and absorption cooling to shops, offices and residential buildings (Göteborg Energi, 2011). In Falun the utility Falu Energi och Vatten has built a CHP plant with integrated absorption cooling which provides cooling to the municipality (Falu Energi och Vatten, 2011).

A DC co-operation could also consist of the industry making the investment in new cooling supply, and delivering cooling to the utility or other industries. An example of such a case is the municipality of Södertälje where the pharmaceutical company Astra Zeneca delivers cool water from a nearby lake to both the local utility Telge Nät and the other large industry in the area, Scania (Karlsson et al., 2010).

The CO₂ emissions related to DC depend on the source of the cooling. Lake water cooling has no emissions except the CO₂ emissions related to the electricity used for pumping. Compression chillers use electricity which can result in rather high CO₂ emissions depending on what assumptions are made for CO₂ emissions for electricity production. Heat-driven cooling such as absorption cooling will result in CO₂ emissions from the heat production. Depending on whether the heat comes from boilers or CHP and what fuel is used, the emissions may vary greatly.

2.3 Third party access (TPA)

Barriers to energy co-operation have resulted in increased demands from energy-intensive industries to allow TPA. TPA means that the owners of a network (e.g. a DH network, a gas network or an electric grid) must allow other suppliers access to the network. Open access to a network through TPA is argued to be the only way to obtain a competitive market concerning e.g. heat, gas or electricity (Nowak, 2010). There has been an intensive debate in Sweden concerning TPA. Today it is
not possible for other heat producers than the grid owners to sell heat through a DH system. However, there is an ongoing investigation concerning the legislation and a decision will be made in the near future (SOU 2011:44, 2011).

In Sweden the main type of TPA that concerns co-operation between industries and utilities is TPA in DH systems. Today’s DH systems are natural monopolies, where the DH grids are owned and operated by the same actors, usually the local utility. However, while the distribution of hot water inevitably is a monopoly (unless there is more than one grid) the production of DH could come from multiple sources. When the Swedish electricity market was deregulated in 1996, the DH market was also affected. The Electricity Act (SFS, 1997) which regulates the electricity market, states that the local utilities that sell electricity must operate commercially, thus also the pricing of DH sold by these companies is free. Due to the fact that DH systems are monopolies, the current situation has been criticized since there is no competition from other possible heat producers (Dir 2009:2009:5, 2009; SEA, 2000; Westin and Lagergren, 2002).

In order to address the problem with lack of competition in the Swedish DH systems, the Swedish Competition Authority (SCA, 2009) suggested a price regulation of the DH prices to prevent unreasonable price levels. An alternative to this type of price regulation would be TPA. If TPA is made possible in the DH systems, the competition in the DH systems would increase. However, since DH systems are local unlike the electricity market, the implementation of TPA could still result in one actor being dominant in the local DH market, thus reducing the positive effect of increased competition. Production and distribution of DH are also more interdependent compared to a corresponding electricity market with the result that negotiated TPA, where the amount of heat delivered is decided through an agreement, could be more efficient from a system optimization point of view (Söderholm and Wårell).
3 Policy instruments and co-operation

In this chapter policy instruments that affect the Swedish energy sector and thus potential energy co-operations are presented.

There are a number of policy instruments that are used in Swedish energy and environment politics in order to achieve the goals set for the future. The DH sector is affected by taxes, fees, legislation and policy programs aiming to reduce the use of fossil fuels, decrease CO₂ emissions and encourage investments in renewable energy. Also the industrial sector is subject to several policy instruments and legislation has become stricter in seeing to it that industries apply energy efficient technologies. Although all energy policy instruments will influence possible energy co-operation to some extent, a few of them can be said to have a greater influence on the development of new co-operation, e.g. the electricity certificates and programs that support investments to reduce energy use and CO₂ emissions. As a consequence of the European Commission 20-20-20 targets (EC, 2009) it is likely that more policy measures will be implemented in order to reach the targets. If the EU is to reach the goals set for the future, or try to reach a society based entirely on renewable energy, new policy measures are required (WWF, 2011).

3.1 The electricity certificate system

As a means to meet the demand for an increased share of renewables in the energy system (EC, 2008), electricity certificates were introduced in order to increase the amount of renewable electricity production through increasing the income from production of renewable electricity. The certificates aim to increase the renewable electricity production in a cost-efficient manner. The producers of electricity are given a certificate for every MWh of produced electricity from renewable sources. The technologies that are included in the system are wind power, solar power, geothermal power, electricity from types of biomass, wave power and some types of hydropower. New utilities producing electricity from renewable sources will receive certificates for 15 years. The demand for certificates is constructed so that all users and producers of electricity are obliged to buy a certain quota of
certificates that correspond to their use or production of electricity, and the quota is increased over time. (SEA, 2009a). The system is primarily made for utilities that produce electricity and heat but also industries that produce electricity from renewable sources will benefit from the system. In energy-intensive industries such as the pulp and paper industry, increased production of electricity is stimulated since investments in back-pressure turbines and condensing turbines are made more profitable (Axelsson et al., 2006b; Olsson et al., 2006).

The fact that electricity production benefits so much from the certificates can sometimes have the result that the incentives for co-operation between industries and utilities are reduced. Electricity production in utilities can be increased if the CHP production is increased. This would result in a reduced potential for industrial heat co-operation since DH systems have a limited heat demand. In the same way, the increased profitability of industrial electricity production can lead industries that have a possibility of using heat for either electricity production or DH production, to find it more advantageous to produce electricity. The electricity certificates aim to increase the amount of electricity from renewable sources, not to increase the level of resource efficiency which can cause conflicts concerning energy policy. (SEA, 2008c)

### 3.2 The EU Emission Trading Scheme (EU ETS)

Since 2005 the EU has a system for trade of CO₂ emissions, the Emission Trading Scheme (EU ETS). The trading system includes all the 25 member states and has been developed in accordance with the Kyoto protocol. At the moment about 40% of the emissions in the 25 member states are included in the system. The purpose of the EU ETS is to reduce the CO₂ emissions in a cost-effective manner, and the system is based on the rule that each member state sets a maximum level of CO₂ emissions allowed for each trading period. The levels set by the member states have to be approved by the European Commission. Each trading certificate equals one tonne of CO₂. For the trading period 2008-2012 a maximum of 90% of the certificates can be given to the included plants for free. (SEA, 2011d)

The price of the certificates has varied greatly since the introduction of the EU ETS in 2005 (see Figure 2). The reason for the great drop in certificate price in the first EU ETS period (2005-2007) is partly that the number of certificates handed out was greater than needed. Due to the great number of certificates released to the involved plants, Swedish industries have not been affected very much by the EU ETS during the first years (SEA, 2007). There are no numbers on how much EU ETS has influenced energy efficiency, and thus the use of energy, on a European level (Wesselink et al., 2010). However, the more restricted levels of allowed CO₂ emissions in future EU ETS periods could have a more substantial impact on energy use and energy efficiency in industries, which could result in more incentives for co-operation.
3.3 Energy taxation

Since the 1950s energy has been the taxed to varying degrees and today energy tax applies to fuels and consumption of electricity. Production of electricity is not taxed; instead the tax is applied to the consumption of electricity, which results in that the customers rather than the producers pay the tax. Heat production, however, is subject to both energy tax and CO₂ tax. The tax rate depends on what fuel is used, but biomass and peat are exempted from energy taxation. The energy taxation system has had an influence on the CO₂ emissions since renewable fuels are not taxed. As a result the tax to some extent favors use of biomass rather than use of e.g. industrial excess heat. (Law (1994:1776), 2011)

The CO₂ tax was introduced in 1991 with the purpose of reducing the use of fossil fuels. But not all combustion of fossil fuels is subject to the tax; fuels used for production of electricity are exempted, just as in the case of the energy tax. Industries, agriculture and forest enterprises have a lower CO₂ tax. The CO₂ tax targets CO₂ emissions in a different way than the EU ETS. While EU ETS sets a limit for the maximum emissions, the CO₂ tax increases the price of fossil fuels, making them less attractive compared to renewable options. (Law (1994:1776), 2011)

Other taxes that apply to the Swedish energy sector are the tax on sulfur emissions and the nitrogen oxide fee. The sulfur tax was introduced in 1991 in order to reduce the emissions of sulfur oxides causing acidification of water and land. The tax favors a conversion from heavier fuel oil with high sulfur content to fuels with less sulfur content such as biomass or lighter fuel oils. The nitrogen oxide fee is not a tax but a fee per kg of emitted nitrogen oxides. The fee is then paid back to companies in proportion to how little nitrogen oxides a company emits in
relationship to how much energy is utilized (SEPA, 2011). The companies that emit the least in comparison to the amount of utilized energy will receive the highest payback of the fee. In this way the nitrogen oxide fee encourages reductions in nitrogen oxides without straining the energy sector as a whole economically.

3.4 Voluntary agreements – The energy efficiency program (PFE)

The energy efficiency program (PFE) is an example of a voluntary agreement between industries and the state. PFE was introduced in 2005 as a compensation for a new energy tax of 0.005 SEK/kWh. The tax was introduced as a response to the European Union energy tax directive (EC, 2003). The tax concerned industries that use electricity in their production processes, but as compensation the industries were invited to take part voluntarily in the program and in return be liberated from the tax. (SEA, 2011b)

Participation in the program brings some substantial advantages. First, the industries participating are liberated from the tax, second they will have to consider energy efficiency measures that in turn will reduce their energy costs. Initially PFE ran from 1 January 2005 until the end of 2009. During these five years 90 industries participated in the program and the Energy Agency (SEA, 2011c) concludes that the program has resulted in energy efficiency measures of about 1.45 TWh of electricity per year. During the first two years the industries were obliged to implement a standardized and certified energy management system and to make extensive energy surveys in order to identify possible areas for efficiency measures. The PFE will run for a second period where industries can join the program until 2014. (SEA, 2011b)

The PFE has been criticized for focusing only on electricity use and not on other energy carriers. When performing the energy audits the industries also identified savings in heat and fuel resources, but these savings are not rewarded in the program. The identified possibilities for improved use of heat can nevertheless result in new co-operations.

The results of programs such as the PFE have also been discussed since the effects sometimes are difficult to measure. Free-rider effects can have the result that energy efficiency measures are attributed to the program in question when they would most likely have been implemented anyway due to the economic profitability of the measure. Another free-rider effect could be that there are other circumstances that influence the profitability of energy efficiency measures. (Thollander et al., 2007)

Apart from PFE there are also other programs that have been introduced in order to reduce the use of energy in industries.
3.5 Legislation

Apart from taxes and governmental programs, there are also laws and directives that influence the Swedish energy sector and the potential for co-operation between utilities and industries.

The Swedish Environmental Code aims to promote sustainable development and ensure future generations a healthy and good environment (SEC, 1998). The Environmental Code also demands resource and energy efficiency and in recent years the authorities responsible for making sure industries and utilities comply with the Code, have become more firm concerning this part of the Code. The demands have so far mainly concerned energy audits and lists of possible energy efficiency measures (SEA, 2011a). The demand for energy audits and inventories of possible measures could make industries more aware of possible energy efficiency measures and thus also increase the interest in co-operations.

The European Commission directive on the promotion of cogeneration based on a useful heat demand in the internal energy market (EC, 2004) aims to increase the energy efficiency and improve the security of supply through development of co-generation. The directive states the rules and reference values for co-generation of heat and power. In June 2011 the European Commission presented a suggestion for a new directive concerning energy efficiency which is suggested to replace this directive and the directive on energy end-use efficiency and energy services (EC, 2006). The new directive suggests energy efficiency measures for industries, the energy sector, services and households.

The EU 20-20-20 targets are stated in a directive from the European Commission (EC, 2009). The targets aim to; reduce the EU greenhouse gas emissions by 20% compared to the 1990 levels, reduce the EU use of primary energy resources by 20% compared to projected levels based on the energy use in 2005 and accomplish that 20% of the EU energy use comes from renewable resources by 2020. For the Swedish industry the directive means that the energy end-use needs to be reduced by 35 TWh/year which requires that new policy measures targeting the use of primary energy resources needs to be implemented in order to reach the goal (Thollander et al., 2010b).
4 District heating and cooling

This chapter will first introduce some background on district heating and cooling in Sweden. This will be followed by a discussion of system aspects of CHP and heat-driven cooling.

District heating (DH) is a well-extended technology in Sweden for heating both residential buildings and industries. The heat production is centralized in a few larger production units enabling higher efficiency and often simultaneous electricity production (CHP). The hot water is distributed through a pipe system to the customers.

The heat demand in the DH systems closely follows the outdoor temperatures over the year. In Sweden the heat demand is large during the greater part of the year, but during the warmest months of the year heating of buildings is not necessary. Most municipalities in Sweden have a similar pattern in the heat demand with higher demand in the winter and lower demand in the summer.

In 2009 55% of the total heating demand in Sweden was covered by DH (SEA, 2009b). In apartment blocks DH is the most common source of heating and about 77% of the heated area is heated by DH. However, only about 9% of the detached houses are heated by DH. The DH production in Sweden has increased consistently since the 1970s mainly because of its fuel flexibility which has enabled conversion from oil. At the same time the technology has improved and the distribution losses have decreased. (SEA, 2009a)
In 1980 90% of the heat distributed in the DH systems originated from oil boilers, but today most of the heat is produced from biomass, waste and peat (see Figure 3). Excess heat makes up a relatively small part of the total heat supplied in the DH systems, but has increased substantially since the first excess heat co-operation took place in the 1970s; the amount of delivered excess heat to the DH systems in 2007 was about 4 TWh (SDHA, 2011b). A large part of the heat in the DH systems is produced in boilers, but a growing part comes from CHP plants fuelled by waste, biomass or fossil fuels. CHP has become increasingly profitable due to increased prices of electricity and policy measures that benefit electricity production from renewables (Danestig et al., 2007; Knutsson et al., 2006; Unger and Ahlgren, 2005). Waste incineration has become increasingly interesting to Swedish utilities due to the fact that waste provides cheap fuel. In some cases there is even a shortage of waste which has led some municipalities to import waste from other countries (SDHA, 2011a).

District cooling (DC) is a growing market in Sweden. The demand for cooling in commercial and residential buildings has increased due to both rising requirements on the indoor climate from the customers and new problems that arise with the increased use of computers and other electronic equipment (FVB, 2011). Today about 0.8 TWh of DC is delivered to residential and commercial clients, and by 2015 the deliveries are expected to rise to about 1.3 TWh (SDHA, 2011b). Office buildings, shopping malls and hospitals are common users of DC, but also industries can use DC for process cooling as well as comfort cooling.

4.1 Heat-driven cooling in CHP systems
In a CHP system both heat and power are produced simultaneously (see Figure 4), resulting in that the CHP plants efficiency is about of 90% which can be compared to about 30-45 % in a condensing power plant. There are CHP plants in about 60
different municipalities in Sweden that combined produced about 12.5 TWh of electricity in 2010 (Swedenergy, 2011a).

In a CHP steam cycle using only a DH system for cooling, an increased heat demand will enable increased electricity production in the system. Depending on what model is used for valuing the carbon dioxide emissions of the system (see section 5), increased electricity production in a system will be given highly varying importance in its contribution to the system’s global carbon dioxide emissions.

A rising demand for comfort cooling in both residential and commercial buildings can contribute to increased operation time in CHP plants when heat-driven cooling such as absorption cooling is used. The use of DH is highly seasonal with a peak demand in the winter, thus introduction of heat-driven cooling in the summer months can result in longer operation time and higher profitability for CHP plants (Maidment and Prosser, 2000; Maidment and Tozer, 2002; Trygg and Amiri, 2007; Udomsri et al.).

4.1.1 Absorption cooling

Absorption cooling is a heat-driven cooling process. Unlike compression chillers that uses electricity, absorption chillers use heat which can be an advantage if flow-cost heat is available (Trygg and Amiri, 2007; Udomsri et al.). Absorption chillers have a coefficient of performance (COP) of about 0.7, to be compared to compression chillers which normally have a COP of about 2.

In an absorption cooling process the compressor in a corresponding compression chiller has been replaced with an absorber, a circulation pump and a generator; see Figure 5. In the evaporator water is cooled when the refrigerant (in this case water) is evaporated, the evaporated refrigerant is then transferred to the absorber where it is absorbed by a lithium bromide solution. The lithium bromide solution is then
pumped to the generator where it is heated by DH, so that the water in the lithium bromide solution evaporates and the pure lithium bromide is transferred back to the absorber. The condenser cools the steam so that it returns to liquid form and then the water goes back to the evaporator.

While a DC system usually is operated at a temperature of about 5°C, which is easily attainable with absorption cooling, absorption technology can also be used for other cooling applications that require lower temperatures. Using other refrigerants than water, such as ammonia, will enable lower temperatures (Borgnakke and Sonntag, 2008; Le Pierrès et al., 2007) for local solutions where the normal DC temperatures will not suffice.

![Diagram of absorption cooling process]

**Figure 5 An absorption cooling process**

The advantage of absorption cooling is that, because it is heat-driven (except that a small proportion of electricity is needed for pumping), it can use the surplus heat, which often is available in summer when the cooling demand is greatest. The heat used to drive absorption chillers can come from an existing DH system (see Figure 6), and depending on the heat input used in this system, the system effects of absorption cooling will vary which will be discussed further in section 5.
4.1.2 Adsorption cooling

Adsorption cooling, unlike absorption cooling, is a local cooling solution. The adsorption cooling should be integrated with an air treatment system and is intended not only to provide cooling, but is part of the ventilation system. Similar to absorption cooling, adsorption cooling is heat-driven.

The adsorption cooling process (see Figure 7) consists in that the outdoor air is heated by the exhaust air from a drying rotor; thus the air becomes hot and dry. The hot air then continues to a rotary heat exchanger where it is cooled down again; the cool air is then humidified to the desired level and is transferred into the building with an inlet fan. The return air in the room first goes through a filter and is afterwards humidified and then cooled in order to cool the supply air. Subsequently, the return air is heated up with a heating coil driven by DH or other available heat and the hot, moist air heats up the incoming outdoor air in the drying rotor. Exhaust air is then collected by means of an exhaust fan (Granryd et al., 1974).

An adsorption cooling system requires that the cooling demand and the air flow are large enough. An example of an appropriate application is e.g. premises with their own cooling system which is not connected to a DC network.

In a CHP system adsorption cooling will share some of the benefits with absorption cooling, since it is a heat-driven process. During the warmer part of the year, heat will be required for the cooling process and provide an increased heat demand and thus increased electricity production. Additional heating is also required when the outdoor temperature is so low that the supply air cannot be heated solely by heat recovery from the exhaust air. (Urrutia, 2010)
Figure 7 The adsorption cooling process
5 Valuation of CO₂ emissions

In this chapter, different models for valuation of carbon dioxide emissions will be introduced and the system boundaries related to the different models are discussed.

The increasing threat from global warming caused by CO₂ emissions and the introduction of policy instruments such as the EU ETS and the EU 20-20-20 targets, have created a need for estimating the CO₂ consequences of new investments and other changes in energy systems.

In the studies of DH and DC co-operations that have been conducted in this thesis the new investments made will result not only in a change in the use of fuel resources and electricity locally; the changes will also have an effect on the global CO₂ emissions. However, depending on which model for evaluating the CO₂ emissions is used, the results may vary greatly.

While fuel resources such as oil or coal are more easily accounted for, the CO₂ emissions for electricity used in a system vary depending on what system boundaries are applied. The CO₂ emissions assigned to biomass are also more difficult to estimate since the increased demand for renewable resources due to e.g. the 20/20/2020 targets and the EU ETS creates both local and international competition for the limited biomass resources (Kautto et al., 2011).

5.1 CO₂ emissions based on marginal electricity production

A marginal perspective on electricity production suggests that if a change occurs in an energy system so that the use or production of electricity increases or decreases, this change will affect the marginal production of electricity. If the system reduces its electricity consumption, the electricity produced at the margin will disappear and the carbon dioxide gain obtained will thus be equal to the carbon dioxide emissions for the electricity that is no longer produced on the margin (Sjödin, 2003; Sköldberg et al., 2006). When using the marginal electricity model for evaluating CO₂ emissions the system boundary is often considered to include the
European electricity system, not just the Nordic or Swedish system; thus the
marginal electricity producer will have the most expensive electricity production
on the European market. A problem with the marginal electricity model is that
depending on what time perspective is used, the technology on the margin will
differ. While the marginal electricity production today often is considered to be
derived from coal condensing power plants, the definition of marginal electricity
suggests that this type of electricity production will in the long run be replaced
with other more efficient technologies, so the marginal production will change.

5.1.1 Coal condensing power on the margin (short term)
In today’s system condensing coal power plants are the technology that has the
highest operating costs and are thus considered the marginal producers of
electricity. If a coal condensing power plant reduces its electricity production due
to an increase in electricity production from a less CO₂-intensive source in the
studied system, the increased electricity production would result in a reduction of
CO₂ emissions. The EU suggests a conversion coefficient of 2.5 for electricity
generation which would correspond to a efficiency of about 40% in the power
plant (EC, 2006). Others suggest that the efficiency of the least efficient
condensing power plants is not more than about 30% (Sjödin, 2003) which would
result in CO₂ emissions of about 1000 kg/MWh for marginal electricity.

5.1.2 Long term marginal power plants
Energy policy measures and energy market prices influence both the European and
the Nordic electricity production and in the long term the marginal producers of
electricity will no longer be the coal condensing power plants available today.

What technology will be the marginal technology is uncertain; natural gas-fired
combined cycle plants (NGCC) are often presented as the future marginal
producer, since they are just below the coal condensing power plants in the supply
curve (see Figure 8), but there are other possibilities. Emission trading favors the
NGCC plants, but in e.g. Germany new more efficient coal power plants are
planned. A disadvantage for the natural gas plants is the high prices of natural gas.
Another important factor is that in a more integrated European electricity market
there will still be coal-fired power plants, which means that this technology will
still be on the margin from a Swedish perspective, even if the Nordic power plants
are phased out (SEA, 2008b). A coal power plant with an efficiency of 48% on the
margin (compared with today’s 30-40%) would mean carbon dioxide emissions of
about 700 kg/MWhel. A NGCC plant on the other hand could result in emissions of
about 350-400 kg/MWh as well as reduced use of primary fuel resources (SEA,
2008b). Coal condensing plants with CCS (Carbon Capture and Storage) could
result in even lower emissions.
Valuation of carbon dioxide emissions can also be based on average emissions per MWh produced electricity in Sweden. The Swedish electricity production consists mainly of nuclear and renewable energy, which means that the average emissions from the Swedish electricity production are low, about 36 kg/MWh (Gode et al., 2011). Even from a Nordic perspective, the average emissions are low since the neighboring countries have relatively low CO$_2$ emissions from their power plants compared to the average European plants (Sköldberg et al., 2006). Today, this model for valuing carbon dioxide emissions has the result that generated electricity corresponds to carbon dioxide emissions of 97 kg/MWh$_{el}$ (Gode et al., 2011). A disadvantage of this method is that it ignores the fact that Sweden's electricity system is not isolated from the European electricity system. The Swedish grid is interconnected with other grids in Europe which means that new investments in electricity production have system consequences outside the national electricity grid.

### 5.2 CO$_2$ emissions associated with marginal use of biomass

Biomass is a renewable energy source, but the availability of biomass is limited. To take this into account, a marginal approach can be applied also to the use of biomass. Unlike electricity, biomass is not sold and purchased on a homogeneous European market; rather there are many small local markets, and prices can vary greatly between them. The EU’s targets for renewable energy can change this situation and it is likely that in future there will be a European market for biomass
just as for electricity (Axelsson E. and Harvey S., 2010; Sköldberg and Rydén, 2006)

Since there currently is no homogeneous biomass market, it is more difficult to identify who is the marginal user of biomass, but coal power plants are a potential user of biomass. For a relatively low investment cost, coal power plants can be converted to co-fire biomass with coal. With rising costs for emissions trading (EU ETS), these power plants could be willing to pay ever more for biomass. If coal power plants are the marginal users of biomass, each MWh of biomass used can replace as much coal, which means that one MWh of reduced use of biomass locally can result in a 336 kg reduction of carbon dioxide emissions globally (Axelsson E. and Harvey S., 2010). Just as for electricity, the marginal user of biomass might be another in the future. Other possible marginal biomass users are e.g. producers of biofuels such as ethanol or DME (Sköldberg and Rydén, 2006). Since the EU has set a goal that 10% of the fuels used for transport must come from renewable sources by 2020 (EC, 2009), a substantial increase in the production of biofuels is necessary, which will increase the producers' willingness to pay for biomass.
6 Methodology

This chapter describes the methods used and how they have been applied in the different case studies.

When conducting a study of co-operation between an industry and a utility there are numerous questions that need to be addressed. The techno-economic questions have in this thesis been analyzed using optimization, but while a techno-economic optimization can answer many of the questions surrounding energy co-operation, there are aspects that are not covered by such an analysis. To get a broader perspective on co-operation, a multi-disciplinary approach has been used in the thesis and two of the appended papers investigate the socio-technical aspects of co-operation.

All papers included in the thesis have been conducted using a systems approach in accordance with Churchmans and Bouldings principles (see 6.1). In papers I-VII case study methodology has been applied. The optimization studies have been performed using the energy systems optimization tool reMIND and using an approach to analyze possible co-operations between industries and utilities that was developed in paper I. Sensitivity analysis of the optimization results was carried out using future energy market scenarios.

6.1 Systems analysis

Systems analysis is an approach to solving problems originating from the operation analysis (Churchman, 1968) which was developed for military purposes during World War II. Operation analysis was distinguished by an open choice of method for solving the problem; the problem should define the choice of method rather than the other way around.

Systems analysis uses the same approach, but according to Churchman (1968) systems analysis has to deal with two issues apart from the problem to be solved. Firstly the purpose of the analyzed system can be hard to define and secondly the system itself must be described thoroughly as a system in order to analyze the
interactions between the different components in the system. The systems approach described by Churchman (1968) states that a system can be analyzed by describing the objective of the system, defining the surroundings and resources of the system, and determining the management of the system.

Boulding (1956) categorized systems according to their degree of complexity. The simplest systems would be simple mechanical systems and the most complex are the ones regarding humans and their interactions. Based on this categorization, Boulding (1956) concludes that when large systems involving groups of individuals and their interactions are studied, it is very difficult to find a general theory that includes all the parameters. In order to study such a system, various perspectives need to be applied to obtain an understanding of the studied system.

6.1.1 System definition and system boundaries used in this thesis

The industrial energy systems studied within this thesis are all part of larger surrounding energy systems. The system boundary has in all cases been drawn around both the industry and the utilities rather than looking at the two parties separately. The objective of the system is mainly to reduce the system cost (see 6.4) but also to reduce the carbon dioxide emissions of the system. The systems’ surroundings can be defined as the factors that interact with the system, but are not actually inside the system. In this thesis those factors are e.g. national legislation, economic and political policy instruments, European Union directives and market aspects.

Boulding’s (1956) approach where very complex systems are studied through applying various perspectives, is used in such a way that the same types of systems have been studied using both a techno-economic perspective and a socio-technical perspective. The techno-economic perspective deals with the technical aspects of the system and the influence of prices and policy instruments, while the socio-technical perspective concerns the human level in the systems.

6.2 Case study research

In papers I-VII a case study approach has been applied. The case study research method is recommended for studies that seek to answer the questions “how” and “why”. It is especially useful in studies which are focused on a contemporary phenomenon where the researcher has little control of the behavioral events and the boundaries between the phenomenon and its real-life context are hard to define (Yin, 2003).

There are several possible ways of designing case studies – e.g. single or multiple case designs and holistic or embedded case designs. A single case study is appropriate either to perform a critical test of an existing theory, or when the case represents a unique circumstance or is very representative for the phenomenon described. Multiple case designs provide more room for comparison between the cases and are often considered more robust than a single case study. However, unusual or unique cases cannot be studied through a multiple case study, and
therefore revelatory cases are often single case designs. In addition, multiple case studies often require extensive resources and are more time-consuming than what is feasible in many studies (Yin, 2003).

A single case study can be made more complex by including sub-units of analysis in the study, thus using an embedded single case design. The sub-units can provide an opportunity for more insight in the specific case and result in a more extensive analysis (Yin, 2003).

6.2.1 Application of case study research in the thesis
In papers I-III the kraft pulp mill and the utility are analyzed as both one coherent unit as well as separate units, resulting in an embedded single case study.

In papers IV and V an embedded single case study design is used to study the effects of further integration of heating and cooling between the two industries and the utility in the case of Södertälje. The whole region is considered as a single case, but several sub-units are analyzed to give further depth to the study.

Paper VI and VII are multiple case studies. In paper VI interviews were conducted with six energy utilities and six industries. In paper VII two kraft pulp mills and two energy utilities situated in the same municipalities as the kraft pulp mills were interviewed.

6.3 Approach for analyzing energy co-operations
In paper I an approach was developed in order to evaluate energy systems with both industries and utilities. In paper I the approach was developed to analyze the trade-off between internal and external use of kraft pulp mill excess heat which was later used in papers II and III, but the same approach was also used for analyzing the trade-off between different cooling options in papers V and VI.

The approach includes the following steps:

1. Choose an energy system and define the system boundaries (e.g. an industry and a utility are modeled within the same system boundary)
2. Define what changes in the energy system will be analyzed (new investments in energy efficiency measures, heating and cooling supply etc.)
3. Define the surrounding system (e.g. energy market prices, policy instruments)
4. Define the objective function and the constraints of the optimization problem.
5. Build a model using the energy systems modeling tool reMIND (see section 6.3.2)
6. Optimize the objective function of the model for different boundary conditions defined in step 3.
7. After optimization other factors influencing the choice of technology such as CO₂ emissions and sharing of profit can be considered.

6.4 reMIND

In papers I-V the energy systems optimization tool reMIND has been used. ReMIND is based on the MIND method which is a method using mixed integer linear programming (MILP) to analyze industrial energy systems (Karlsson, 2011). The method has primarily been used to model industrial plants (Karlsson and Wolf, 2008; Thollander et al., 2009) but has also been used to make integrated models of industries and DH systems (Jönsson et al., 2008; Svensson et al., 2008) and models of pure DH systems (Difs et al., 2010).

When using the reMIND tool the system is modeled by defining each component as a node and connecting energy and material flows with a set of equations within each node. A node can represent either a small component or a whole process depending on the system level of the model. To enable dynamics in the model, the model can be divided into time steps. The time steps can be defined to suit each specific model and reflect hourly, weekly or yearly variations in the system.

The optimization is performed using the optimizer CPLEX (CPLEX, 2009). Carbon dioxide emissions of an optimal system can be calculated after the optimization to compare the environmental performance of economically optimal systems.

6.5 Energy market scenarios

In papers I, II, III and IV energy market scenarios developed by Axelsson and Harvey (2010) have been used to estimate future energy market prices.

To evaluate the profitability of new energy investments and their potential for reducing carbon dioxide emissions, the investments must be analyzed within a future energy market context. Future energy market prices are difficult to predict and therefore future energy market scenarios containing prices of fuels and carbon dioxide emissions related to energy flows can be a valuable tool to evaluate the impact of new investments. Unless the energy market parameters within a scenario are consistent and the energy prices are related to each other correctly, it is difficult to attain reliable results. The energy market scenarios developed by Axelsson and Harvey (2010) are constructed using a scenario tool called ENPAC (Energy Price and Carbon Balance Scenarios) which bases the energy prices and carbon dioxide emissions for different energy carriers on world market fossil fuel data and assumed values for climate policy instruments. Using this input, the tool provides probable marginal energy conversion technologies which subsequently result in consistent energy prices and carbon dioxide emissions related to the marginal use of energy carriers.

Out of the eight scenarios developed from the tool for the time period 2010 to 2050, 4 scenarios have been used in this thesis. The four scenarios used are
calculated for 2020 and represent high or low fossil fuel prices combined with two levels of carbon dioxide charge. An overview of the scenarios used is given in Table 2.

Table 2 Energy market scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel price</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>CO2 charge</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Prices and policy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity [€/MWh]</td>
<td>49</td>
<td>66</td>
<td>51</td>
<td>74</td>
</tr>
<tr>
<td>Low grade biomass</td>
<td>12</td>
<td>23</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>Pellets</td>
<td>21</td>
<td>35</td>
<td>22</td>
<td>36</td>
</tr>
<tr>
<td>Waste</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>45</td>
<td>54</td>
<td>62</td>
<td>72</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>29</td>
<td>38</td>
<td>42</td>
<td>51</td>
</tr>
<tr>
<td>CO2 charge [€/ton CO2]</td>
<td>20</td>
<td>52</td>
<td>20</td>
<td>52</td>
</tr>
<tr>
<td>Electricity certificate price</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>CO2 emissions [kg/MWh]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>722</td>
<td>345</td>
<td>722</td>
<td>722</td>
</tr>
<tr>
<td>Low grade biomass</td>
<td>336</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Pellets</td>
<td>336</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Waste</td>
<td>101</td>
<td>101</td>
<td>101</td>
<td>101</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>267</td>
<td>267</td>
<td>267</td>
<td>267</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>274</td>
<td>274</td>
<td>274</td>
<td>274</td>
</tr>
</tbody>
</table>

a Low grade biofuel such as tops and branches, sawdust etc
b A Swedish policy instrument giving the producers of electricity extra revenue for sold electricity from renewable sources
c The CO2 effect per MWh is based on the marginal electricity producer or marginal biomass user of each scenario.

6.6 Drivers for and barriers to co-operation

In papers VI and VII drivers for and barriers to co-operation have been discussed. These papers explore why it is that even if a co-operation is technically possible, co-operations are often difficult to obtain due to both social and economic factors.

6.6.1 Drivers for co-operation

Fors (2004), in a report where five Swedish excess heat co-operations were investigated, concluded that the most important success factors for obtaining a co-operation were that there is good communication between the parties and that both parties benefit equally from the co-operation. The importance of good communication has been stressed also in other studies. Grönkvist and Sandberg (2006) pointed out that if there is a technical possibility for excess heat co-operation, the main factor influencing whether the co-operation will occur or not is that there are people in both the industry and the utility who have the ambition to co-operate.
6.6.2 Barriers to co-operation

Thollander et al. (2010a) have classified barriers to energy efficiency, where co-operation could be considered as an energy efficiency measure, in two categories: the technology level and the technology/human level.

For the technology level the barriers concern the technology itself and associated costs. Examples of barriers in this category could be *lack of access to capital, hidden costs, or heterogeneity* which means that a certain energy efficiency measure might be suitable in one industrial plant or utility but not in another.

The second category, the technology/human level, concerns barriers that are connected with the technology but where the human factors have a great influence. Examples of such barriers are: *imperfect information* when possible efficiency measures are missed due to lack of information; *adverse selection* meaning that the purchasers of a product may know less about the energy performance than the seller, with the result that the purchaser chooses a product based on other aspects; *split incentives* which could mean that the person or organization making the investment does not gain benefits from the investment; the *form of information* is important since it has been shown that the way information is presented will influence the acceptance; and *risk* is a factor that could result in measures not being taken e.g. when short pay-back is required on an investment.

Barriers even more influenced by the human factors and less by the technology are: *credibility and trust* in the sense that information concerning a measure need to come from a trustworthy source to be accepted; *inertia* when people within the organization may oppose change; *bounded rationality* when decisions are made by rule of thumb rather than by perfect information; *power* is an issue if the energy issue has low status in the organization; and *values* and *culture* e.g. when environmental values within an organization reflect on the willingness to make investments in energy efficiency.

The barriers used in papers appended in this thesis are summarized in Table 3.
Table 3 Categorization of barriers considered in this thesis (Jaffe and Stavins, 1994; Sorrell et al., 2000; Stern and Aronsson, 1984)

<table>
<thead>
<tr>
<th>System levels</th>
<th>Theoretical perspectives</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The technology level</td>
<td>Heterogeneity</td>
<td>A district heating implementation is dependent on the specific company’s conditions etc.</td>
</tr>
<tr>
<td>Hidden Costs</td>
<td>Hidden costs associated with district heating implementation such as overhead, cost of collecting and analyzing information, production disruptions, etc. may limit the investment.</td>
<td></td>
</tr>
<tr>
<td>Access to Capital</td>
<td>Access to capital is naturally a factor of importance when a district heating implementation is undertaken.</td>
<td></td>
</tr>
<tr>
<td>Risk</td>
<td>Risk is affecting district heating implementation and may either promote or inhibit an investment.</td>
<td></td>
</tr>
<tr>
<td>Imperfect information</td>
<td>Imperfect information may result in the overlooking of a district heating implementation.</td>
<td></td>
</tr>
<tr>
<td>Asymmetric information*</td>
<td>If energy costs are not allocated to the one responsible for the use of the investment, or that one party cannot observe the other, the investment might be terminated</td>
<td></td>
</tr>
<tr>
<td>The technology/human level</td>
<td>Credibility and trust</td>
<td>The information source should be credible and trustworthy in order to successfully deliver information regarding the investment.</td>
</tr>
<tr>
<td>Inertia</td>
<td>Individuals who are opponents to change within an organization may result in that a district heating implementation is not carried out.</td>
<td></td>
</tr>
<tr>
<td>Values</td>
<td>Efficiency improvements such as a district heating implementation are most likely to be undertaken if there are individuals with e.g. environmental values, preferably represented by a key individual within top management.</td>
<td></td>
</tr>
</tbody>
</table>

*Asymmetric information can be divided into; adverse selection, split incentives and principal-agent relationships.
7 Case studies

In this chapter the two case studies of industries and utilities on which papers I-V in the thesis are based are described.

The optimization studies in papers I-V are all based on two case studies of industries in co-operation with energy utilities. Papers I-III were based on a theoretical case study of an average Scandinavian kraft pulp mill which had the possibility to co-operate with a nearby utility. Papers IV and V were instead based on the real case of Södertälje, where the two large industries Astra Zeneca and Scania and the utility Telge Nät have the possibility to increase the level of co-operation concerning DH and DC. The data in the kraft pulp mill case study are mainly based on previous work by other researchers and existing statistic while data for the case study of Södertälje have been collected by the author of this thesis from the industries and the utility Telge Nät.

7.1 Kraft pulp mills in co-operation with utilities

The pulp and paper industry is the largest industrial energy user in Sweden, and large amounts of excess heat are available especially in market pulp mills where the excess heat is not used in paper production. The study of kraft pulp mills aimed to investigate the trade-off between internal and external use of kraft pulp mill excess heat, since the heat could be used either for internal efficiency measures or externally as DH. The data for the mill used in the optimization study originated from the FRAM (Future Resource Adapted Pulp Mill) project, and the data for the DH systems with which the mill was optimized were based on statistics from Swedish DH systems.

The mill and the DH system were modeled as a coherent system where the optimization aimed to minimize the system cost of the system as a whole, not the separate companies. An overview of the model can be seen in Figure 9. The utility (ECO) supplies heat to the DH system and the kraft pulp mill can either sell the heat to the utility or use it for internal energy efficiency measures. The utility on
the other hand can invest in new heat supply either from new boilers or through purchasing heat from the mill.

Figure 9 The model of the kraft pulp mill and a district heating system

7.1.1 FRAM
In the optimization studies concerning kraft pulp mills, the reMIND model was based on data from a model of an average pulp mill in Scandinavia which was developed in the national Swedish research program Future Resource Adapted Pulp Mill (FRAM) (FRAM, 2005). The FRAM project focused among other things on energy savings, and possible energy efficiency measures that were identified within the project were used in the optimizations in paper I-III. The mill has available excess heat of medium quality (100°C) and low quality (40/60°C). The medium-quality excess heat has alternative uses, which means that all measures that would require medium-quality excess heat cannot be taken at the same time. The low-quality excess heat will be available independent of the other measures, but the temperature will vary.

Axelsson et al. (2006a; 2006b) identified a number of possible investments in new efficient technology: process-integrated evaporation (PIvap), a new conventional evaporation (Convap), an increase in the dry solids content, a retrofit of the hot and warm water system (HWWS), steam savings at the wood yard, and a new three-stage flash on the black liquor stream from the digester. The reduction in steam use from the suggested measures results in more available steam for electricity production. Some of the measures will generate more excess heat, while others such as the PIvap will use available excess heat. Additional heat can be made available from flue gas heat recovery (FGHR), and this heat could be used either to produce more DH, for pulp drying or for the PIvap (Axelsson et al., 2006a).
In addition to the measures suggested by Axelsson et al. (2006a; 2006b), the option of selling medium-quality excess heat to a nearby utility was included, as well as the option of upgrading low-quality excess heat through heat pumping and selling it as DH. An overview of all the possible new investments included in the model of the mill is given in Table 4.

**Table 4 Possible investments in the kraft pulp mill**

<table>
<thead>
<tr>
<th>Generated steam surplus [MW]</th>
<th>Generated heat available for production of district heating [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIvap* 25</td>
<td>-</td>
</tr>
<tr>
<td>Convap* 22</td>
<td>-</td>
</tr>
<tr>
<td>Increased dry solids*</td>
<td>6</td>
</tr>
<tr>
<td>New HWWS* 6</td>
<td>-</td>
</tr>
<tr>
<td>Wood Yard* 2</td>
<td>-</td>
</tr>
<tr>
<td>New 3-stage flash*</td>
<td>9</td>
</tr>
<tr>
<td>FGHR used for PIvap*</td>
<td>5</td>
</tr>
<tr>
<td>FGHR used for pulp drying*</td>
<td>4</td>
</tr>
<tr>
<td>FGHR used for district heating*</td>
<td>4</td>
</tr>
<tr>
<td>Medium-quality excess heat as district heating**</td>
<td>13</td>
</tr>
<tr>
<td>Low-quality heat as district heating (heat pumped)**</td>
<td>43***</td>
</tr>
</tbody>
</table>

*Axelsson et al. (2006a)  **New possibility, excess heat data from Axelsson et al. (2006a)  ***Before heat pumping.

In order to further increase the electricity production in the mill another three options were added in the model. These investment options were based on the results of Olsson et al. (2006) who concluded that the existing turbines in the mill are too small to make use of all available steam, even if none of the previously mentioned steam-saving measures were implemented. To increase the electricity capacity of the mill, investments could be made in an external super-heater, a new back-pressure turbine and/or a new condensing turbine. The possible investments in new electricity production are shown in Table 5.

**Table 5 Investments in the kraft pulp mill to increase the electricity production**

<table>
<thead>
<tr>
<th>Possible increase in electricity production/ Size of new turbines [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superheater 0-10*</td>
</tr>
<tr>
<td>New BP-turbine 24-50***</td>
</tr>
<tr>
<td>New Condensing turbine 5-12.25***</td>
</tr>
</tbody>
</table>

*Limited by the quantity of steam surplus that can be generated  **In accordance with Olsson et al. (2006)  ***The existing turbine has a capacity of 24 MW; further electricity production requires a new investment.

7.1.2 Swedish DH systems

In paper I and II, the optimization model was made using three different types of DH systems. Since the size of the heat demand as well as the production mix in a
DH system has a great influence on the results, the three systems were chosen since they are of different sizes. The heat demand in the three different models was based on the DH demand in three Swedish municipalities. The systems were categorized as small (S), medium (M) and large (L). Statistics concerning Swedish DH systems within a radius of 30 km from a kraft pulp mill were used to establish what type of production plants and what types of fuels are the most common in small, medium and large DH systems. The statistics showed that in larger DH systems there is a higher occurrence of CHP plants, while in smaller systems it is more common to have just heat production. It was also concluded that larger DH systems typically use more types of fuel than smaller systems. The production mix of the three different systems used in the study is shown in Table 6. Since use of excess heat was one of the investment options in the study, it was assumed that the DH systems did not currently use excess heat for DH production.

Table 6 Existing capacity in the district heating systems

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat demand [GWh]</td>
<td>117</td>
<td>797</td>
<td>1651</td>
</tr>
<tr>
<td>Peak load [MW]</td>
<td>42</td>
<td>331</td>
<td>483</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percent of total heat demand</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste boiler [%]</td>
<td>7</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Waste CHP [%]</td>
<td></td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Biomass boiler [%]</td>
<td>90</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Biomass CHP [%]</td>
<td></td>
<td>26</td>
<td>36</td>
</tr>
<tr>
<td>Coal boiler [%]</td>
<td></td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Peak load, oil boiler [%]</td>
<td>3</td>
<td>29</td>
<td>20</td>
</tr>
</tbody>
</table>

7.2 SEAST

SEAST (System design for Energy efficiency – Astra Zeneca and Scania in co-operation with Telge Nät) is a project that was carried out by the Division of Energy Systems in co-operation with Astra Zeneca, Scania and Telge Nät in Södertälje from 2007 until 2010. The SEAST project was very large and had a number of objectives. The objectives that were of relevance for this thesis are:

- Highlight the structure of the energy use in the industries and whether it could be changed.
- Analyze the energy supply, electricity production, and heat, steam and cooling production for both process and comfort applications.
- Investigate the potential for use of excess heat.
- Investigate the environmental impact such as global CO₂ emissions.
- Highlight the interaction between the industries and the surrounding energy system.
- Analyze the importance of the dynamic in the interaction between the industries and the surrounding energy system.
- Illustrate the importance of system boundaries for the results.
A significant part of the project was to understand the system relations concerning energy supply and energy use through analyzing the industries and the DH and DC systems as a coherent system. Possible co-operations and new investments were evaluated with an optimization model in which the system cost of the entire system of Astra Zeneca, Scania and Telge Nät was minimized. An outline of the model is shown in Figure 10.

Figure 10 The model of Astra Zeneca, Scania and Telge Nät

7.2.1 Scania
Scania develops and produces trucks, buses and engines, and has about 9000 employees in Södertälje. The headquarters and a research and development department are located in Södertälje, as are the production of engines and gear-boxes and assemblage of trucks and buses. Energy and energy efficiency is a major
priority at the Södertälje site, and Scania aims to continuously reduce the specific energy demand per production unit.

Heating and cooling make up for a large part of the energy demand at Scania. DH is used for heating the industrial facilities and office spaces. In order to decrease the need for DH, some excess heat from the production is used in the heating system. Scania also has heat pumps which complement the DH. The cooling demand is covered mainly by lake water which is supplied by a pipeline from Astra Zeneca through Telge Nät. To cover the peak demand of cooling, Scania has compression chillers, and there are also some buildings that have separate cooling systems supplied only by compression chillers.

7.2.2 AstraZeneca

Astra Zeneca in Södertälje develops and produces pharmaceutical products. The main products are bulk substances, pills and inhalers. In its work for sustainable development and responsible enterprising, Astra Zeneca focuses mainly on climate change, emissions to the environment, waste, pharmaceuticals in the environment, and energy use.

Astra Zeneca in Södertälje is located on two different industrial sites. In Snäckviken, an area of about 280,000 m², about 5400 people work with research, production and marketing. At the Gärtuna site (1,370,000 m²), about 2400 people work with research and production.

The energy use in the production is related to the high demands on the indoor environment. Many of the production processes require very exact conditions concerning temperature, humidity and cleanliness. Both sites use DH supplied by Telge Nät to heat the facilities. The cooling demand at Snäckviken is satisfied by lake water from Lake Mälaren in close proximity to the Snäckviken site, although compression cooling is used to cover the peaks in the cooling demand. At Gärtuna the entire cooling demand is supplied by compression chillers.

7.2.3 District heating in Södertälje

Telge Nät is the supplier of DH in Södertälje. The DH is mainly produced by Söderenergi which is owned to 42% by Telge AB, the other 58% being owned by SFAB which is the utility owned by the municipalities of Huddinge and Botkyrka. Most of the DH production takes place in Igelsta, but there are also facilities in Fittja, Huddinge and Geneta. The total delivery to the Södertälje grid is about 800 GWh/year.

The Igelsta site consists of a CHP plant (IKV) and three boilers (IGV-P1, IGV-P2 and IGV-P3). The boilers were converted in the 1990s from coal powder to waste, peat, wood pellets and recycled wood. The properties of the Igelsta production plants are summarized in Table 7. The efficiency of the CHP plant includes the flue gas heat recovery.
Table 7 The Igelsta site

<table>
<thead>
<tr>
<th>Igelsta</th>
<th>Power [MW]</th>
<th>Efficiency [%]</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKV</td>
<td>200(heat)/85 (el)</td>
<td>112</td>
<td>Biomass/waste</td>
</tr>
<tr>
<td>IGV-P1</td>
<td>80</td>
<td>90,7</td>
<td>Waste</td>
</tr>
<tr>
<td>IGV-P2</td>
<td>100</td>
<td>94,2</td>
<td>Biomass</td>
</tr>
<tr>
<td>IGV-P3</td>
<td>95</td>
<td>89,4</td>
<td>Biomass</td>
</tr>
</tbody>
</table>

Another site in the Södertälje area is Fittjaverket, situated in Botkyrka. The boilers in Fittjaverket are only used for peak demands during the winter, and the three boilers are fuelled by wood pellets and fuel oil. The properties of the boilers are presented in Table 8.

Table 8 Fittjaverket

<table>
<thead>
<tr>
<th>Fittja</th>
<th>Power [MW]</th>
<th>Efficiency [%]</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIV-P1</td>
<td>60</td>
<td>82,3</td>
<td>Oil</td>
</tr>
<tr>
<td>FIV-P2</td>
<td>160</td>
<td>96,3</td>
<td>Oil</td>
</tr>
<tr>
<td>FIV-P4</td>
<td>125</td>
<td>88,9</td>
<td>Biomass</td>
</tr>
</tbody>
</table>

In Huddinge and Geneta there are four oil boilers. These plants are only used as stand-by plants. The four stand-by plants are presented in Table 9.

Table 9 Huddinge and Geneta

<table>
<thead>
<tr>
<th>Huddinge</th>
<th>Power [MW]</th>
<th>Efficiency [%]</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMC-P1</td>
<td>80</td>
<td>90</td>
<td>Oil</td>
</tr>
<tr>
<td>HMC-P2</td>
<td>80</td>
<td>90</td>
<td>Oil</td>
</tr>
<tr>
<td>Geneta</td>
<td>2 boilers</td>
<td>90</td>
<td>Oil</td>
</tr>
</tbody>
</table>

7.2.4 District heating in the south and central Stockholm area
The Södertälje DH system is not isolated; it is connected to other DH systems in the Stockholm area. The connection between the DH systems makes it possible to buy and sell DH when there is a DH surplus or deficit. Today, the Södertälje system, which is part of the southern DH grid, is connected to other parts of the southern grid as well as the central grid of Stockholm. The transfer capacity between the southern and the central DH systems is about 100 MW. In other parts of the southern grid and in central Stockholm there are a number of other DH production plants. A summary of the production capacity in southern and central Stockholm is given in Table 10.
Table 10 DH production facilities in south and central Stockholm (Fortum and parts of SFAB)

<table>
<thead>
<tr>
<th>Stockhom (Fortum and SFAB)</th>
<th>Power</th>
<th>Efficiency</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal CHP</td>
<td>260 heat/125 el</td>
<td>0.88</td>
<td>Coal</td>
</tr>
<tr>
<td>Oil CHP</td>
<td>330 heat/200 el</td>
<td>0.89</td>
<td>Oil</td>
</tr>
<tr>
<td>Waste CHP</td>
<td>225 heat/65 el</td>
<td>0.89</td>
<td>Waste</td>
</tr>
<tr>
<td>Biomass boilers</td>
<td>570</td>
<td>0.9</td>
<td>Biomass</td>
</tr>
<tr>
<td>Oil boilers</td>
<td>About 1600</td>
<td>0.9</td>
<td>Oil</td>
</tr>
<tr>
<td>Electric boilers</td>
<td>360</td>
<td>0.98</td>
<td>Electricity</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>500</td>
<td>3.0</td>
<td>Electricity</td>
</tr>
</tbody>
</table>

7.2.5 District cooling in Södertälje

In addition to the DH deliveries, Telge Nät also delivers DC to customers in Södertälje. The DC is pumped from the lake by Astra Zeneca and then distributed to other clients by Telge Nät. Some of the cool water distributed is used for cooling of buildings to improve the thermal comfort; thus the cooling demand varies with the outdoor temperature. However, a large part of the cooling is used in the industries’ production processes and therefore the cooling demand is relatively large also in the winter (see Figure 11). In the SEAST project, only cooling demands at temperature levels that could be satisfied by DC (i.e. at about 5 °C) were considered. There are other cooling applications in both industries that require much lower temperatures, but these were not included in the study.

Figure 11 Cooling supply in Södertälje
8 Results and analysis

In this chapter an overview will be given of the results in relation to the research questions presented in the thesis. The results have been selected from the seven papers included in the thesis.

The thesis is based on seven papers which analyze three research questions:

- **Research question 1**
  How do factors such as policy measures, structure of the DH systems and energy market prices influence the potential for excess heat co-operations between kraft pulp mills and energy utilities? How does the choice of use of excess heat influence the system’s carbon dioxide emissions?

- **Research question 2**
  How will investments in increased DC co-operation between industries and a utility influence the heat production, electricity use, carbon dioxide emissions and resource use of a large CHP system?

- **Research question 3**
  What socio-technical factors influence the potential for co-operations between industries and utilities?

While most of the papers deal with only one research question, some of the papers can be related to several research questions. An overview of how the research questions are related to the papers is given in Table 11.
Table 11 Research questions related to the papers

<table>
<thead>
<tr>
<th>Research question</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I, II, III</td>
</tr>
<tr>
<td>2</td>
<td>III, IV, V</td>
</tr>
<tr>
<td>3</td>
<td>VI, VII</td>
</tr>
</tbody>
</table>

8.1 Research question 1 – Paper I, II and III

In papers I and II the trade-off between internal and external uses of kraft pulp mill excess heat was analyzed through optimizations using the energy system modeling tool reMIND. In the first paper a methodology was developed for analyzing industries and utilities through a joint perspective. In the second paper the methodology was applied and a sensitivity analysis using future energy market scenarios was performed.

As described in section 7.1.2, three different sizes of DH systems were analyzed together with the kraft pulp mill. A number of investments were modeled in both the DH system and the mill (see 7.1.1 and Table 12).

The optimizations showed that the size of the DH system that can receive excess heat from the kraft pulp mill has a significant effect on the results. While larger CHP systems more often have CHP and/or waste incineration, smaller DH systems are more likely to have pure heat production since the smaller heat demand makes CHP less profitable. This has the result that for the small DH system it is more profitable to use the excess heat in the DH system than to use it in the mill for internal energy efficiency measures independently of the energy price scenario (see Figure 12 and 6.5). For the large and medium DH systems, however, the optimal use of excess heat varies depending on the energy market scenarios (see Figure 13 and Figure 14). For all scenarios with a high CO₂ charge (scenarios 2 and 4, see 6.5) except one, external use of excess heat is optimal for the medium and large DH systems; but for the scenarios with lower CO₂ charge internal use in combination with waste and biomass CHP is more profitable. As can be seen from Figure 15, the size and production mix of the surrounding DH system are of importance for the trade-off between internal and external use of excess heat.
The system cost was reduced in all cases when energy efficiency measures were taken, suggesting that independently of whether excess heat is used internally or externally, there is a potential for reduced costs when investing in energy efficiency. The global CO₂ emissions were calculated after the optimization by assuming marginal emissions for electricity and biomass. All scenarios but one showed lower emissions than the baseline scenario. The extent of the reduced emissions depends on the marginal production technology and thus varies with the energy market scenarios.

The production of electricity in the system could be increased both in the mill and in the DH system, depending on what investments were made. In the small and medium DH systems, the electricity produced in the mill makes up for most of the electricity production, while the large DH systems produce more electricity than the mill. In the small DH system the electricity production is almost doubled in all scenarios. For the medium-sized DH system the increase in electricity production depends on the energy market scenario. In the scenarios where excess heat is used internally, an investment is simultaneously made in increased CHP in the DH system, which results in increased electricity production. In the scenarios where the excess heat is used externally, the electricity production increases in the mill. For the large DH system, the increase in electricity production in the mill is the same as for the small and medium systems, but since the mill makes up for a much smaller part of the electricity production the effect is less visible. In the utility, the electricity production increases the most in the scenarios where the excess heat is used internally, since this is combined with an investment in biomass CHP. To sum up, the electricity production is higher in the scenarios with internal use of excess heat but the internal use is combined with increased biomass CHP which results in increased use of biomass.

<table>
<thead>
<tr>
<th></th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess heat 100°C (MW)</td>
<td>0-13</td>
<td>0-13</td>
<td>0-13</td>
</tr>
<tr>
<td>Excess heat 40/60°C (MW)</td>
<td>0-43</td>
<td>0-43</td>
<td>0-43</td>
</tr>
<tr>
<td>FGHR (MW)(^a)</td>
<td>0-4</td>
<td>0-4</td>
<td>0-4</td>
</tr>
<tr>
<td>Waste CHP (MW(_\text{heat}))(^b)</td>
<td>0.4-0.8</td>
<td>8.5-17</td>
<td>-</td>
</tr>
<tr>
<td>Bio CHP (MW(_\text{heat}))(^b)</td>
<td>18.5-100</td>
<td>18.5-235</td>
<td>18.5-235</td>
</tr>
<tr>
<td>NGCC CHP (MW(_\text{heat}))(^b)</td>
<td>18.5-37</td>
<td>18.5-126</td>
<td>18.5-126</td>
</tr>
</tbody>
</table>

\(^a\) In accordance with Axelsson et al. (2006a).
\(^b\) In accordance with Bärring et al. (2003)
Figure 12 Overview of production techniques used for production of district heating in system S for the case of business as usual (S:BAU) and for the four future energy market scenarios.

Figure 13 Overview of production techniques used for production of district heating in system M for the case of business as usual (M:BAU) and for the four future energy market scenarios.
Figure 14 Overview of production techniques used for production of district heating in system L for the case of business as usual (L:BAU) and for the four future energy market scenarios.

Figure 15 The trade-off between internal and external uses of excess heat together with potential investments in new biomass CHP for the different analyzed cases.

*For the cases with small heat loads (S:1-4) the flue gas excess heat, which is not needed to satisfy the district heating load, is used internally. However, the majority of the excess heat is used externally and an investment in culverts is made, thus the placement in the top-left corner.

Figure 15 The trade-off between internal and external uses of excess heat together with potential investments in new biomass CHP for the different analyzed cases
Research question 2 has been discussed in papers III, IV and V, selected results are presented below.

In paper IV the impact of investments in either new lake water cooling or absorption cooling was investigated in the system of Södertälje (see section 7.2). The optimizations were made to analyze the profitability and CO₂ effects of absorption cooling and additional lake water cooling in the system. Both technologies would result in a decreased need for electricity for cooling, but absorption cooling will also increase the possibility for electricity production in the CHP plant. In order to investigate whether investment in absorption cooling could also be profitable if there was another way to increase the electricity production in the Södertälje CHP plant, an option was added where an investment could be made in a cold condenser for the CHP plant (case a, see Table 13). In the other case no cold condenser was present (case b). Both cases were compared to reference cases where no new investments in cooling supply were made.

Table 13 Studied cases in paper IV

<table>
<thead>
<tr>
<th>New case</th>
<th>New</th>
<th>No new cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold condensing in CHP plant</td>
<td>a</td>
<td>a ref</td>
</tr>
<tr>
<td>No cold condensing in CHP plant</td>
<td>b</td>
<td>b ref</td>
</tr>
</tbody>
</table>

The optimizations in paper IV showed that independently of whether condensing power production was possible or not, investments in increased lake water cooling and absorption cooling were still profitable. The cost of electricity for cooling is at present high enough to make new investments in cooling supply with lower specific electricity use profitable. While the cases with condensing power production (a and a ref) show a higher electricity production than those without (b and b ref), implementation of absorption cooling will also give a noticeable effect in electricity production in the Södertälje CHP plant due to the increased heat production (see Figure 17 and Figure 18).

The use of fuel resources in the system is very much related to the operating hours of the CHP plant. In the cases with condensing power production, the operating time is longer and more fuel resources are needed to supply the plant. Also absorption cooling will increase the use of fuel resources, but to a smaller extent. The CO₂ emissions of the system are related not only to the use of fuel resources but also to the use and production of electricity. Depending on how the CO₂ emissions from electricity are valued, the results will vary widely. In Figure 16 an overview of system cost and CO₂ emissions is presented. When calculating with marginal electricity, where increased production of electricity in the system is assumed to replace electricity produced on the margin (in this case coal condensing power plants), the cases with the highest electricity production result in the lowest CO₂ emissions.
In paper IV sensitivity analysis was performed for both energy market prices and the heat transfer capacity between the Södertälje DH system and the southern and central Stockholm DH systems. The sensitivity analysis of the energy market prices showed that the profitability of new investments in cooling supply is not influenced very much by the price differences in the energy market scenarios (see section 6.5). The heat transfer capacity between Södertälje and Stockholm does, however, make a difference for the results. The heat export makes it possible for the Södertälje plants to sell heat in order to increase the operating time of the CHP plant. When the transfer capacity between the DH systems was doubled, optimization results showed that absorption cooling was no longer profitable in case a where the CHP plant could operate as a condensing plant during parts of the year. When more heat could be exported to Stockholm, the economic benefits of increasing the heat demand through absorption cooling were reduced.
Research question 3 – Paper VI and VII
Research question 3 is discussed in papers VI and VII, the results below are selected from paper VI. Paper VI is based on an interview study conducted with 6 industries and 6 utilities. The study focused on the factors that inhibit or promote DH co-operations between industries and utilities. The factors were divided into two levels, the technology level and the technology/human level.
8.3.1 The technology level
Three different perspectives that were identified by Jaffe and Stavins (1994) were addressed on the technology level; heterogeneity, hidden costs and access to capital.

- **Heterogeneity**

Heterogeneity would mean that DH would not be an appropriate technology in the specific context. None of the interviewed companies suggested that any technology-specific factors had played an important role in determining whether a co-operation had been achieved or not. However, there was one example of a successful co-operation where the temperature requirement from the industry was initially higher than what could be delivered from the utility. The industry made an effort to lower the temperature levels, and thus the heterogeneity in this case was solved.

- **Hidden costs**

*Hidden costs* refer to costs such as those of collecting and analyzing information, production disruptions etc. (Jaffe and Stavins, 1994). The companies that were interviewed use consultants and lawyers, but the costs for these were not considered by the respondents to have an influence on possible collaborations. On the contrary, some of the companies stated that increased overhead costs were acceptable in order to achieve a co-operation.

- **Access to capital**

*Access to capital* is often considered an important factor affecting energy efficiency investments, and this was confirmed by the interview results. In a case where a co-operation had been planned and all agreements had already been signed, the co-operation failed when an investment subsidy was withdrawn. However, none of the respondents considered limited *access to capital* a major obstacle to co-operations. A reason for this could be that in the cases where co-operations have been obtained, the profits have been high. The profits can be related to increased energy prices which have influenced investment calculations in a positive direction.

8.3.2 The technology/human level
On the technology/human level six different perspectives were considered; *Risk, Imperfect information, Asymmetric information, Credibility and Trust, Inertia, and Values* (Jaffe and Stavins, 1994; Sorrell et al., 2000; Stern and Aronsson, 1984)

- **Risk**

*Risk* is of great importance when trying to obtain a co-operation. Sorrell et al. (2000) categorized *risk* in three groups: external risks, business-related risks and technical risks. External risks could be e.g. changed energy prices, business-related
risks are often related to the general economic situation and lending capital, and technical risks are related to how well the technologies used work.

The interviewed companies considered risk aversion a very important factor when deciding to enter a co-operation or not. One company stated that “We would have gone bankrupt if we had signed the agreement”. One respondent from the industrial side claimed that the size of the utility and the ownership structure were of importance for a co-operation to take place. A larger utility could be willing to take larger business-related risks while a smaller company cannot afford them. Another factor that was stressed by industry respondents was the question of business strategy. A co-operation with a company with a very short-term business strategy could be considered risky. Another risk-related problem could be that many utilities are publicly owned and the companies are reluctant to take risks that could affect their owners, i.e. the people of the municipality. From the utilities’ point of view, a big risk is also possible ownership changes or even that the business will close down; one utility respondent said “The biggest risk is that the industry will shut down”. As a conclusion, risk was considered a very important factor for DH collaborations by both industries and energy utilities.

- **Imperfect information**

  *Imperfect information* in this context would mean that collaboration would fail to take place due to lack of information concerning the benefits. One utility stated that a possible collaboration had failed because the industry lacked information and did not employ external consultants to do the calculations. Another utility CEO said that a key factor for cooperation to take place was competent workers, and another company confirmed that what had started off a cooperation was the involvement of a university that had made an optimization model of the utility and included the industry to show the potential. A conclusion drawn from this is that imperfect information can be minimized by involving an external party.

- **Asymmetric information**

  *Asymmetric information* is a common explanation for why energy efficiency measures do not take place (Jaffe and Stavins, 1994). It can be categorized in terms of principal-agent relationships, split incentives and adverse selection. An example of asymmetric information that was revealed in the interviews was when a utility respondent said, “One problem is when the production manager at an industry wants to keep his guys within the organization – he wants to have the responsibility for the boilers”. Another example was when the board of directors of a utility pushed the utility to keep the investment calculations for a co-operation down in order to establish the industry in the town. When the subsidy that was required to keep the slim budget was denied, the collaboration failed.

An instance of how asymmetric information has been reduced is when the staff of the industry was involved already before the collaboration was established. An industry respondent stated that “The key to success is to include the staff”.

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• **Credibility and trust**

*Credibility and trust* are factors that depend very much on personal contacts and recommendations. If there is a lack of *credibility*, information may be neglected. The importance of *trust* was stressed by respondents from both utilities and industries, and showing professionalism and integrity was appreciated when trying to achieve collaboration. The long decision-making periods and different business culture of municipal companies could sometimes pose a threat to co-operations, since it resulted in a lack of *trust* from the industrial party.

• **Inertia**

Inertia can in this context be defined as existing when change is opposed by individuals and this is justified by not accepting information that contradicts the current setup. This type of obstacle to co-operation was present in the interviews. The general image that emerged from the interviews was that a co-operation often requires plenty of time before it is established. “In 1999 we began negotiations with X (the industry) and it took three years and there were many laps run with the industry… It takes time to establish this kind of collaboration… it’s a long process. We have had contact with X (the industry) for 20 years.” Another respondent said that “We need to see the possibilities… One should not be satisfied and I believe this is easy among utilities… it has been easy to make money… Then you have to find people on both sides who see the possibilities, who do not defend their position…”

• **Values**

*Values* concerning the environment and energy efficiency are often a driver for collaborations to take place. A person with great motivation can make a big difference and influence a co-operation in a positive direction. Thus *values* can be seen as an explanation for willingness of a company to initiate a co-operation. In one case where co-operation previously had been difficult to achieve, the situation changed when new people with other values entered; the respondent from a utility said, “Then they changed the board of directors (at the industry)... a group of younger leaders who understand the environmental focus.” The importance of values is also stressed by another quote from the interviews: “The primary reason why we do like this is the environment... We work not only with profitability, but also with the environment... Energy prices, yes, but the environmental benefits are large – financially it is a zero-sum game. The environment is important.”

Another important factor mentioned by the respondents was the issue of business culture. Differences in what is considered “normal” practice could be revealed during negotiations and could inhibit possible co-operations. In order to overcome these problems, leadership and values of the organization are vital.
9 Conclusions
In this chapter the conclusions from the papers included in the thesis are presented in relation to the research questions and ideas for future work are presented.

9.1 Research question 1
How do factors such as policy measures, structure of the district heating systems, and energy market prices influence the potential for excess heat co-operations between kraft pulp mills and energy utilities? How does the choice of use of excess heat influence the system’s carbon dioxide emissions?

Optimizations showed that a determining factor, when deciding the optimal use of kraft pulp mill excess heat, is the size and production mix of the DH system to which the heat can be sold. A smaller DH system is less likely to have CHP production and is thus well suited for excess heat co-operation, since there will not be any competition between heat from CHP and the industrial excess heat. Larger DH systems are for the same reasons less likely to benefit from excess heat co-operation since existing CHP would lose some of its profitability. From a joint systems perspective, a kraft pulp mill in close proximity to a larger DH system mostly benefits more from using excess heat for internal measures, e.g. through saving steam and increasing the electricity production in its own turbines, unless the price of electricity is very low. In scenarios where the price of electricity is low and combined with high prices of biomass, the profitability of electricity production through biomass CHP is reduced and excess heat co-operation is more beneficial. The CO₂ emissions of the system depend on both the use of fuel resources and the net production of electricity. For the system as a whole, the electricity production is the highest when the kraft pulp mill excess heat is used internally and the utility invests in biomass CHP. This results in increased use of biomass, but the increase in electricity production also reduces the global CO₂ emissions when replacing marginal electricity production.
9.2 Research question 2
How will investments in increased district cooling co-operation between industries and a utility influence the heat production, electricity use, carbon dioxide emissions and resource use of a large CHP system?

Conversion of compression cooling, through investments in both heat-driven cooling and free cooling based on lake water, result in reduced use of electricity. Heat-driven cooling will increase the heat demand in the system and thus also the electricity production. However, the increased heat demand will have the result that the use of energy resources will increase in the system. Free cooling on the other hand will reduce the use of energy resources, since the use of electricity is reduced without changing the heat production. Just as for heat-driven cooling, investment in a cold condenser in the CHP plant will result in increased electricity production but also increased use of fuel resources. The CO₂ emissions in the system will be lower for the scenarios with the highest electricity production if marginal emissions are assumed for electricity.

9.3 Research question 3
What socio-technical factors influence the potential for co-operations between industries and utilities?

There are numerous aspects that influence the likelihood of achieving energy co-operations. While economic aspects such as policy instruments and energy market prices are very important, other factors more related to human relationships are equally significant.

Risk is a significant factor concerning both purely technical risks, such as fear of production disruptions, and risks related to fluctuating energy market prices and changes in the owner-structure of the involved companies. This is also related to the fact that trust between the parties is necessary if a co-operation is to take place. Different business cultures can result in a lack of trust between companies and therefore pose a threat to co-operations. The values expressed in an organization are also important, since a company with e.g. a clear environmental vision may be more likely to enter a co-operation. Lack of information considering the benefits can be a barrier to possible co-operation, and in order to overcome this problem an external party provides new perspectives. Another obstacle is when members of an organization oppose change. This type of inertia can also have the result that even when co-operation takes place, it is a very long process to reach an agreement.

9.4 Future work
There are many possible developments of the studies made in this thesis. Some of the questions that could be explored are presented here.

The study of the FRAM kraft pulp mill integrated with a DH system could be further developed. In paper III a study was made on how absorption cooling would influence the trade-off between internal and external use of kraft pulp mill excess
heat. The cooling load used in this study was relatively small and it would be interesting to investigate the influence on the system of larger cooling loads.

In the study concerning Södertälje the investment costs of new investments in cooling supply could be further investigated. Since the true potential for adsorption cooling has not yet been surveyed, the investment cost of adsorption cooling in the industries Scania and Astra Zeneca has not been estimated. The investment costs for absorption cooling and free cooling were estimated, based on previous investments in the industries, but a more extensive analysis of the costs could be performed. Since the system was first modelled, changes have been made in the system, and for a future study of Södertälje the model needs to be updated with new data.

Other aspects that would be interesting for future research are: analysis of the expansion of DC and new industrial cooling supply in other municipalities, the influence of new policy instruments on industrial energy systems, further socio-technical studies of the barriers to and drivers for different types of energy cooperation, and the potential for excess heat co-operations in different types of industry.
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