LINKÖPING STUDIES IN SCIENCE AND TECHNOLOGY
Dissertation No. 1601

With district heating toward a sustainable future

System studies of district heating and cooling that interact with power, transport and industrial sectors

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Linköping, June 2014

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Linköping Studies in Science and Technology
Dissertation No. 1601
ISBN 978-91-7519-314-4
ISSN 0345-7524

Distributed by:
LINKÖPING UNIVERSITY
Department of Management and Engineering
SE-581 83, Linköping, Sweden
Phone: +46(0)13-28 10 00

Printed by:
LiU-Tryck, Linköping, Sweden, 2014.

Cover photography:
District Heating plants silhouette of Tekniska Verken, Linköping, Sweden.
Photograph taken by Fredrik Nilsson, Inrego AB, Stockholm, Sweden.
Cover design:
Tomas Hägg, LiU-Tryck, 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 analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that constitute the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Research Theme Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm. Associated research groups are the Division of Environmental Systems Analysis at Chalmers University of Technology in Göteborg as well as the Division of Electric Power Systems at the Royal Institute of Technology in Stockholm.

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ABSTRACT

From a system perspective, district heating (DH) is characterized by a number of environmental benefits, such as: flexibility in the fuel mix, the possibility of industrial waste heat utilization, and the possibility of combining heat and power (CHP) production. However, due to climate change and sustainable development of other energy systems, those benefits will not be so obvious in the future.

The aim of this thesis is to identify measures which should be taken in DH systems (DHSs) in order to contribute to the development of the DHSs and other energy systems (especially transport, industrial and power sectors) toward sustainability.

The scope of the thesis is system studies of Swedish DHSs considering fully deregulated European electricity and free biomass markets. Four business strategies were analysed: delivering excess heat from biofuel production industry to DHSs, conversion of industrial processes to DH, integration of biofuel production in DHSs and integration of DH-driven absorption cooling technology in DHSs. Delivering excess heat from biofuel production industry to DHSs was analysed with a focus on the biofuel production costs for four biofuel production technologies. Integration of biofuel production and integration of DH-driven absorption cooling technology in DHSs were analysed with a focus on Stockholm's DHS, using an optimisation model framework called MODEST. When the conversion of industrial processes to DH was analysed, DHSs and industrial companies in Västra Götaland, Östergötland and Jönköping counties were used as case studies; a method for heat load analysis called MeHLA was used to analyse the effects on the local DHSs. The studies include techno-economic evaluation, and evaluation of the effects on global fossil fuel consumption and on global greenhouse gas (GHG) emissions. Two different time frames were employed: a short-term time frame where energy market (EM) and DHS conditions from the year 2010 were considered and a long-term time frame where the analysed time period was from the year 2030 to the year 2040.

The results showed that when considering biomass an unlimited resource, by applying the abovementioned business strategies DH has a potential to reduce global fossil fuel consumption and global GHG emissions associated with power, industrial and transport sectors.

DH producers may contribute to the sustainable development of the *transport sector* by buying excess heat from the biofuel production industry. This business strategy results in lower biofuel production costs, which promotes development of biofuel production technologies that are not yet commercial. Moreover, introduction of large-scale biofuel production into local DHSs enables development of local biofuel supply chains; this may facilitate the introduction of biofuel in the local transport sectors and subsequently decrease gasoline and fossil diesel use. Conversion of industrial processes from fossil fuels and electricity to DH is a business strategy which would make *the industry* less

dependent on fossil fuels and fossil fuel-based electricity. DH may also contribute to the sustainable development of the industry by buying waste heat from industrial processes, since this strategy increases the total energy efficiency of the industrial processes and reduces production costs. Furthermore, DH has a possibility to reduce fossil fuel consumption and subsequently GHG emissions in the *power sector* by producing electricity in biomass- or waste-fuelled CHP plants.

When the marginal electricity is associated with high GHG emissions (e.g. when it is produced in coal-fired condensing power (CCP)) plants, the reduction of the marginal electricity production (due to the conversion of industrial processes from electricity to DH and due to the conversion of compression cooling to DH-driven absorption cooling) results in higher environmental benefits. On the other hand, the introduction of biofuel production into DHSs becomes less attractive from an environmental viewpoint, because the investments in biofuel production instead of in CHP production lead to lower electricity production in the DHSs.

The increased DH use in industry and introduction of the biofuel production and DH-driven absorption cooling production into the DHSs lead to increased biomass use in the DHSs. Because of this, if biomass is considered a limited resource, the environmental benefits of applying these business strategies are lower or non-existent. If the alternative users of biomass are plants for “traditional” biofuel production, the increased biomass use in the DHSs leads to increased use of fossil fuels in the transport sector. Consequently, in this case, the environmental benefits of applying the referenced strategies are lower. If the alternative use of biomass is co-firing in CCP plants the suggested business strategies in most of the analysed cases lead to increases in global fossil fuel consumption and global GHG emissions, due to increased coal use in the power sector.

Most of the business strategies analysed in this thesis may also lead to a reduction in DH production costs, due to the higher revenues from by-production.

SAMMANFATTNING

Ur ett systemperspektiv kännetecknas fjärrvärme (FJV) av en rad miljöfördelar, som till exempel flexibilitet i bränslemixen, möjlighet till utnyttjande av industriell spillvärme och kraftvärmeproduktion. I ett framtida hållbart samhälle är dock fjärrvärmens fördelar inte lika stora.

Syftet med denna avhandling är att identifiera åtgärder som bör vidtas i FJV-system (FJVS) för att bidra till en hållbar utveckling av FJV och andra relaterade energisystem som transport, industri- och energisektorn.

Avhandlingen omfattar systemstudier av svensk FJV i en helt avreglerad europeisk el- och biomassamarknad. Fyra affärsstrategier är analyserade: att leverera överskottsvärme från produktion av biobränsle för transportsektorn, konvertering av industriella processer till FJV, integration av biobränsleproduktion för transportsektorn i FJVS och integration av FJV-driven absorptionskylteknik i FJVS. Att leverera överskottsvärme från produktion av biobränsle till transportsektorn analyserades med fokus på kostnader för fyra olika produktionstekniker. Integration av biobränsleproduktion till transportsektorn och integration av FJV-driven absorptionskylteknik i FJVS analyserades på Stockholms FJVS med optimeringsmodellen MODEST. När konvertering av industriella processer till FJV analyserades, användes FJVS och industriföretag i Västra Götaland, Östergötlands och Jönköpings län som fallstudier. Metoden MeHLA som används för analys av värmebelastning tillämpades för att analysera effekterna på de lokala FJVS. Samtliga studier omfattar teknisk ekonomisk utvärdering och analys av effekterna på den globala konsumtionen av fossila bränslen samt utsläpp av globala växthusgaser. Två olika tidsramar har använts; en kortsiktig tidsram med energimarknadens (EM) och FJVS villkor från år 2010 och en långsiktig som omfattar 2030 till 2040.

Resultaten från studierna visar att när biomassa anses vara en obegränsad resurs har FJV en potential att minska den globala konsumtionen av fossila bränslen och de globala utsläppen av växthusgaser som förknippas med transport-, industri- och energisektorn, för samtliga analyserade affärsstrategierna.

FJV producenter kan bidra till en hållbar utveckling av transportsektorn genom användningen av överskottsvärme från produktion av transportbiobränsle. Den analyserade affärsstrategin ger lägre produktionskostnader för transportbiobränsle vilket främjar utvecklingen av produktionsteknik som ännu inte är kommersiell. Dessutom möjliggörs utveckling av lokala försörjningskedjor av transportbiobränsle på grund av den storskaliga produktionen av transportbiobränsle i lokala FJVS. Detta kan sedan underlätta införandet av transportbiobränsle i lokala transporter och även minska användningen av bensin och fossil diesel. Konvertering av industriella processer från fossila bränslen och el till FJV är en affärsstrategi som skulle göra FJV-branschen mindre beroende av fossila bränslen. Att använda spillvärme från industriprocesser ökar den

totala energieffektiviteten i de industriella processerna och minskar produktionskostnaderna. Genom att dessutom öka FJV-användningen inom industriella produktionsprocesser och genom att konvertera eldriven kompressionskyla till FJV driven komfortabsorptionskyla, minskar säsongsvariationerna av FJV lasten, vilket leder till ett bättre utnyttjande av produktionsanläggningar för FJV. Om produktionsanläggningarna för baslast i FJVS är kraftvärmeverk, leder dessa två affärsstrategier till en ökad elproduktion i FJVS.

När marginalproducerad el förknippas med höga utsläpp av växthusgaser (t.ex. när det produceras i koleldade kondenskraftverk), resulterar en minskning av den marginella elproduktionen (på grund av konvertering av industriella processer från el till FJV och på grund av konvertering eldriven kompressionskyla till FJV-driven absorptionkyla) i minskade globala emissioner av växthusgas. Om man däremot tittar på införandet av produktion av transportbiobränsle i FJVS är denna affärsstrategi mindre attraktiv ur ett miljöperspektiv. Orsaken till detta är att investering i produktion av transportbiobränsle istället för i kraftvärmeproduktion, leder till minskad elproduktion i FJVS.

Den ökade FJV-användningen inom industrin och införandet av produktion av biobränsle för transportsektorn och FJV driven absorptionskylproduktion i FJVS leder till en ökad användning av biomassa i FJVS. När biomassa anses vara en begränsad resurs, är de miljömässiga fördelarna med att tillämpa dessa affärsstrategier relativt låga eller till och med obefintliga. Om alternativ användning av biomassa sker i produktionsanläggningar för "traditionellt" transportbiobränsle, leder den ökade användningen av biomassa i FJVS till ökning av fossila bränslen inom transportsektorn. Följaktligen är i detta fall de miljömässiga fördelarna med de nämnda strategierna lägre. Om den alternativa användningen av biomassa är sameldning i koleldade kondenskraft leder de föreslagna affärsstrategierna i de flesta av de analyserade fallen till ökning av den globala konsumtionen av fossila bränslen och av de globala utsläppen av växthusgaser, på grund av en ökad kolanvändning inom energisektorn.

De flesta av de affärsstrategier som analyseras i denna avhandling kan också leda till en minskning av FJV produktionskostnader, tack vare högre intäkter från bi-produktion (el och transportbiobränsle).

*To my beloved husband Dejan
and my daughter Andjela*

"Of all the frictional resistances, the one that most retards human movement is ignorance, what Buddha called 'the greatest evil in the world.' 'The friction which results from ignorance can be reduced only by the spread of knowledge and the unification of the heterogeneous elements of humanity. No effort could be better spent. "

- *Nikola Tesla (1856 - 1943) Serbian-American Inventor, Mechanical and Electrical Engineer, Inventor of Alternating Current and Holder of Over 1200 Patents*

Appended papers

This thesis is based on the work described in the following papers. The papers are appended at the end of the thesis.

- I. Djuric Ilic, D., Dotzauer, E., Trygg, L. **District heating and ethanol production through polygeneration in Stockholm.** *Applied Energy* 91(1) 2012, pp. 214-221
- II. Djuric Ilic, D., Trygg, L. **Introduction of absorption cooling process in CHP systems - An opportunity for reduction of global CO₂ emissions.** *Proceedings of ECOS, 4-7 July 2011, Novi Sad, Serbia.*
- III. Djuric Ilic, D., Dotzauer, E., Trygg L., Broman G. **Introduction of large-scale biofuel production in a district heating system - An opportunity for reduction of global greenhouse gas.** *Journal of Cleaner Production*, 64 (1) 2014, pp. 552-561
- IV. Djuric Ilic, D., Dotzauer, E., Trygg L., Broman G. **Integration of biofuel production into district heating - Part I: An evaluation of the biofuel production costs.** *Journal of Cleaner Production*, 69, 2014, pp. 176-187
- V. Djuric Ilic, D., Dotzauer, E., Trygg L., Broman G. **Integration of biofuel production into district heating - Part II: An evaluation of the district heating production costs using Stockholm as a case study.** *Journal of Cleaner Production*, 69, 2014, pp. 188-198
- VI. Djuric Ilic, D., Trygg L. **Economic and environmental benefits of converting industrial processes to district heating.** *(Submitted for journal publication)*

Acknowledgements

This study was conducted under the auspices of the Energy Systems Programme at Linköping University, which is financially supported by the Swedish Energy Agency. Parts of the study were conducted within the projects “Sustainable Cities in a Backcasting Perspective” and “Conversion of industrial processes to district heating – a possibility for more efficient operation of district heating production plants and for reduction of global greenhouse gas emissions”, which were financially supported by the Swedish District Heating Association. The financial support is gratefully acknowledged.

First and foremost, I would like to thank Professor Bahram Moshfegh for giving me the opportunity to conduct my PhD studies at the Division of Energy Systems.

I owe special thanks to my supervisor, Associate Professor Louise Trygg for all the encouragement and guidance during this lengthy and challenging process. She has given me great support and was truly an inspiration for me.

I also wish to express particular gratitude to Professor Björn Karlsson, who was my supervisor during the first few months of my time as a PhD student, for helping me to understand the basic principles of the energy system approach and for always believing in me.

Special thanks to Adjunct Professor Erik Dotzauer for his valuable ideas, suggestions, for helping me with input data for the model, and for having patience to answer all my important and less important questions.

I would like to thank my co-supervisor, Professor Göran Bruman, for giving me new perspectives on sustainability and for many stimulating discussions.

In particular, thanks to Dr. Dag Henning for all the help during my PhD study period and for the valuable comments on the draft of this thesis; this helped me to make it so much better.

Special thanks to Maria Johansson for being such a good friend and for being my personal supporter through all these years.

I would also like to thank to Dick Magnusson and Malin Henriksson for the great time and productive cooperation during the work with our multidisciplinary project report.

I owe special thanks to Kristina Difs, who gave me valuable inputs to the work during my first year as a PhD student, and to Shahnaz Amiri and Dr. Alemayehu Gebremedhin for all their help with the MODEST model framework.

I am also grateful for all constructive comments on my work from Elisabeth Wetterlund and Sarah Broberg Viklund.

I also wish to express gratitude to Adjunct Professor Shelley Torgnyson, who has greatly contributed to improving my writing skills.

I would like to thank all the PhD students in D08 for the pleasant atmosphere and the valuable discussions during the courses in the multidisciplinary Energy Systems Programme, and to my colleagues within our division for the great cooperation.

I owe a special gratitude to all my friends here in Sweden and in Serbia for encouraging me through this work.

Special thanks to my husband Dejan for always believing in me and for encouraging me, and to my daughter Andjela for being patient and for all the smiles and kisses which made these years so much easier for me.

Finally I would like to thank my family (mama Ljubinka, papa Branimir, sister Zorica, Jeca, Milan) for showing interest in my research and their long-distance support and love.

Thesis outline

The thesis consists of two parts. Part I gives an introduction to the research field and includes a summary of the studies from the appended papers, as well as some additional analyses performed in order to improve those studies. Part II contains the appended papers.

Part I includes the following chapters:

Chapter 1 contains a brief introduction to the research field, hypothesis and research questions on which the thesis is based, the scope and delimitations, brief description of the appended papers, and co-author statement.

Chapter 2 discusses energy policy instruments affecting district heating and describes the context in which the studies in the research papers were made.

Chapter 3 gives a description of the fundamental concept of district heating and an overview of the history of Swedish district heating. The chapter also contains a summary of related studies.

Chapter 4 gives an overview of the cases studied.

Chapter 5 describes the methodologies applied, provides input data for the technologies included in the study, and gives an overview of the additional analyses performed in order to give more concrete answers to the research questions.

Chapter 6 aims to present a summary of the results from the research papers with respect to the research questions. This chapter also includes the results from the additional analyses provided for the purposes of this thesis.

Chapter 7 includes discussion of the results and conclusions with respect to the research questions.

Chapter 8 gives suggestions for further work.

Part II includes the papers which form the basis of the thesis.

Abbreviations

BCHP, biomass-fuelled combined heat and power;

BHOB, biomass-fuelled heat-only boiler;

CH₄, methane;

CHP, combined heat and power;

CO₂, carbon dioxide;

COP, coefficient of performance;

CCP, coal-fired condensing power;

CCS, carbon capture and storage;

DC, district cooling;

DCS, district cooling system;

DH, district heating;

DHS, district heating system;

DME, dimethyl ether;

EM, energy market;

EMS, energy market scenario;

ENPAC, Energy Price and Carbon Balance tool;

FTD, Fischer-Tropsch diesel;

GHG, greenhouse gas;

HOB, heat-only boiler;

IEA, International Energy Agency;

MeHLA, Method for Heat Load Analysis;

MODEST, Model for Optimization of Dynamic Energy Systems with Time-dependent components and boundary conditions;

N₂O, nitrous oxide;

NG, natural gas;

NGCC, natural gas combined cycle;

PHEV, Plug-in Hybrid Electric Vehicle;

RES-E support, support for electricity produced from renewable energy sources;

RES-T support, support for transportation fuel produced from renewable energy sources;

TS, transport sector.

SNG, synthetic natural gas;

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Part II – Included papers:

Paper I - District heating and ethanol production through polygeneration in Stockholm

Paper II - Introduction of absorption cooling process in CHP systems - An opportunity for reduction of global CO₂ emissions

Paper III - Introduction of large-scale biofuel production in a district heating system - An opportunity for reduction of global greenhouse gas

Paper IV - Integration of biofuel production into district heating - Part I: An evaluation of the biofuel production costs

Paper V - Integration of biofuel production into district heating - Part II: An evaluation of the district heating production costs using Stockholm as a case study

Paper VI - Economic and environmental benefits of converting industrial processes to district heating

1 Introduction

This chapter includes a brief background of the study and description of its aims, as well as descriptions of the hypothesis and research questions. Furthermore, the scope and delimitations are described and overviews of the appended papers and co-author statements are given.

There are a number of different definitions of sustainable development. One of the most frequently quoted definitions is that “*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (Brundtland, 1987).

Based on this definition, a framework for ecological, social and economic sustainability, consisting of four sustainability principles, was developed by Robèrt (2007). The principles are stated as follows:

“In a sustainable society, nature is not subject to systematically increasing

(1) concentrations of substances extracted from the Earth’s crust,

(2) concentrations of substances produced by society,

(3) degradation by physical means

and, in that society

(4) people are not subject to conditions that systematically undermine their capacity to meet their needs” (Robèrt, 2007).

Using these sustainability principles during a strategic planning process is an effective way to deal with possible trade-offs, situations that may lead to positive effects in certain aspects and to negative effects in others (Robèrt, 2007).

A strategy for sustainable development of energy systems generally should involve three major measures: replacement of fossil fuels by various sources of renewable energy; more efficient use of energy on the demand side; and efficiency improvements in energy

sectors in order to reduce losses. In order to get closer to the goal of sustainability the European Council adopted the integrated energy and climate change policy known as the 20-20-20 targets. This policy refers to three targets to be achieved by the end of the year 2020. According to those targets, primary energy use should be reduced by 20% calculated from a projected level based on the primary energy use in 2005, greenhouse gas (GHG) emissions should be reduced by 20% compared to the levels from the year 1990, and 20% of the total energy use in the EU should come from renewable sources. An additional target is to increase the share of renewable energy (renewable electricity or biofuel*) in the transport sector (TS) up to 10% (European Commission, 2008; European Parliament, 2009).

From a system perspective, district heating (DH; energy services based on centralized heat production and on delivering heat and cooling from production facilities to customers) is characterized by a number of environmental benefits. Some of those benefits are the flexibility in the fuel mix, the possibility of industrial waste heat utilization, the possibility of energy recovery through waste incineration, and the possibility of combining heat and power (CHP) production. CHP production implies high primary energy efficiency and a possibility to decrease the fossil fuel share in the power sector if biomass is used as fuel (Gebremedhin, 2012; Amiri et al., 2009; Andersen and Lund, 2007). However, due to the likely future sustainable development of the power sector, the electricity production in the future will no longer be linked to high GHG emissions. For example, Jeffries et al. (2011) estimated that more than 85% of the global power in the year 2050 may be produced by wave, wind, solar, hydro and geothermal energy. As a consequence, the benefits of CHP production would be less obvious despite the fact that the CHP technology is a resource-efficient technology compared to producing electricity in condensing power plants. Moreover, climate change and energy efficiency measures in the building sector induce possible reduced DH demand in the existing district heating systems (DHSs). Consequently, DH producers will face new challenges in the future and need to develop new business strategies. Development of new business strategies for DH producers would make DH production more competitive with other heating technologies, and might ensure a new role for DH in a sustainable society (Magnusson, 2012).

* In this study, the term "biofuel" is used to denote renewable transport fuels.

1.1 Aim and research questions

The aim of this thesis is to identify measures which should be taken in DHSs in order to contribute to the development of the DHSs and other energy systems toward sustainability in a profitable way.

The hypothesis of the thesis is:

- DH can contribute to a sustainable development of other energy systems, especially of the transport, industrial and power sectors.

The hypothesis is evaluated through the following research questions:

1. *Can the following business strategies ensure profitable DH production and contribute to DH having an important role toward a future sustainable energy system?*
 - *introduction of biofuel production into DHSs*
 - *integration of DH-driven absorption cooling technology in DHSs*
 - *delivering industrial waste heat (from biofuel production industry) to DHSs*
 - *increasing DH use in industrial processes.*
2. *How can heat production in DHSs contribute to reduction of global fossil fuel consumption and global GHG emissions?*

Table 1 gives an overview of which research questions are considered in each of the appended papers.

Table 1. Overviews showing in which papers the research questions are explored.

Research question	Papers					
	I	II	III	IV	V	VI
1.	*	*	*	*	*	*
2.	*	*	*		*	*

Analyses of new business strategies (the first research question) were included in all appended papers. These business strategies were analysed through different aspects: profitability for DH producers or some other actors included in the business strategy, influences on global GHG emissions, and influences on global fossil fuel consumption; the last two aspects overlap with the second research questions. The second research question is based on *the first principle of sustainability* and *the second principle of sustainability* (see section 1). In order to give more concrete answers to this question, some additional analyses have been performed (see sections 5.6, 5.7 and 5.8). The

question is addressed in Papers I, II, III, V and VI. *The third principle of sustainability*, which is about degradation of nature by physical means (e.g. by overuse of biomass), was discussed through sensitivity analyses regarding the alternative use of biomass; these analyses are associated with the second research question. In those analyses it is assumed that in order not to overuse the biomass, the global biomass use during the year should be limited. This means that the increase of biomass use in the DHSs would lead to a reduction of biomass use somewhere else. Assuming different alternative users of biomass, the effects on global fossil fuel consumption and on global GHG emissions caused by this reduction of biomass use were analysed.

1.2 Scope and delimitations

The scope of the thesis is system studies of Swedish DHSs considering fully deregulated European electricity and free biomass markets and different energy market (EM) conditions. In four papers (Paper I, II, III and V) the focus of the study was Stockholm's DHS. The study in paper VI includes about 80 DH networks and 83 small and medium-sized manufacturing companies, located in three counties in the south of Sweden (Västra Götaland, Östergötland and Jönköping).

Two different time frames were employed: a short-term time frame in Papers I and II where EM and DHS conditions from the year 2010 were considered, and a long-term time frame in Papers III, IV, V and VI where the analysed time period was from the year 2030 to the year 2040.

Impacts on global warming were analysed in Papers I, II, III and VI. The analyses in Papers I and II were restricted to carbon dioxide (CO₂), while in Papers III and VI emissions of methane (CH₄) and nitrous oxide (N₂O) were considered as well. To be able to compare the results from those papers and in order to improve the research, additional analyses which include CH₄ and N₂O were performed based on the results from Paper I and II. The results from those analyses are presented in this thesis.

1.3 Overview of the papers used as a basis for the thesis and co-author statement

The thesis is based on the following six papers:

Paper I

Danica Djuric Ilic, Erik Dotzauer, Louise Trygg

District heating and ethanol production through polygeneration in Stockholm. *Applied Energy* 91(1) 2012, pp. 214-221

The paper aimed to evaluate the effects of introducing an ethanol polygeneration plant (with ethanol capacity of 95 MW and with biogas, electricity and heat as by-products) into the DHS in Stockholm, Sweden. The focus was on DH production costs and on possible changes of global CO₂ emissions. The analyses were performed by using an optimization model framework called MODEST. The results showed that the revenues from ethanol and biogas production (about €66 million and €10 million annually), and the revenues from the electricity produced in the polygeneration plant (about €130 million annually), would increase the total revenues from the by-products in the DHS by 70%. This would also lead to lower DH production costs. Introducing the plant into the DHS would lead to a reduction of global CO₂ emissions as well. Assuming that the ethanol and biogas produced would replace gasoline in the TS, and that the electricity produced would reduce electricity production in coal-fired condensing power (CCP) plants, the reduction of global CO₂ emissions would be about 0.7 million tonnes annually.

Paper II

Danica Djuric Ilic, Louise Trygg

Introduction of absorption cooling process in CHP systems - An opportunity for reduction of global CO₂ emissions. *Proceedings of ECOS*, 4-7 July 2011, Novi Sad, Serbia

The aim of this study was to analyse the potential for reduction of global CO₂ emissions by converting from vapour compression cooling to absorption cooling in Stockholm's district cooling system (DCS) and in Stockholm's industrial sector. The system was studied using MODEST, an optimization model framework developed for analysis of dynamic energy systems. The results showed that more than 95% of the compression cooling produced during the months from April to October should be converted to DH-driven absorption cooling. This would lead to a better utilization of the CHP plants in Stockholm's DHS. Moreover, the electricity used for compression cooling production

would be reduced. If CCP plants are assumed as marginal electricity sources, the increased electricity production in the CHP plants and the decreased electricity use would lead to a reduction of global CO₂ emissions by 0.15 million tonnes annually. The potential for reduction of global CO₂ emissions is higher when the cooling demand increases.

Paper III

Danica Djuric Ilic, Erik Dotzauer, Louise Trygg, Göran Broman

Introduction of large-scale biofuel production in a district heating system - an opportunity for reduction of global greenhouse gas. *Journal of Cleaner Production*, 64 (1) 2014, pp. 552-561

In this study, cooperation between Stockholm's transport and DH sectors by introducing large-scale biofuel production into the DHS was suggested as a strategy for reduction of global GHG emissions. It was assumed that all biofuel produced would be used in the local TS. The analyses were performed using the MODEST optimization model framework. The results showed that the introduction of large-scale biofuel production into the DHS opens up a possibility for a reduction of fossil fuel consumption in the TS and DHS by between 20% and 65%, depending on assumed TS development and assumed EM conditions; the results are based on an assumption that all biofuel produced would be used locally. The potential for GHG emissions reduction depends on the assumption regarding biomass availability. When the biomass is considered an unlimited resource, the large-scale biofuel production implies a possibility for global GHG emissions reduction. However, since biomass is a limited resource, the increased biomass use in the DHS would lead to decreased biomass use in other energy systems. In this case the potential for reduction of GHG emissions depends on the alternative use of biomass. When the alternative use is traditional biofuel production, which does not include co-production of heat and electricity, the potential for reduction of GHG emissions through biofuel production still exists but is much lower. If co-firing in CCP plants is considered the alternative for biomass use, biomass use in CHP plants is more desirable from a GHG viewpoint than for biofuel production through polygeneration.

Paper IV

Danica Djuric Ilic, Erik Dotzauer, Louise Trygg, Göran Broman

Integration of biofuel production into district heating - Part I: An evaluation of the biofuel production costs. *Journal of Cleaner Production*, 69, 2014, pp. 176-187

This study analysed how profitability of biofuel production through polygeneration would be affected by selling the waste heat from production to a local DHS under the different EM conditions. Sensitivity analyses of DH price level, annual operating time, and discount rate were performed as well. The analyses have been performed for four different technology cases for biofuel production, which include ethanol, biogas, Fischer-Tropsch diesel (FTD) and dimethyl ether (DME) production. Assuming that the prices for which the biofuel would be sold are based on the crude oil price, the profitability of biofuel production depends on the price ratio between biomass and crude oil. Moreover, higher price ratios between district heating and biomass, and between electricity and biomass, would also make biofuel production more profitable because of the higher revenues from the secondary production of heat and electricity. The profitability of the biofuel production also depends on the efficiency for production of biofuel and the by-products electricity and heat. The economic benefit from introducing a polygeneration plant into a DHS and the sensitivity to the DH price level depends on the heat efficiency of the plant. The results also showed that an increase of the discount rate from 6% to 10% would not have a significant influence on profitability.

Paper V

Danica Djuric Ilic, Erik Dotzauer, Louise Trygg, Göran Broman

Integration of biofuel production into district heating - Part II: An evaluation of the district heating production costs using Stockholm as a case study. *Journal of Cleaner Production*, 69, 2014, pp. 188-198

The paper analysed how introduction of large-scale biofuel production into the Stockholm DHS would influence DH production costs. The types of biofuel produced were chosen depending on the future development of Stockholm's TS. The system was optimized by the MODEST model framework. The results from the scenarios with the large-scale biofuel production were compared with the reference scenarios in which it is assumed that the DH producers would invest in CHP production instead. The period analysed was between 2030 and 2040. Two different EM scenarios (EMSs) were considered. The results showed that the profitability of investing in biofuel production is highly dependent on the types of biofuel production plants and EMS. The large-scale biogas and ethanol production may lead to a significant reduction in the DH production costs in both EMSs. Investments in FTD and DME production are shown not to be competitive to the

investments in CHP production if high support for transportation fuel produced from renewable energy sources is not included.

Paper VI

Danica Djuric Ilic, Louise Trygg

Economic and environmental benefits of converting industrial processes to district heating (Submitted for journal publication)

The study aimed to analyse the possibilities of converting industrial processes to DH use in 83 manufacturing companies in three counties located in the south of Sweden: Jönköping, Östergötland and Västra Götaland. Possible impacts on global GHG emissions and economic effects of the conversion to DH use were studied considering two different EMSs for the year 2030. The Method for Heat Load Analysis (MeHLA) was used to explore how the conversions would affect the heat load duration curves in the local DHSs. The results showed that the DH use in the manufacturing companies can increase by nine times in Jönköping, by two times in Östergötland, and by four times in Västra Götaland. The conversion to DH would open up a possibility for a reduction of global GHG emissions. However, the potential for the reduction of global GHG emissions is highly dependent on the alternative biomass use and on the type of marginal electricity production plants. The energy costs for the manufacturing companies decrease. The conversion of the industrial processes to DH would lead to a better utilization period of the CHP plants in the local DHSs, which would increase revenues from electricity production and increase the potential for reduction of global GHG emissions.

In **Papers I, III and V** Erik Dotzauer provided detailed DH production data for the DHS, which helped me to shape the model of the DHS according to the real production. The literature research, study design, modelling work, model runs, analysis, and writing were done by me. Louise Trygg contributed valuable comments on all three papers (**Papers I, III and V**). Göran Broman contributed valuable comments on **Papers III and V**, and wrote the last paragraph in the results and discussion section in **Paper V**, as well as some parts of the introduction section in the same paper.

The idea for **Paper II** was mine alone. The literature research, data collection, modelling, analysis of the results, and writing were done by me. Louise Trygg contributed discussions and valuable comments on the paper.

I provided the idea for **Paper IV**. The idea was developed from the reviewers' comments for **Paper V**. I did literature research, calculations, analysis of the results, and writing. After getting permission from the editor of the journal to which **Paper V** was sent, **Paper V** was rewritten so that **Paper IV** can also be used as an introduction to the

research presented in **Paper V**; this is also obvious from the titles of those two papers. Erik Dotzauer, Louise Trygg and Göran Broman contributed valuable comments on **Paper IV**.

Paper VI is based on a research project which Louise Trygg and I performed for Swedish District Heating Association (see section 1.4). I was responsible for literature research and data collection, calculations, analysis of the results, and writing. Louise Trygg also contributed discussions and valuable comments on the paper.

1.4 Other publications by the author of the theses

Magnusson, D., Djuric Ilic, D. Modelling district heating co-operations in Stockholm – an interdisciplinary study of a regional energy system. Proceedings of the 12th International Symposium on District Heating and Cooling, 5-7 September 2010, Tallinn, Estonia

Djuric Ilic, D., Trygg, L. Conversion of industrial processes to district heating – a possibility for more efficient operation of district heating production plants and for reduction of global greenhouse gas emissions. June 2013. Swedish District Heating Association. (This project is not publicly available.)

Djuric Ilic, D., Trygg, L. Ökad fjärrvärmeleverans till industrin. January 2014. Swedish District Heating Association. (A shorter Swedish version of the report Conversion of industrial processes to district heating – a possibility for more efficient operation of district heating production plants and for reduction of global greenhouse gas emissions; the project is not publicly available)

Djuric Ilic, D., Henriksson, M., Magnusson, D. Stockholms fjärrvärmenät idag och imorgon - en tvärvetenskaplig studie av ett regionalt energisystem. Arbetsnotat nr 44, Program Energisystem. Linköpings universitet, 2009

Djuric Ilic, D. Olika metoder – olika verktyg för systemanalys av Stockholms fjärrvärmesystem, i Karlsson, M och Palm, J (red.) På spaning efter systemteori och tvärvetenskaplig metod - essäer från doktorandkursen Systemanalys med metodexempel från energiområdet. Arbetsnotat nr 41, Program Energisystem. Linköpings universitet, 2009

2 Background

This chapter gives a description of the context in which the studies in the papers were performed.

2.1 The deregulated European electricity market

The objective of a common, deregulated electricity market is above all to ensure a secure supply of electricity, and to increase the efficiency of the electricity sector through the introduction of competition between different electricity production plants. In 1996 Sweden and Norway established a common electricity market (the Nordic market), into which Finland was integrated in 1998, and Denmark in 2000. In recent years the Baltic countries have been integrated into this market as well (Difs, 2010; Nord Pool, 2014). The whole European electricity market was deregulated in 2004 for non-household customers and in 2007 for all customers (EC, 1996; EC, 2003; EC, 2009). However, the European electricity market is still far from fully integrated, which results in existence of regional monopolies and in large electricity price differences between countries; for an overview of electricity prices see Difs (2010). One of the reasons for the price differences is low power transmission capacities, not only within the countries, but transnationally as well (COM, 2008).

2.1.1 Accounting environmental impact of electricity production and use

The European electricity market is characterized by a wide range of possible electricity production technologies with different production and environmental costs. Trygg (2006) argues that this makes it impossible to evaluate those costs for one specific kWh of

electricity in a specific moment. Sjödin and Grönkvist (2004) discuss different methods for how to evaluate changes in GHG emissions which are results of changes in electricity production. When the changes in GHG emissions are evaluated for a chosen time period, the average electricity production method can be used. This method assumes that the changes in electricity demand lead to changes in electricity production in all types of production plants (even in the base power plants) by the same percentage. However, this method does not illustrate the dynamic of the power system. Sjödin and Grönkvist (2004) argue that the most feasible method for GHG emissions accounting when the electricity demand varies during that time is accounting according to marginal production. The appropriate approach with a short-term perspective is accounting according to the “operational” marginal electricity production, while accounting according to the “build” marginal electricity production is recommended when a long-term perspective is taken (Ådahl and Harvey, 2007). The “operational” marginal electricity production is the production in the operating power plants which have the highest variable costs in the power sector. As a result, any changes in electricity demand or in electricity production in some other type of plant (e.g. in CHP plants) should lead to increased or decreased marginal electricity production. The Swedish Energy Agency (SEA, 2002) identified CCP plants in Denmark as the “operational” marginal production sources in the Nordic market. The “build” marginal electricity production is the electricity production in the plants which would not be built in the future, if the electricity demand decreases or if the electricity production in some other kind of plants increases (Sköldbberg and Unger, 2008; Sköldbberg et al., 2006; Ådahl and Harvey, 2007).

2.2 Biomass – a limited resource

Bioenergy sources can be classified as crops, crop residues, wood, and organic waste. In this study, the term “biomass” is used to denote woody biomass originating from the forest.

There are a number of studies that deal with the issue of balance between future energy demand and available renewable energy resources. In many of those studies biomass was found to be a key factor for reaching fossil fuel-free energy systems, on regional (Dahlquist et al., 2007), national (Dahlquist et al., 2008), European (Dahlquist et al., 2012), and even on global (Dahlquist, 2012) scales.

The gross inland use of primary energy in EU-27 in the year 2010 was approximately 20 PWh. Approximately 2 PWh of this energy was supplied by renewable energy; the share of biomass and waste in this total renewable energy use was 68% (Eurostat, 2014). In Sweden, renewable energy accounted for approximately 34% (202 TWh) of the gross

inland use of primary energy in 2010; approximately 65% of this renewable energy was supplied from biomass and waste (Eurostat, 2014).

When discussing the availability of biomass for energy supply, it is important to define the type of potential being estimated. Torén et al. (2011) presented four different types of potential for biomass: theoretical, technical, economic, and implementation. Wetterlund (2012) gave an overview of studies which discuss increase of biomass availability in the future, and pointed out a remarkably wide range of various estimations for the same type of potential, on both a global and a European level. Moriarty and Honnery (2012), who reviewed studies that estimated global technical potential of renewable energy in 2050, noted that the biomass available for energy supply may even decrease in the future, due to possible changes in precipitation and soil moisture levels, and a rise in extreme weather events, insect infestations and fire outbreaks.

Uncertainty regarding biomass availability makes it of essential importance to increase efficiency of biomass use. Therefore, the technologies that imply high fuel efficiency, such as CHP and polygeneration production, become of great interest. Furthermore, due to an increased competition for biomass use in the future, biomass will no longer be considered GHG emissions neutral, since an increase of biomass use in one energy system will result in a reduction of biomass use (and consequently an increased use of fossil fuel) in some other energy system. This issue is further discussed in sections 5.6 and 5.7.

2.3 Related policy instruments

Concerns over climate change and energy supply security puts the task of creating climate and energy policy at the top of EU and national political agendas.

Increasing energy efficiency and use of renewable energy sources is the key strategy for the transition to a more sustainable energy system. In 2009 a climate and energy package, known as the “20-20-20” targets, was adopted (European Parliament, 2008).

This policy includes the following set of targets which should be achieved by 2020:

- to reduce EU’s primary energy use by 20% compared to a projected level based on the primary energy use in 2005;
- to reduce EU GHG emissions by 20% compared to the levels from the year 1990;
- to increase the share of renewable energy in the EU’s total energy use to 20%;

- to increase the share of renewable energy (renewable electricity or biofuel) in the TS to 10% (European Parliament, 2008).

In order to enable the EU to reach these targets, Member States have taken on binding their own national targets which depend on their different starting points and potential. Sweden has set targets to increase the share of renewable energy in the total energy use to 49% and the share of renewable energy in the TS to 10% by 2020, as well as to reduce energy intensity (supplied units of energy per unit of gross domestic product) by 20% in 2020 compared with 2008. Sweden has also set an additional long-term goal to have a vehicle fleet which is independent of fossil fuel by 2030 (SEA, 2014).

One of the key tools of the EU climate and energy policy is the Emissions Trading Scheme, which aims to reduce GHG emissions in energy-intensive industry and the power and heating sectors in a cost-effective way. The Emissions Trade Scheme has been in place since 2005. For each participant in the Trade Scheme this system limits the total amount of CO₂ which can be emitted. However, emissions allowances can be traded up to the limit; one emissions allowance is equivalent to one tonne of CO₂ (European Parliament, 2003, 2009; SEA, 2010). The price of the emissions allowance varies significantly from year to year (ICE-ECX, 2011). However, approximately 60% of the total GHG emissions in the EU come from sectors outside the trading scheme (such as housing, agriculture, waste and TS excluding air traffic). Therefore, Member States have established binding targets, which differ according to Member States' relative wealth, for reducing their GHG emissions from these sectors. The binding target for Sweden is to reduce these GHG emissions by 40% in 2020 compared with 1990 (European Commission, 2013; SEA, 2014).

The EU climate and energy policy usually includes revisions over time. A major revision of the Emissions Trading Scheme concerns reductions in the cap. The cap will be gradually reduced each year, and by 2020 the cap will be 21% lower than 2005 (European Commission, 2013).

2.3.1 Economic policy instruments related to the district heating sector

Economic policy instruments are essential for reaching the targets which are set as part of the climate and energy policy. The economic policy instruments related to the studies performed in this thesis include: energy taxes (such as taxes on electricity and fuels, the CO₂ tax, the sulphur tax and the environmental charge for emissions of NO_x); support for electricity produced from renewable energy sources (RES-E support); and support for transportation fuel produced from renewable energy sources (RES-T support). According to SEA (2014), the economic policy instruments which have the largest impact on the fuel

mix in the DHSs and on the share of DH produced by CHP are the CO₂ taxes and RES-E support.

The taxes on fuels vary depending upon the purposes for fuel use, while the taxes on electricity vary depending upon the area in which the electricity will be used. The CO₂ tax on DH production in CHP plants was reduced from 15% to 7% of the base amount in 2011. From the beginning of 2013, CHP production and DH production for purposes of industrial sector use were exempted from the CO₂ taxation.

RES-E support in Sweden is based on an electricity certificate system that took effect in May 2003 (SEA, 2010). The electricity certificate system aims to increase the share of the electricity produced from renewable sources. For every MWh of renewable electricity produced, the producer receives an electricity certificate, which is traded between the producers and other electricity suppliers and certain electricity users, which are obliged to buy a certain proportion (quota) of electricity certificates. This proportion varies from one year to another depending on the expected expansion of renewable electricity production, expected electricity sales and electricity use of the actors who are obligated to buy the certificate (SEA, 2010). Currently, all EU Member States promote renewable electricity production by policy instruments Wetterlund (2012).

Because of the possibility to integrate biofuel and DH production in DHSs, RES-T support also becomes a policy which may influence the future development of the DHSs. For an overview of policy measures for promoting biofuel production and renewable electricity production in EU Member States, see Wetterlund (2012).

3 District heating and sustainability

This chapter includes a description of the fundamental idea of district heating and an overview of the history of Swedish district heating. Furthermore, potential development of DHSs is discussed and a summary of related studies is presented.

In contrast to individual heating alternatives, DH technology is characterized by centralised heat production. A DHS consists of DH production facilities and DH networks built of pipelines used for distribution of the heat energy to final users; in Sweden, water is used as the medium. DHSs are characterized by local conditions. For most Swedish DHSs the maximum temperature limit for the medium (water), which is namely the design temperature level for the pipes, is approximately 120 °C (Frederiksen and Werner, 1993). Since DH in Sweden is mainly used for space heating and preparation of domestic hot water, the heat load demand curves in the DHSs are characterized by high seasonal variations. The supply temperatures (the temperature of the medium) in the DH networks usually vary during the year together with the DH demand. The temperature usually varies within a range from 75 °C to 95 °C, but when the outdoor temperature is very low the supply temperature can even exceed 100 °C. The lower supply temperature during the summer leads to decreased distribution heat losses and enables increased electricity efficiency (power-to-heat ratio) in the system's CHP plants (Frederiksen and Werner, 2013).

Frederiksen and Werner (2013) and Werner (2004) detected strategic heat resources suitable for DHSs (Figure 1). The most favourable resource for DH production is *secondary energy supply* (Figure 1). *Secondary energy supply* is recovered secondary heat which refers to heat recycled from thermal power generation (CHP production), as well as to utilization of useful excess heat from industrial processes, waste incineration, and fuel refineries. According to Euroheat & Power (2011), more than 75% of the total EU27 DH supply consisted of recovered secondary heat. However, the heat losses in the energy system in the European Union still correspond to more than half of the total primary energy supply (Frederiksen and Werner, 2013). Those heat losses appear during the central conversion (22.4 EJ; those losses can be reduced through CHP production), local conversion (17.1 EJ; can be reduced by switching from private boilers to DH), and energy use (12.6 EJ; can be reduced by utilization of the industrial excess heat). *Renewable*

energy sources (Figure 1) which are suitable for DH production are geothermal energy, solar energy and biomass. *Fossil fuels* (coal, NG and oil) should be used only for backup supplies and peaks during the coldest days (Frederiksen and Werner, 2013; Werner, 2004).

Figure 1. The fundamental concept of DH.

There are five characteristics which are usually mentioned as possible benefits of DHSs: *economy of scope*, *economy of size*, *flexibility*, *security of supply*, *possibility for a reduction of global CO₂ emissions* and *positive impact on local environment* (Frederiksen and Werner, 2013). The possibility to use secondary energy supply and the possibility to use fuels difficult to handle (e.g. straw, peat and wood waste) are examples of *economy of scope*. *Economy of size* characterizes the technologies that have lower costs or higher energy efficiency at higher production volumes. Moreover, using larger heat production units rather than smaller ones also makes better emission control possible. A high degree of *flexibility* and diversity in fuel use and a wide range of possible energy supply sources are also some of the positive characteristics of DH. The *positive impact on local environment* can be discussed as one of the benefits but only if the DH production does not include CHP production. If CHP production is included, despite the fact that DH production is characterized by better environmental performance and control of boilers

than individual boilers, the local environmental impact can even be greater due to the additional fuel use for electricity production. On the other hand, in a number of previous studies (e.g. Knutsson et al., 2006; Danestig et al., 2007; Gebremedhin, 2012; Andersen and Lund, 2007) the CHP production has been recognised as a technology which opens up a possibility for a *reduction of global CO₂ emissions* due to decreased coal use in the power sector. Because of the possibility of using domestic renewable fuels and waste fuels for DH production, and possibility to utilize excess heat from industrial processes, the *security of supply* is also higher with DH.

DH is well developed in Sweden and is a strong competitor with other heating options, especially in multi-family residential buildings and in the service sector. The first DHS in Sweden was built in Karlstad in 1948. A decade later, DH technology was introduced in several other Swedish cities (Swedish District Heating Association, 2009; Sjödin, 2003). Today, there are over 400 DHSs in Sweden, which deliver approximately 60 TWh* of DH annually (Swedish District Heating Association, 2013). In the beginning, the main fuel used in the DHSs was oil (approximately 90% of the total energy supplied). However, after the oil crises in the 1970s and 1980s, and due to strong energy policy instruments, oil use rapidly decreased. Today, fossil fuels represent only about 10% of the total energy used in Swedish DHSs, while the share of biomass, peat and waste is higher than 70% (SEA, 2009; Swedish District Heating Association, 2013). Another factor which had high influence on the development of the DHSs is the historically lower electricity price in Sweden, compared with the prices in most other EU counties. The reason for the lower electricity price was high share of nuclear and hydro power with low power production costs in the Swedish electricity sector. As a consequence, in 2012 the share of DH produced in CHP plants was only approximately 50% of total DH production (Swedish District Heating Association, 2013). This share is considerably lower than in other EU counties, e.g. compared with Denmark and Finland, where this share is approximately 80% (Energiatollisuus, 2010; ENS, 2008).

3.1 Related system studies of district heating production

Future development of the DH sector was the subject of several studies (Nielsen and Möller, 2013; Münster et al., 2012; Lund et al. 2010). Magnusson (2012) argues that Swedish DHSs are heading into a stagnation phase. By using large technical system theory, Magnusson (2012) analysed reasons for this, as well as possible strategies for

* The standard unit for *heat/DH energy* is the Joule, which is equal to Watt-second ($J=W*s$). However, in the studies presented in this thesis, the *heat/DH energy* is presented in Wh (MWh, GWh or TWh). This is in order to make it possible to compare this type of energy with other types of energy (e.g. electricity), and to present them in the same diagrams.

preventing such a development. The conclusion in this study was that in order to avoid stagnation DH producers must develop new business strategies which include increased by-production (e.g. electricity through CHP technology) in the DHSs and using the alternative value of the technical system for new applications. Below, some of those new business strategies are presented through a review of some previous studies.

3.1.1 Related studies about integration of biofuel and district heating production

In several studies the introduction of biofuel and other types of biomass gasification applications into DHSs was analysed. In this thesis the results which refer to biofuel production are presented from some of those studies.

Egeskog et al. (2009) analysed the possibility for integration of biomass gasification-based biofuel production with DH production in the EU countries by estimating the heat sink capacity of the DHSs. They found that the heat sinks in DHSs in the EU countries are large enough to accept the entire amount of surplus heat produced during the production of the amount of biofuel which would correspond to the 2020 renewable transportation target (see section 2.3). However, when the cost-competitiveness with other DH technologies is considered the possibility is not so obvious. The cost-competitiveness is highly dependent on the future EM scenarios (EMSS; biofuel prices and the prices of by-products, e.g. electricity and DH prices), the existing DH technologies (e.g. existing fossil fuel-based CHP plants, available industrial waste heat, and available excess heat from waste incineration), and the required investment costs. Beside those factors, the future development of other DH production technologies, as well as the possibility for further expansions of the DHSs will also influence the amount of biofuel which may be produced in a profitable way. When the attractiveness from a CO₂ viewpoint is assessed, a further development of carbon capture and storage (CCS) technology may have a positive influence, but not necessarily if the profitability is considered at the same time. The attractiveness of the biofuel production in the DHSs differs considerably among the different EU countries (Egeskog et al., 2009). Therefore it is of high importance to assess the optimal locations of the biofuel production plants.

Results from a few studies showed that revenues from the surplus heat may have a high impact on the final biofuel production cost, and as such these revenues should be included in analysis when the location of the biofuel production plant is considered (Leduc et al., 2010a; Leduc et al., 2008; Leduc et al., 2010b; Wetterlund et al., 2012; Wetterlund, 2010). Leduc et al. (2010a) assessed the proper locations for lignocellulosic ethanol refineries in Sweden by minimizing the final ethanol cost, with respect to the biomass transportation costs, the ethanol transportation costs and the possibility for selling the surplus heat. They showed that the optimal locations to set up ethanol polygeneration plants in Sweden are in the vicinity of small to medium-size cities in forested areas since

those locations would enable delivering the surplus heat to local DHSs, delivering the produced ethanol to a local TS at a competitive cost (compared to imported ethanol), and using the local biomass. The same type of study was performed considering biomass-based methanol production plants and using the country of Austria (Leduc et al., 2008) and Norrbotten county in Sweden (Leduc et al., 2010b) as the case studies. When the biomass availability and the biomass costs in Austria (Leduc et al., 2008) and in Norrbotten in Sweden (Leduc et al., 2010b) were considered, the results showed that by selling the surplus heat, methanol production costs may decrease by 12% and 10%, respectively. While Leduc et al. (2010a; Leduc et al., 2008; Leduc et al., 2010b) investigated the optimal locations of biofuel production plants on regional and national scales, Wetterlund et al. (2012; Wetterlund, 2010) assessed advantageous locations for ethanol, methanol and Fischer-Tropsch diesel (FTD) production plants on a European scale. The locations are assessed with a focus on parameters which may affect the biofuel production costs, such as biomass availability, heat delivery opportunities, capital costs, energy prices, and energy policies. A general conclusion in those two studies was that both the biofuel production costs and the potential for reduction of global CO₂ emissions highly depend on the possibility of utilizing the surplus heat and electricity. The results also showed that the price for which the surplus heat is sold may have a significant influence on biofuel production costs. When the heat is sold to a local DHS, this price is above all determined by the existing DH technologies, as was also found in Egeskog et al. (2009).

A number of studies showed that the profitability of integration of biofuel and DH production is highly dependent on EM conditions and energy policy. The aim of a study performed by Difs et al. (2010) was to analyse how the profitability of integration of different biomass gasification applications with DH production depends on different EM conditions. Those investment options were compared with investment in biomass-based CHP production. The potential for reduction of global CO₂ emissions was analysed as well. The city of Linköping was used as the case. They found that higher oil prices make the investments in synthetic natural gas (SNG) production in Linköping's DHS more profitable; the higher oil prices lead to higher biofuel prices and subsequently to higher revenues from surplus SNG. On the other hand, higher CO₂ charge makes it more profitable for DH producers to invest in CHP production. The reason for this is that the higher CO₂ charge increases the price ratio between electricity and oil (since electricity production is characterized by higher CO₂ emissions than oil consumption); higher electricity prices result in higher revenues from surplus electricity produced in the CHP plants. They also discussed that existing long-term policy instruments which promote biofuel production are of extreme importance, since the investments in the biofuel production plants are very capital intensive and as such present a high financial risk for the DH companies. Börjesson and Ahlgren (2010) and Wetterlund and Söderström (2010) assessed the biofuel subsidy levels required to make the investments in different types of large-scale biomass gasification applications into 15 DHSs in the southwest region of Sweden (Börjesson and Ahlgren, 2010) and into Linköping's DHS (Wetterlund and Söderström, 2010) attractive for DH producers. Börjesson and Ahlgren (2010) found that

biofuel subsidy levels in the range of €30-40/MWh are required to make the introduction of DME and SNG production into the DH sector in the southwest region of Sweden attractive for DH producers. Wetterlund and Söderström (2010) came to a conclusion which is in line with this result. They found that biofuel subsidy levels in the range of €24-42/MWh are needed to make the investments in SNG production in Linköping's DHS competitive to the investments in CHP production. Fahlén and Ahlgren (2009) assess the changes in DH production costs and the potential for CO₂ reduction when different biomass gasification applications are integrated with an existing natural gas (NG) combined cycle CHP plant in Gothenburg's DHS. The investments were compared with reference scenarios that did not include any new investments. Sensitivity analyses of different EM conditions were performed. They found that the profitability of introduction of SNG and DME production through gasification into Gothenburg's DHS is dependent on the price ratio between biomass and fossil fuels, and the level of policy instrument support for biofuels and renewable electricity. They also showed that the introduction of SNG and DME into Gothenburg's DHS would be advantageous from a CO₂ emission perspective, as was also found in Difs et al. (2010) when the introduction of SNG into Linköping's DHS was considered.

Starfelt et al. (2010) analysed the performance of a polygeneration system which is built by integrating a lignocellulosic ethanol production process with an existing CHP plant, while Starfelt et al. (2012) assessed economic benefits of this integration. The results were compared with stand-alone ethanol and CHP production. The result showed that integration of vehicle fuel processes with biomass-based CHP plants may be good strategy from an economic and environmental viewpoint. Starfelt et al. (2010) showed that the integration of ethanol production with biomass-based CHP production would lead to an improvement of total efficiency by 11%. The total biomass consumption would be reduced by 14% compared to the stand-alone configurations, while producing the same amounts of ethanol, heat and electricity. Furthermore, according to Starfelt et al. (2012), integration of these two processes can be profitable even without long-term development of the process steps and even without reaching high ethanol yield. The reasons for this are the increased total energy efficiency and increased revenues from electricity production in the CHP plant due to the increased heat production for purposes of ethanol production during the low DH demand periods (e.g. during the summer).

3.1.2 Related studies about integration of absorption cooling production into district heating systems

Fahlén et al. (2012) and Trygg and Amiri (2007) analysed possibilities and potential of introduction of DH-driven absorption cooling into existing DHSs. Fahlén et al. (2012) assessed the economic and environmental effects of introduction of DH-driven absorption cooling production into Gothenburg's DHS. This strategy was compared with the

reference scenario where it was assumed that the cooling is produced by vapour compression chillers. The results from the study showed that the introduction of DH-driven absorption cooling production into Gothenburg's DHS would increase the utilization of industrial excess heat or the utilization of the system's CHP plants. The DH demand in the DHS would increase by 30% during the summer. However, the effects on annual DH demand would be minor. Even when the recent advances of vapour compression chillers are considered, conversion from compression cooling to DH driven absorption cooling results in a cost-effective reduction of global CO₂ emissions when the existing DH production technologies in Gothenburg's DHS are considered, although the potential for reduction is highly dependent on the type of marginal electricity production technology. The CO₂ emission reduction is a result of the increased electricity production in the DHS's CHP plants (due to an increased operation of those plants), and the decreased electricity use for compression cooling production. Fahlén et al. (2012) also discuss the DH-driven absorption cooling technology as an economically attractive business strategy for Swedish DHSs with existing or planned biomass-based CHP plants. The study performed by Trygg and Amiri (2008) aims to identify the most cost-effective technology for cooling in seven industrial companies in Norrköping, Sweden. DH-driven absorption cooling was compared with vapour compression cooling. They found that if higher European electricity prices are considered, cooling production by DH-driven absorption chillers is more cost effective than cooling production by vapour compression chillers. They also found that when CCP plants are assumed to be the marginal electricity sources, the conversion from vapour compression to DH-driven absorption chillers in the analyzed industrial companies would lead to a reduction of global CO₂ emissions.

Udomsri et al. (2011) and Cosar et al. (2013) analysed possibilities for development of new process technologies which would include utilization of municipal solid waste for purposes of heat-driven absorption cooling production. Udomsri et al. (2011) discuss that municipal solid waste plants which provide both electricity and absorption cooling are of special interest in tropical locations where the annual demand for space heating is low. According to Udomsri et al. (2011), such a plant with 1350 tons/day of municipal solid waste input may have a cooling capacity of 77 MW and electricity capacity of 21.5 MW. When it is assumed that the electricity would otherwise be produced by natural gas combined cycle (NGCC) plants and that the cooling would otherwise be produced by vapour compression chillers (driven with electricity from NGCC plants), the estimated global CO₂ emission reduction achieved through absorption cooling is 0.13 kg CO₂/kWh of cooling (Udomsri et al., 2011). Another possibility is to connect a local space heating and heat-driven absorption comfort-cooling system with an anaerobic digester, as was shown in the study performed by Cosar et al. (2013). When considering Turkey's climate which is characterized by long warm seasons, this heating and cooling system is profitable and has a potential to reduce global CO₂ emissions compared to the compression comfort-cooling production.

3.1.3 Related studies about cooperation between industrial and district heating sectors

Cooperation between DH and industrial companies has been of great interest during the last decade. The most common forms of cooperation are: utilization of DH in the industry sector for purposes of space heating and for production of hot tap water, utilization of DH and steam from the DH production facilities in industrial processes, and delivery of industrial excess heat into local DHSs. According to Thollander et al. (2010) the relationship between the DH company and the industrial company has greater importance for successful cooperation between DH and industrial sectors than the economic and technical factors. The human factors (such as credibility and trust, imperfect and asymmetric information, willingness to take risks, inertia among individuals and within organizations) have been shown to have the greatest influence. Those results are in line with the results from Grönkvist and Sandberg (2006), which underline the importance of people with the ambition to cooperate. They also highlight the benefits of cooperation, such as a reduction of primary energy use, possible cost savings, and environmental benefits.

According to a study performed by Persson and Werner (2012) the theoretical potential to increase the excess heat recovery use (not only from industrial processes but also from thermal power generation and waste incineration) for purposes of DH in EU-27 countries is by about 300%. Theoretically, about 6.2 EJ of industrial heat can be recovered for purposes of DH. When the direct feasible distribution costs are considered the potential is about 35% lower. They did not find any direct barriers with respect to available heat sources or feasible distribution costs for expansion of DH within EU-27. The potential for increased utilization of industrial excess heat in DHSs exists in Sweden as well. Broberg et al. (2012) analyse this potential in two counties in the south of Sweden, Örebro and Östergötland. After scaling up the results from the analysed case studies to a national level, they conclude that there is approximately 21 TWh/year of industrial excess heat in Sweden, which can be used in the local DHSs, although the largest share of the heat is at lower temperatures. The potential in the form of primary excess heat is only about 10% of this amount. Broberg Viklund and Johansson (2014) found a large untapped industrial excess heat potential in Gävleborg County. This excess heat represents approximately 8% of the total energy use in the analysed industrial companies. Two technologies for heat recovery were considered: delivery to a local DHS and use for electricity production. The results from the study showed that the possible impact of the heat recovery on global CO₂ emissions depends highly on the technology used and on EM conditions. When NGCC electricity production is considered as the build marginal electricity production technology, and when the alternative use of biomass is in CCP plants, from the CO₂ emissions perspective it is better to use the industrial excess heat in a DHS based on biomass combustion than to use it for electricity production. On the other hand, if the alternative for biomass use is for traditional FTD production (FTD production that does not include co-production of heat) and if the build marginal electricity production

technology is CCP technology, the heat delivery to a DHS based on CHP production from biomass may even result in increased global CO₂ emissions. The reason for this is that the heat delivery to the DHS would reduce electricity production in the CHP plants, which consequently would lead to increased coal use in the CCP plants. Thus in this case it would be a better option to use the excess heat for electricity production (Broberg Viklund and Johansson, 2014). (For more detailed explanation of the term “build marginal electricity” and for more detailed discussion of alternative use of biomass see sections 5.2, 5.6 and 5.7.) Kapil et al. (2012) showed that the economic benefit of utilization of industrial waste heat in DHSs is also case-specific. Since the delivery of the excess heat decreases the heat production from the existing DH production facilities (e.g. CHP plants), the economic benefit is highly dependent on those existing DH production technologies and on the EM conditions (e.g. heat and electricity prices).

Several previous studies include analysis of possible cooperation between industrial and DH sectors by converting the industrial processes from fossil fuel and electricity to DH. Henning and Trygg (2008) recognized the conversion of industrial processes to DH as a vital measure when redirecting the energy systems toward sustainability. They found that converting industrial processes from electricity to DH produced in CHP plants would have a dual impact on the power sector, as it would reduce marginal electricity production in the sector due to decreased electricity use, as well as due to increased electricity production in the CHP plants. Subsequently, this would lead to reduction of global CO₂ emissions. The processes whose conversion to DH has the highest potential to increase electricity production in the CHP plants are those which have relatively even energy use during the year (Henning and Trygg, 2008).

The purpose of a study performed by Difs et al. (2009) was to identify the industrial processes in 34 Swedish industrial companies from different sectors of trade, which may be converted to DH use. The influences on the DH load duration curves were analysed, as well as the possible reduction of global CO₂ emissions. They showed that by converting the industrial processes to DH, the electricity use in the companies would be reduced by 11% and the oil and liquefied petroleum gas use by 40%. The conversion would lead to a DH demand curve which is less dependent on outdoor temperature, resulting in more efficient use of the existing CHP plants during the year. The decreased fossil fuel and electricity use in the industry, and the increased electricity production in the CHP plants (which would decrease the marginal electricity production in the power sector), would lead to a reduction of global CO₂ emissions. Difs and Trygg (2009) analysed how pricing according to marginal cost for DH production in Linköping's DHS would affect the potential for conversion of industrial processes to DH in eight local companies in a cost-effective way. According to results from this study, applying the marginal costs for DH production as DH tariffs for the industry would increase potential for DH use in industrial processes in the analysed companies in Linköping, Sweden. The conversions would lead to economic benefits for both the local DHS and industrial companies; the DH companies would benefit from higher revenues from electricity produced in CHP plants. When CCP

plants are assumed to be the marginal electricity sources, this business strategy would result in lower global CO₂ emissions as well (Difs and Trygg, 2009).

4 Studied systems

This chapter gives an overview of the systems studied in the appended papers.

Five of the papers of this thesis (Papers I, II, III, V and VI) are case studies. In Papers I and II Stockholm's DHS from the year 2010 was studied. Paper II also includes data about Stockholm district cooling (DC) production and cooling production in Stockholm's industrial sector. For the purposes of Papers III and V assumptions about future DHS and TS in the county of Stockholm have been made; in those papers, the period between 2030 and 2040 was analysed. Paper VI includes case studies of about 80 DHSs and 83 manufacturing companies in three counties located in the south of Sweden: Jönköping, Östergötland and Västra Götaland; the analysed period was between 2030 and 2040 so the assumptions for future DHSs in those counties have been made.

4.1 Case study – county of Stockholm

Stockholm, the capital of Sweden, together with its surrounding communities covers an area of approximately 6,500 km² and has about two million inhabitants. Since 1995, Stockholm has been committed to an ambitious climate policy. Some of the measures which have been taken are: increasing the renewable energy share of the total energy use in the region, expanding the DHS, and encouraging the use of public transportation by introducing a congestion charge.

4.1.1 Stockholm's district heating system

Stockholm's DHS consists of three large DH networks (Table 2). The networks started as smaller ones that have gradually been expanded and interconnected during the last three

decades (Magnusson, 2011). In the DHS, there are about 70 DH plants owned by five different companies, which deliver about 12 TWh of DH annually. Six of the plants are CHP plants with a total electricity capacity of about 600 MW, and an annual electricity production of over 2 TWh; the CHP plants produce about 50% of the total DH produced in the DHS. Four CHP plants are fuelled by biomass and waste, and two CHP plants with the highest installed electricity capacity (200 MW and 145 MW) are fuelled by oil and coal (Dahlroth, 2009; Dotzauer, 2003). The DHS is characterized by a high degree of fuel flexibility. The share of biomass of the total fuel and electricity use in the system is about 50%, and the share of waste use is about 20%. The waste is collected in the county, while about 30% of the biomass is transported by train or truck from the north of Sweden, and some is imported from the Baltic countries by boat.

The DH demand curves in the DH networks are highly dependent on outdoor temperature (Figure 2). The differences in base production and in DH demand in the networks cause differences in DH production costs among them. Because of lower DH loads during the summer when the load consists almost solely of domestic hot water consumption, the CHP plants and larger biomass-fuelled heat-only boilers (BHOBs) are usually taken out of operation during this period (Dotzauer, 2010a).

Table 2. Major DH networks in Stockholm in the year 2010 (Dahlroth, 2009; Dotzauer, 2003; Dotzauer 2010a).

Network	Heat production	Installed heat capacity	Installed electricity capacity	Types of base production
	TWh/year	MW	MW	
South-central	9.4	4000	500	waste-fuelled CHP; coal-fuelled CHP
Northwest	2.2	700	105	biomass-fuelled CHP; waste-fuelled CHP
Southeast	0.5	300	20	biomass-fuelled CHP

In November 2013 a new waste-fuelled CHP plant was introduced into the northwest DH network (Dotzauer, 2014). This CHP plant was not included in the studies presented in Papers I and II. However, since the plant has been planned to be built for two years, it was included in the studies which analysed periods from 2030 to 2040 and which used Stockholm’s DHS as the case study (Papers III and V; see Table 3 in the next section).

Figure 2. The monthly average DH demand of the system networks

4.1.1.1 Stockholm's district heating system in 2030

By the year 2030, Stockholm's DHS is expected to change. The DH demand is expected to decrease by about 10%. Moreover, one biomass-fuelled CHP (BCHP) plant which today is almost 50 years old and coal- and oil-fuelled CHP plants would probably be phased out. According to some calculations made by Byman (2009) in 2009, the annual amount of household waste in the region would increase to 5 TWh by the year 2030. Thus, a new waste-fuelled CHP plant is already built and introduced into the DHS in November 2013 (see previous section). One more waste-fuelled CHP plant, which would include biogas production as well, is planned to be built during the next two years (E.ON, 2011). Some economic and technical characteristics of those two plants are presented in Table 3. The investments in those plants were not included in the studies. However, even after the introduction of those plants into the DHS, the total heat production capacity of the system would still be 650 MW lower than the present capacity.

4.1.2 Cooling production in Stockholm

Stockholm's DC system (DCS) supplies office buildings in the region with approximately 350 GWh of comfort-cooling annually. The DCS uses free seawater cooling to cover the base load demand during the year. When the maximum free cooling capacity is lower than the cooling demand, (which is usually during the summer when the seawater has a higher temperature, while at the same time cooling demand increases significantly and is at its peak), the DCS is supplied by modified heat pumps and by compression chillers. Figure 8 in Paper II gives an overview of the comfort-cooling load demand variation during the year (Dotzauer, 2010a).

Table 3. Economic and technical characteristics of the new waste-fuelled plants.

	Waste-fuelled CHP plant (Hansson et al., 2007)	Waste-fuelled biogas and CHP plant (E.ON, 2011)
Plant capacity (MW _{input})	136	91
Efficiency		
Electricity	0.22	0.22
Biogas	-	0.12
Heat	0.69	0.59
Economic characteristics		
Operating and maintenance costs ^a (€/MWh _{input})	13.5	16
Operating time (h/year)	8000	8000
Economic lifespan (year)	25	25

^a The fuel costs are not included.

There are also two large manufacturing companies in the county of Stockholm with a considerable cooling demand for industrial processes: biopharmaceutical company AstraZeneca and automotive industry manufacturer of commercial vehicles Scania. This cooling demand is not characterised by strong seasonal variation. About 60% of this cooling demand is supplied by free seawater cooling while the rest of the cooling (approximately 65GWh annually; Figure 9 in Paper II) is produced by vapour compression chillers that are situated within the companies. AstraZeneca also delivers about 6 GWh of cooling to the DCS (Karlsson et al., 2010).

4.1.3 Stockholm's transport sector

Presently, there are about one million registered vehicles in the county of Stockholm (Table 4). About 25% of the total energy used and about 40% of the total GHG emissions in the county are related to the TS (Byman, 2009).

Introduction of “clean” vehicles and alternative fuels in the TS started as early as 1994. As a result, by the end of 2010, the percentage of biofuel-propelled cars increased to 7% and the percentage of public buses that run on biofuel was 37%. However, according to a study performed by Hjalmarsson et al. (2011), poor biofuel supply in the region can present a threat for future sustainable development of the TS. Presently, the ethanol used in the TS is mainly produced from sugarcane in Brazil. Other biofuels used in the TS (e.g. biogas, biodiesel) are imported from other regions in Sweden.

Due to the introduction of the congestion charge which was implemented on a permanent basis in the year 2007, Stockholm’s public TS has significantly developed during the last decade. The number of public buses has increased, as well as annual electricity use for the underground & commuter trains and local railway, which in 2010 were approximately 160 GWh and 440 GWh, respectively (SL, 2011).

4.1.3.1 Stockholm’s transport sector in 2030

It is expected that the number of vehicles in the county of Stockholm will increase by 35% until the year 2030 (Byman, 2009). Assumptions regarding the future changes in the Stockholm’s road TS are presented in Table 4; the truck sector is not included in the study. Furthermore, according to Casemyr and Blomquist (2009), by the year 2030 the annual electricity demands for the underground & local railway and for the commuter trains are expected to increase by 50% and by 100% respectively compared to the demands in 2010 (see previous section); the total electricity use for public rail transport will be about 980 GWh annually.

Table 4. Stockholm’s TS in the years 2010 and 2030 (the truck sector is not included in the study).

		Passenger cars ^a	Taxi and mobility service	Buses
Number of vehicles in the year 2010 (SIKA, 2011)		796,531	4,003 ^b	3,974
Number of vehicles in the year 2030 (Byman, 2009)		1,026,840	5,160 ^b	5,123
Average annual distance travelled by vehicle (SIKA, 2011)	(km/year)	12,500	30,000	57,000
Total annual distance in the year 2010	(10 ⁶ km/year)	9,957	120	227
Total annual distance in the year 2030	(10 ⁶ km/year)	12,836	155	292

^a Excluding taxi and mobility service.

^b Assumed as 0.5% of the number of passenger cars in the region.

General assumptions regarding improvement of the technology of vehicles have been made as well. It was assumed that future fuel economies would improve by 25% compared to

today's values (Table 5), and that the average hybrid car will run about 50% on electricity and the average hybrid bus will run on about 30% electricity.

Table 5. Fuel economy in the year 2030 (kWh/100 km), (Hjalmarsson et al., 2011; SIKA 2011).

	Cars	Buses
Gasoline	52	-
Diesel	41	447
Ethanol	43	437
Biogas	42	457
FT diesel	40	447
DME	-	440
Electricity (PHEV ^a)	22	110

^a Plug-in Hybrid Electric Vehicles

4.2 Case study - Västra Götaland, Östergötland and Jönköping counties

The case studies chosen for the analyses performed in Paper VI are Västra Götaland, Östergötland and Jönköping counties (Figure 3). One of the reasons for choosing those counties is that they are situated in the south of Sweden, where the outdoor temperature is much higher during the summer than in the north of Sweden. In those counties a number of DH networks already exist and the large temperature variation leads to a less efficient utilization of the base production plants (e.g. CHP plants) in those DHSs. Moreover, the number of industries located in those counties is higher.

4.2.1 District heating systems in Västra Götaland, Östergötland and Jönköping counties

There are approximately 60, 10 and 20 DH networks in Västra Götaland, Östergötland and Jönköping counties, respectively. The characteristics of the DHSs (such as fuel mixes, DH technologies and the types of base production plants) differ significantly. Figures 4 and 5 and Table 6 give an overview of those characteristics for the year 2010 (Swedish District Heating Association, 2013) and assumptions for future developments of the DH networks for the year 2030 (explained further in the next section).

Figure 3. Overview of the positions of DHSs and industries included in the study in Västra Götaland, Östergötland and Jönköping. (No. of industries = number of industries; DH prod. = DH production)

4.2.1.1. District heating systems in Västra Götaland, Östergötland and Jönköping counties in 2030

Figure 4. Annual DH production with different technologies in the DHSs in Västra Götaland, Östergötland and Jönköping counties. (HOB = heat-only boiler). The data for the year 2011 were found in Swedish District Heating Association (2013), while the data for the year 2030 were calculated based on the described assumptions.

In Paper VI, a number of assumptions regarding the future development of the DHSs in the counties of Västra Götaland, Östergötland and Jönköping have been made (Figures 4 and 5; Table 6). It was assumed that the existing DH networks in those counties will gradually be expanded and interconnected in three large DHSs by the year 2030. Furthermore, it was assumed that all available waste fuel would be used for CHP production, and that the waste amounts in the counties would follow the population trend. Thus waste amounts would increase by 1.2% in Västra Götaland, and by 1.1% in Östergötland and Jönköping counties (ITPS, 2008). Coal-fuelled DH plants are expected to be phased out, and oil is expected to be used only for peak demand during the winter (it is assumed that 2.5% of annual DH production would be produced in oil-fuelled heat-only boilers). In addition to this, the amount of waste heat delivered to the DHSs is assumed to remain the same. Since a well-developed NG supply network already exists in Västra Götaland, it is also assumed that the capacity of the existing NG-fuelled CHP plant in this county would be unchanged. The total capacities of the BCHP plants in the DHSs are assumed to increase by 30%. The expectation that the DH

demands in the DHSs are going to decrease by 10% by the year 2030 (Göransson, 2009) was also taken into account.

Figure 5. The annual fuel mixes used in the DHSs in Västra Götaland, Östergötland and Jönköping counties (for DH and electricity production).

The data about the total electricity production in the DHSs in the year 2011 (Table 6) have been found in Swedish District Heating Association (2013). The total electricity production for the year 2030 (Table 6) was calculated based on the future development of CHP plants presented in Hansson et al. (2007), and based on the DH production in the CHP plants (Figure 4).

Table 6. DH and electricity production in the DHSs in Västra Götaland, Östergötland and Jönköping counties.

		Västra Götaland		Östergötland		Jönköping	
Year		2011	2030	2011	2030	2011	2030
DH produced	(GWh/year)	8096	7287	3140	2826	1680	1512
Electricity produced	(GWh/year)	1312	2763	570	1093	185	444
alfa-system ^a		0.162	0.379	0.182	0.387	0.110	0.294
The share of DH produced in CHP plants	(%)	48	64	71	94	51	69

^a The total power-to-heat ratio of the DHS.

4.2.2 Industrial sectors in Västra Götaland, Östergötland and Jönköping counties

The analyses in Paper VI were applied to 83 manufacturing companies: 43 companies located in Västra Götaland, 23 companies located in Östergötland, and 17 companies located in Jönköping county. The data about the companies were compiled from energy efficiency audits, which have been performed during the period 2010 – 2012 and collected by the Division of Energy Systems at Linköping University and the Energy Agency of South East Sweden. Most of those companies are located near a DHS (Figure 3). However, despite this only 28% of them are connected to the DHS; 13 in Västra Götaland, 10 in Östergötland, and 5 in Jönköping. Due to a non-disclosure agreement the industries included in the study are not presented by name but only by sector of trade (Table 7).

Table 7. The industries included in the study presented in Paper VI.

Industrial code	Line of business	Västra Götaland	Östergötland	Jönköping	Per line of business
10	Manufacture of food products	4	3	1	9
13	Manufacture of textiles	4			4
15	Manufacture of leather and related products	1			1
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	1		2	3
20	Manufacture of chemicals and chemical products	3	3		6
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations		2		2
22	Manufacture of rubber and plastic products	6	2	1	9
23	Manufacture of other non-metallic mineral products	5		1	6
24	Manufacture of basic metals		1	2	3
25	Manufacture of fabricated metal products, except machinery and equipment	4	4	5	13
27	Manufacture of electrical equipment	2			3
28	Manufacture of machinery and equipment	5	4	3	12
29	Manufacture of motor vehicles, trailers and semi-trailers	3			3
30	Manufacture of other transport equipment	1	1	1	3
31	Manufacture of furniture	1			1
32	Other manufacturing	1		1	2
33	Repair and installation of machinery and equipment	2	3		5
Total		43	23	17	83

5 Methodology

This section describes the methodologies and approaches applied in the papers.

As previously mentioned in section 1.1, all papers aimed to evaluate different business strategies for DH providers. Those business strategies would be realized through cooperation between the DHS and transport, industrial or building sectors (Table 8). The analyses were carried out through different case studies. Four papers used the county of Stockholm as the case study (Papers I, II, III and V), and the research in one paper includes three counties located in the south of Sweden: Västra Götaland, Östergötland and Jönköping (Paper VI). Paper IV was also done as a case study, since all analyses in this paper were done for four chosen types of plants (four technology cases).

Two different time frames were used in the papers. In Papers I and II a short-term time frame was employed. The EMS considered in those papers present the EM conditions from the year 2010 (described in section 5.2), and the characteristics of the energy sectors (DHS, DCS, TS and industrial sector) from the year 2010 was used as the input data (see section 4.1). In the other four papers (Papers III, IV, V and VI) a long-term time frame was employed and the analysed time period was from the year 2030 to 2040. In those papers, future EMSs (four EMS_{level}, two EMS_{WEO} and EMS_{WWF}) for the year 2030 were applied (described in section 5.2), and the future changes in the DHSs and the TS were considered as well (see sections 4.1.1.1, 4.1.3.1 and 4.2.1.1). The reason to choose the time period between 2030 and 2040 in Papers III, IV and V is because the technologies for biofuel production through gasification of biomass (see Wetterlund [2012] for a review of recent research and demonstration projects) and biofuel production through simultaneous saccharification and fermentation (for a description see Papers I, III, IV and V) would probably be developed for commercial operation by 2030. This assumption has been made considering the study about historical diffusion of energy technologies performed by Wilson (2012). Additional reasons for choosing this time period in Papers III and V is Sweden's ambition to have a vehicle fleet independent of fossil fuels by 2030 (SEA, 2014), as well as due to the future changes in Stockholm's DHS (see section 4.1.1.1) which most probably will be performed during the next 15 years (Dotzauer, 2012). Based on how fast Stockholm's DHS developed from small DH networks to a large regional network (Magnusson, 2011), it was assumed that the DH

networks in Västra Götaland, Östergötland and Jönköping counties would probably be more developed and connected to large regional networks by the year 2030. This is the reason for choosing the time period from 2030 to 2040 in Paper VI as well.

In four papers (Papers I, II, III and V) Stockholm's DHS was analysed by using an optimisation model framework called MODEST (see section 5.3.2). In Paper VI a method for heat load analysis called MeHLA (see section 5.3.3) was used. The analyses in Paper IV were performed by using calculations in Excel (see section 5.3.1).

Four papers include discussions about the profitability of the suggested business strategies. In Papers I and V the techno-economic evaluation was performed from the perspective of the DHS (Table 8); in those papers it was analysed whether the business strategies included in study would be profitable for DH producers. In the other two papers whether the business strategies would be profitable for IS was evaluated (Papers IV and VI; Table 8). In Paper IV biofuel production industry was considered, while in Paper VI 17 different lines of business were included in the study. In Papers II and III there were no detailed discussions about profitability, since the aim in those papers was to evaluate the impacts on global GHG emissions. But even in those papers the techno-economic evaluations were performed through optimization by MODEST in order to choose the best operation of plants at the right time in the DHS before the impacts on global GHG emissions were analysed.

Evaluation of the effects on global GHG emissions was performed in Papers I, II, III and VI. Two papers (Papers I and II) employed simplified analysis which included only CO₂ emissions during the combustion processes in the DHS and influences on global CO₂ emissions caused by biofuel by-products and changes in electricity use and production. In Papers III and VI two more GHGs were included in the analysis, CH₄ and N₂O, and the emissions during the whole life cycle of the fuels were considered, as well as the impact on other energy systems by increasing the biomass use in the DHS.

In order to make the results from the different papers comparable to each other, and in order to improve the research presented in the papers, some additional analyses were performed. Those additional analyses are described in section 5.8.

5.1 System approach

Applying a systems approach when analysing complex environmental, economic, technical and social systems is of extreme importance. This is in order to handle possible trade-off situations that may occur and to enable better understanding of the system.

Table 8. An overview of methods and approaches applied in the papers.

	Papers					
	I	II	III	IV	V	VI
Sectors of interest ^a	TS, DHS	IS, BS, DHS	TS, DHS	IS, DHS	TS, DHS	IS, DHS
Analyzed business strategy	Biofuel by-products	Absorption cooling production	Biofuel by-products	Excess heat recovery from biofuel production industry	Biofuel by-products	Use of DH in industrial processes
Geographical case studied	Stockholm County	Stockholm County	Stockholm County	-	Stockholm County	Västra Götaland, Östergötland and Jönköping counties
Time frame applied	Short-term; (2010-)	Short-term; (2010-)	Long-term; (2030-2040)	Long-term; (2030-2040)	Long-term; (2030-2040)	Long-term; (2030-2040)
EMSs applied	EMS ₂₀₁₀	EMS ₂₀₁₀	EMS _{levels}	EMS _{WEO}	EMS _{WEO}	EMS _{WEO}
Model framework and tool applied	MODEST	MODEST	MODEST	Excel	MODEST	MeHLA
Techno-economic evaluation						
Viewpoint (perspective)	From DH producers	(From DH producers) ^b	(From DH producers) ^b	From IS	From DH producers	From IS
Evaluation of the impact on global GHG emissions						
GHGs included in the study	CO ₂	CO ₂	CO ₂ +CH ₄ +N ₂ O	-	-	CO ₂ +CH ₄ +N ₂ O
Approach ^c	Simplified	Simplified	Comprehensive	-	-	Comprehensive

^a TS = transport sector; IS = industrial sector; BS = building sector.

^b In Papers II and III the techno-economic evaluations were performed through optimization by MODEST only in order to choose the best operation of plants at the right time in the DHS before the impacts on global GHG emissions were calculated. In those papers profitability was not discussed in detail.

^c Simplified = only the CO₂ emissions during the combustion processes in the DHS and the influence on the power and transport sectors from by-products of biofuels and changes of electricity use and production were considered; Comprehensive = GHG emissions during the whole life cycle of the fuels were considered, and the effects on the other energy systems caused by biomass use in the DHS were considered as well.

In the literature about system theory, a number of different definitions of a system can be found. Wallén (1996) and Ingelstam (2002) define a system as a group of components that interact, while Bertalanffy (1972) points out in his definition of a system the fact that those components interact with their surroundings as well. According to Churchman (1968), a system is a group of elements that interact among themselves and work together to fulfil a common goal.

The identification of the system boundaries and the system surroundings is the central issue when applying the system approach and should be made considering the specific perspective from which a research question should be answered. According to Ingelstam (2002) and Wallén (1996), all components (and interconnections) which an actor can control should be considered the system, while the components which cannot be controlled by the actor but which can determine in part how the system performs should be considered the surroundings. Wallén (1996) also points out that it is important to consider how the system changes over time. Two examples of how system boundaries for a DHS can be determined depending on the research question can be found in Difs (2010) and Fahlén (2012).

In this study, the system consists of the local DH, parts of the transport, industrial and building sectors, and parts of the European electricity sector. The choice of local sectors differs from paper to paper, depending on the research question (see “sectors of interest” in Table 8). The system surroundings consist of EM conditions (EM prices and energy policy), waste management, development of new technologies, energy demands (e.g. DH demands, biofuel demands, DC demands, and fuel and electricity demands in the industrial sector), and alternative use of fuels and resources (e.g. alternative for biomass use); some of the components from the surroundings were explained in section 2.

5.2 Choice and development of energy market scenarios

Eight different EMSs were used in the appended papers. One EMS (EMS₂₀₁₀) was based on EM conditions from the year 2010 (Table 9), and seven scenarios were future EMSs for the year 2030. The future scenario EMS_{WWF} which was used in Paper III is not included in this thesis. The six future EMSs included in the thesis are presented in Table 11.

In all EMSs the types of marginal electricity production technologies were considered assuming a fully deregulated European electricity market (see section 2); although in some of the scenarios where EMS₂₀₁₀ was applied it was assumed that the Swedish electricity prices differ from European electricity prices. Two different principles which concern marginal electricity production were considered. In the EMS for the year 2010 a short-term perspective was taken. In this case “operational” marginal electricity production technology was considered when the influences on the power sector were analysed (see section 2.1.1). In the

future EMSs (EMS_{level} and EMS_{WEO}) a long-term time frame was used and the effects on the power sector caused by changes in electricity use and production are analysed by considering the “build” marginal electricity production (see section 2.1.1).

EM prices from the year 2010 were applied in Papers I and II. The prices of waste and fossil fuels were not presented in the papers due to the DH companies’ privacy policies. For the same reason those prices are not presented in this thesis either. In the EMS_{2010} CCP production technology was assumed as marginal electricity production technology. The electricity and biofuel prices for the year 2010 (EMS_{2010}) are presented in Table 9.

Table 9. Electricity, biofuel and average biomass prices (€/MWh) used in Papers I and II (EMS_{2010}).

Swedish electricity market	
Purchase	70.10
Sale	35.46
Sale with TGC included	67.56
European electricity market	
Purchase	83.30
Sale	48.65
Sale with TGC included	80.77
Biomass and biofuel market	
Average biomass price	20
Biogas	18
Ethanol	67
Ethanol (including the import tax)	87

The future EMSs for Sweden denoted as EMS_{WEO} (two EMSs applied in Papers IV, V and VI) and EMS_{levels} (four EMSs applied in Paper III) were developed using the ENPAC price-setting tool (Energy Price and Carbon Balance tool). This tool was developed by Axelsson et al. (2009; Axelsson and Harvey, 2010) who considered the prices on the EM as interdependent parameters. Figure 6 gives a simplified overview of the calculation procedure in the ENPAC tool. The input data to the tool are future world market fossil fuel prices and a number of assumptions (such as availability of CCS technology, policy instrument measures, and expected technological improvements associated with electricity, DH and biofuel production). Policy instruments which can be included are for example CO_2 charges, RES-T support and RES-E support.

The world market fossil fuel prices and the CO_2 charges used as the input data in Papers IV, V and VI (Table 10) were found in two global EMSs which have been developed by the International Energy Agency (IEA, 2011). The first scenario is based on the recent government policy commitments, known as “New Policies Scenario” (denoted as EMS_{WEO-np} in this thesis). The second scenario is based on energy policies which according to the International Energy Agency would enable the 2°C target (explained further in Pachauri and Reisinger, 2007) to be reached at a reasonable cost. This scenario is known as the “450 Scenario” (denoted as $EMS_{WEO-450}$ in this thesis). When EMS_{levels} (EMSs used in Paper III) was developed, the world market fossil fuel prices used as the input data were assumed by

combining two levels of CO₂ emissions charge and two levels of fossil fuel prices (Table 10); the assumptions regarding the levels were made by Axelsson and Harvey (2010). The levels of the RES-E and RES-T supports (Table 10) were assumed based on the average values for Europe. CCS technology was assumed to be an economically attractive technology in EMSs where the CO₂ charge has a high level (EMS_{level-3} and EMS_{level-4}).

The fossil fuel prices for Swedish EM (Table 11) were calculated from the world market fossil fuel prices considering the CO₂ charges assumed. Based on the calculated fossil fuel prices and assumptions associated with electricity production technologies (e.g. the future electricity efficiencies, investment costs, operating times, and operating and maintenance costs), the “build” marginal technology for electricity production was determined and the electricity price was calculated. The fossil diesel and gasoline prices were calculated from the crude oil price (Figure 6; Table 10; Table 11). The biofuel prices were calculated assuming that the users will be willing to pay for biofuel only if the final biofuel price at filling stations (also considering the biofuel transportation costs) is not higher than the price of the fossil fuel replaced. The prices were not compared per MWh; instead the fuel economies for different fuels (kWh/100 km) were taken into account. Biogas and ethanol were considered as replacements for gasoline, and FTD and DME as replacements for fossil diesel (Figure 6; Table 11).

It is assumed that biomass will be subject to competition in the future; this issue has been discussed more in section 2.2. Thus, the high-volume user with the greatest willingness to pay for the biomass will probably be the price-setting user (Axelsson and Harvey, 2010). By comparing different biomass users, and based on the previously calculated electricity and biofuel prices (Figure 6; Table 11), Axelsson and Harvey (2010) have identified two possible price-setting users for the biomass: plants for FTD production and CCP plants where biomass can be co-fired. Those users were also considered as alternative users for biomass when environmental effects of increased biomass use in a DHS were evaluated. This is explained more in sections 5.6 and 5.7. When the biomass price was calculated, the costs for biomass transportation were also considered.

Unlike the other energy prices in the EMSs, DH prices are also determined by local conditions. Because of this, even though the same EMSs were used in Papers IV and VI there are large differences between the DH prices used in the papers. After assuming that in Sweden in 2030 only a negligible percentage of DH production would be based on fossil fuels, two different levels of DH prices were calculated in Paper IV. One price level will characterise large DHSs, and it would be set by DH production in BCHP plants during six months and by DH production in BHOBs during the rest of the year. This DH price level is denoted as BCHP-DH price in this thesis. The other DH price level will characterise small DHSs, and it would be set by DH production in BHOBs. This DH price level is denoted as BHOB-DH price. Calculations of the future DH prices in Paper VI were performed based on the DH production technologies in the DHSs included in the study (Figure 4; section 4.2.1.1), and considering the operation and maintenance costs, the fuel costs including taxes and fees, as well as the revenues from the co-produced electricity (Figure 6).

In all future EMSs it was assumed that the waste fuel will not be subject to any purchasing costs or taxes. The only costs connected to waste use included in the studies (in Papers III, V and VI) are operating and maintenance costs for the waste-fuelled plants.

The biomass and biofuel transportation costs were calculated based on the data presented in Börjesson and Gustavsson (1996). The assumptions about transportation distances are described in Papers III and V.

All prices and costs have been adjusted to €2010 using the Chemical Engineering Plant Cost Index (CEPCI, 2010).

Figure 6. An overview of the calculation flow in the ENPAC tool.

Table 10. Input data to the Swedish future EMSs developed by the ENPAC and used in Papers III, IV, V and VI.

EMSs ^a	Papers IV, V and VI		Paper III			
	EMS _{WEO-00}	EMS _{WEO-450}	EMS _{I-1}	EMS _{I-2}	EMS _{I-3}	EMS _{I-4}
World market fossil fuel prices excluding CO₂ charges (€/MWh)						
Crude oil	55	46	29	29	49	49
Natural gas	34	28	22	22	37	37
Coal	11	7	7.5	7.5	10	10
Energy policy instruments^a						
CO ₂ charge (€/t)	30	72	27	85	27	85
RES-E support (€/MWh)	20	20	20	20	20	20
RES-E quota (%)	20	20	20	20	20	20
RES-T support, "diesel fuels" (€/MWh)	26	26	-	-	-	-
RES-T support, "petrol fuels" (€/MWh)	35	35	-	-	-	-

^a EMS_{I-1, 2, 3, 4} = EMS_{level-1, 2, 3, 4}. RES-E and RES-T supports = supports for electricity and for transportation fuel produced from renewable energy sources.

Table 11. The future EMSs calculated by the ENPAC and used in Papers III, IV, V and VI.

EMSs ^a	Papers IV, V and VI		Paper III			
	EMS _{WEO-00}	EMS _{WEO-450}	EMS _{I-1}	EMS _{I-2}	EMS _{I-3}	EMS _{I-4}
Fossil fuel prices on Swedish EM including CO₂ charges (€/MWh)						
Light fuel oil	74	75	53	70	76	93
Heavy fuel oil	56	61	35	52	52	70
Natural gas	46	49	-	-	-	-
Coal	23	35	-	-	-	-
Electricity market						
Build margin	CCP	NGCC	CCP	CCP, CCS ^a	CCP	CCP, CCS ^a
Electricity price (€/MWh)	67	86	53	70	58	76
Gate biofuel prices excluding RES-T support (€/MWh)						
Ethanol	87	89	45	61	69	85
FTD	78	79	43	60	67	84
DME	71	72	44	61	68	85
Biogas	103	109	44	60	68	84
Biomass prices (€/MWh)						
Low grade biomass	33	41	25	45	28	48
High grade biomass	47	57	38	64	41	67
DH prices – Paper IV (€/MWh)						
BCHP-DH price	27	31	-	-	-	-
BHOB-DH price	40	47	-	-	-	-
DH prices – Paper VI (€/MWh)						
Västra Götaland	19	20	-	-	-	-
Östergötland	5	3	-	-	-	-
Jönköping	15	16	-	-	-	-

^a CCP plants with CCS; EMS_{I-1, 2, 3, 4} = EMS_{level-1, 2, 3, 4}.

5.3 Methodologies used to perform analyses in the appended papers

Three different methodologies were used to perform analyses in the papers. The analyses in Paper IV were performed by using the calculation procedure described in section 5.3.1. In Papers I, II, III and V the optimisation model framework MODEST was used (section 5.3.2), and in Paper VI a heat load analysis was performed using MeHLA (section 5.3.3).

5.3.1 The calculation procedure performed when biofuel production casts were estimated in Paper IV

Four different types of biofuel production plants have been included in the study in Paper IV. Economic and technical characteristics of the plants are presented in Table 12 in section 5.4.1. The profitability of the biofuel production depends on the plant capacity (Faaij, 2006), so in order to make the results for different plants comparable to each other it was assumed that all the plants have the same input capacity of 300 MW.

The biofuel production costs for the chosen plants were calculated considering the *investment costs* and the *annual costs*.

The investment costs for the plants were calculated from the data available in Barta et al. (2010), Wetterlund (2010), Wetterlund et al. (2009), and Wetterlund et al. (2011) using an overall scaling factor (R) of 0.7 (Remer and Chai, 1990) according to the equation:

$$\frac{\text{Cost}_a}{\text{Cost}_b} = \left(\frac{\text{Capacity}_a}{\text{Capacity}_b} \right)^R$$

Cost_a represents the investment costs of the base polygeneration plant (the costs found in the referenced study) and Cost_b represents the investment costs of the new plant (the plant included in the thesis). Capacity_a and Capacity_b are the capacities of the base plant and the new plant, respectively. The estimated investment costs for the new plants were adjusted to €2010 using the Chemical Engineering Plant Cost Index (CEPCI, 2010).

The period chosen to be studied was 10 years. Since the economic lifespans of the plants are longer than 10 years (Table 12; section 5.4.1), the plants have some economic value after the end of this period. This value was adjusted back to the beginning of the analysed period by using the assumed discount rate and then subtracting from the investment costs (Henning, 1999; Henning, 2013).

The annual biofuel production costs consist of feedstock costs, and operating and maintenance costs. The feedstock costs are related to the input capacity; see the biofuel production efficiencies presented in Table 12, section 5.4.1. The operating and maintenance costs can be variable costs or fixed costs (presented as a certain percentage of the investment costs); see Table 12, section 5.4.1. The revenues from the co-produced heat and electricity are also included in the annual costs as negative costs.

5.3.2 Energy systems optimisation by MODEST performed in Papers I, II, III and V

Analyses in Papers I, II, III and V were performed by using an optimisation model framework called MODEST (Model for Optimization of Dynamic Energy Systems with Time-dependent components and boundary conditions).

In MODEST, the aim of the optimisation is to minimize the system cost of supplying the heat or some other energy demand (e.g. biofuel, electricity, cooling) during the analysed period. The optimization is performed by choosing the best operation at each time from existing and potential new plants in the system. The system cost includes: new investments, operation and maintenance costs, fuel costs including taxes and fees, as well as revenues from by-products, and lastly, the present value of all the capital costs. The plants in the model are described in terms of their efficiencies, maximum capacity, power-to-heat ratio (if it is a CHP plant), maintenance periods and costs, technical lifetime, economic lifetime and, if it is a new plant, investment cost. The input data that also needs to be defined are studied period, time division, discount rate, and the system's energy demands that must be fulfilled (Henning, 1999; Gebremedhin, 2003; Henning, 2011). The MODEST optimisation model was developed at Linköping University in Sweden, and during the last 20 years it has been applied to different kinds of energy systems with different purposes.

In this study a model of Stockholm's DHS has been built according to the data from Dahlroth (2009). The period analysed is 10 years and the costs in the model are based on a discount rate of 6%. Each year is divided into 88 periods that depict seasonal, weekly and diurnal variations in the heat demand, prices, and plant efficiencies. For each of the months from April to October, four time periods are modelled: days and nights during weekdays, as well as days and nights during weekends. For the remainder of the year, heat demand peaks and heat demand variations are significant. During this time frame the time division is at its most detailed; the months are divided into 12 periods and parameter variations are sometimes modelled hour by hour. This time division was earlier used in several MODEST studies and is described in more detail in Henning et al. (2006). Based on the DH production in 2007, the curves of the DH demands for the different parts of the system have been calculated and adjusted to the time division. The operation and maintenance periods for plants have also been included in the model. After that, the model has been calibrated according to detailed production data from 2007.

5.3.3 Analysing district heat load duration curves using MeHLA performed in Paper VI

The effects of the conversion of industrial processes to DH on the existing DH load duration curves were analysed in Paper VI using MeHLA.

Processes which can be converted to DH were identified and examined according to heat demand and time-dependency. After this, heat load duration curves for those processes and the present DH load duration curves for the industrial processes (for industrial companies that already use DH) were adjusted to the chosen time division. For each industrial company studied, the present (if any) and the predicted new DH load duration curves for each separate process (drying, space heating, hot tap water, melting, process heating and other) were introduced as input data to the MeHLA (Difs et al., 2009). Some of the outputs from the MeHLA are DH load duration curves for the different unit processes for all of the industrial companies together. These outputs offer a possibility to identify which of the processes has the highest potential to increase DH use in the industrial sector and which of the processes has the highest potential to increase DH production in the base production plants during the summer. DH load duration curves for each respective industrial company, and DH load duration curves for each industrial sector of trade, are also outputs from the MeHLA. The outputs make it possible to identify which type of industry has the highest potential to increase DH use. The results can also be presented as monthly energy demands.

5.4 Input data for the technologies included in the study

In all papers investment in new technologies was considered. Biofuel production technologies were included in analyses in four papers (Papers I, III, IV and V), and in two papers (Paper II and Paper VI) replacement of compression cooling with DH-driven absorption cooling was considered. In some of the scenarios from Paper III, analyses were made assuming that CCS technology will be applied in the new plants introduced into the DHS. In two papers (Papers III and V) introduction of new CHP plants into the DHS was considered as well.

5.4.1 Economic and technical data of the biofuel production plants

The analyses in Paper IV were performed for four technology cases: a FTD production plant, a DME production plant, and two types of ethanol production plants. In both ethanol

production plants raw biogas is a by-product of ethanol production. In one of those plants this raw biogas is upgraded and sold as biofuel for purposes of TS, and surplus electricity and heat are produced as well. In the other plant this raw biogas is directly used for CHP production so only electricity and heat are final by-products during the ethanol production (see Paper IV for a more detailed description). From this point forward, the plant where upgraded biogas is a by-product, and the ethanol produced in this plant, are denoted as “Ethanol 1 plant” and “Ethanol 1”, respectively. The plant where only electricity and heat are by-products, and the ethanol produced in this plant, are denoted as “Ethanol 2 plant” and “Ethanol 2”, respectively (Table 12).

Since the profitability of the biofuel production depends on the plant capacity (Faaij, 2006), all biofuel production plants included in the papers have an input capacity higher than 200 MW. The investment costs for the plants were calculated using the equation presented in section 5.3.1 and adjusted to €2010 using the Chemical Engineering Plant Cost Index (CEPCI, 2010).

Based on the descriptions of the biofuel production process (see Papers I, III and IV), simplified models of the biofuel production plants have been created and introduced into the DHS models in Papers I, III and V. In Paper I, only one “Ethanol 1 plant” with input capacity of 279 MW was introduced into the DHS (Table 12). The capacity of the plant was chosen to fulfil the current annual ethanol demand in Stockholm’s TS (the research was performed in the year 2010). In the scenarios with large-scale biofuel production in Papers III and V the types and capacities of the plants introduced into the DHS were decided based on the biofuel demand in the TS. This demand was calculated based on assumptions for the TS for the year 2030 described in section 4.1.3.1, and based on three assumed scenarios for future development of the TS which are described later in section 5.5. All biofuel production plants included in the analysis in Paper IV have an input capacity of 300 MW. Economic and technical data of the biofuel production plants are presented in Table 12.

In Papers III and V, in order to make the scenarios comparable to each other, the total heat capacity of the new plants introduced into the DHS was assumed to be 600 MW in all scenarios. Because of this, in all scenarios new CHP plants were also introduced into the DHS. Characteristics of those plants are given in Table 12 as well. Furthermore, in the reference scenarios in these papers only new CHP plants were introduced into the DHS since it was analysed how the characteristics of the DHS would be changed if DH producers invested in biofuel production instead of CHP production.

Table 12. Economic and technical characteristics of the plants included in studies in Papers I, III, IV and V.

	BCHP plant (Hansson et al., 2007)	"Ethanol 1 plant" (Barta et al., 2010)	"Ethanol 2 plant" (Barta et al., 2010)	FTD plant (Wetterlund, 2010)	DME plant (Wetterlund et al., 2011)
Papers	III, V	I, III, IV, V	III, IV, V	III, IV, V	III, IV, V
Efficiency					
Electricity	0.34	0.05	0.12	0.06	-
Biofuel 1	-	0.34	0.34	0.45	0.62
Biofuel 2 ^a	-	0.25	-	-	-
Heat	0.74	0.28	0.44	0.06	0.15
Total efficiency	1.08	0.92	0.90	0.57	0.77
Economic characteristics					
Input plant capacity (MW _{input})	200-300 ^b	279-308 ^c	250-304 ^c	300-302 ^b	259-300 ^d
Base investment cost (€ million)	-	263-282	254-292	304-305	289-320
Spec. investment cost (€/kW _{input})	807	-	-	-	1200-1280
Fixed operating and maintenance costs (% of the total investment cost)	1.5	2.5	2.4	4.2-3.5	3.5
Variable operating and maintenance costs (€/MWh _{input})	2.8	-	-	0-3.5	3.2-3.4
Operating time (h/year)	8000	8000	8000	8000	8000
Economic lifespan (year)	25	20	20	20	20

^a The biogas efficiency in the "Ethanol 1 plant".^b The biomass input. The choice of input plant capacity differs in the papers (described more in section 5.5)^c The number includes not only the biomass input but also 1.5% molasses and 0.6% enzymes.^d The number represent 95% biomass and 5% electricity used.

5.4.2 Economic and technical data of the cooling technologies

Two different cooling technologies were included in the studies performed in Papers II and VI: DH-driven absorption cooling technology and compression cooling technology.

While the DH-driven absorption chillers use heat as their main energy source and a very small amount of electricity for pumping, compression chillers are powered only by electricity; for detailed descriptions of the technologies see Larsson and Nilsson (2009), Rydstrand et al. (2004) and Swedish District Heating Association (2007). In both papers (Paper II and Paper VI) it was assumed that the coefficient of performance (COP) of compression coolers is 3.0. The COP of absorption chillers is highly dependent on the power medium temperature. Heat-supplying temperature in DHSs varies during the year (between 71°C in the summer and 95°C in the winter) which leads to variation of COP of the DH-driven absorption chillers in the DHS as well. Since the cooling demand included in the

analyses in Paper II is mostly comfort-cooling demand, which is highest during the summer when the heat-supplying temperature in the DHS is lowest, the COP for the absorption chillers was assumed to be 0.4 in this paper (Rydstrand et al., 2004; Zinko et al., 2004; Lindmark, 2005). On the other side, the highest percent of the cooling demand analysed in Paper VI is process-cooling demand which is less dependent on outdoor temperature. Thus, in Paper VI the COP of the absorption chillers was assumed to be 0.7. The electricity demand for pumping was assumed to be 10% of absorption cooling production in Paper VI, while this electricity demand in Paper II was assumed to be insignificant. In order to get more reliable results in Paper II, new analyses have been performed for this thesis. In those analyses it was assumed that the electricity demand for pumping would be 10% of absorption cooling production.

5.4.3 Assumptions regarding the carbon capture and storage technology

When the CCS technology was applied (Paper III) it was assumed that the CO₂ capture efficiency is about 90% in all new plants and that the electricity requirement for CO₂ capture and compression to 110 bar is about 0.14 kWh/kgCO₂ (Damen et al., 2009; Möllersten et al., 2003). The investment costs for the CCS technology were not included in the study. Based on the CO₂ emission factors (kg/MWh) from total combustion for biomass and the biofuels (which are presented in Edwards et al. [2011]), and based on the biofuel and total efficiencies presented in Table 12, the CCS potentials per biomass input for the plants were calculated (Table 13).

Table 13. The CCS potentials per biomass input for the new plants.

Captured CO ₂ (kg/MWh)	
Ethanol 1	207
Ethanol 2	252
FT diesel	227
DME	217
CHP	330

5.5 Description of scenarios and sensitivity analyses performed per paper

In **Paper I**, the effects of introducing an “Ethanol 1 plant” into the existing DHS in Stockholm, Sweden, were analysed. The capacity of the plant was chosen to fulfil the present ethanol demand (the study was performed in 2010) in Stockholm’s TS. The existing DHS and the DHS with the “Ethanol 1 plant” introduced were analysed considering following possible EM conditions for the future:

1. The fossil fuel, biomass, electricity, and biofuel prices from the year 2010 were considered (EMS₂₀₁₀; Table 9). The ethanol price is calculated including the import tax, since it is assumed that the ethanol will be sold at the same price as the ethanol imported from Brazil (see section 4.1.3).
2. The electricity price increases to the European level (Table 9).
3. The biomass price increases by 20%.
4. Both the electricity price and the biomass price increase.

Every scenario with the “Ethanol 1 plant” was compared with the corresponding reference scenario (the scenario with no new plants introduced into the DHS and considering the same EM conditions). When the profitability was analysed, a scenario where the import tax for ethanol is not included in the ethanol price was analysed as well.

Paper II aims to analyse the potential for reduction of global CO₂ emissions by converting from vapour compression cooling to absorption cooling in Stockholm’s DCS and industrial sector. This potential was estimated through four scenarios. In those scenarios an allowance is made for the model to have a possibility to compare and choose between those two cooling technologies. In the first scenario the total cooling demand that is currently met by compression cooling production in the DCS and in the industrial sector has been analysed. In the second one the research has focused only on the compression cooling production in the industrial sector. Since the comfort-cooling demand is expected to increase in the future, mostly due to climate change, in order to analyse future potential for absorption cooling production, two more scenarios were included in the study. In those scenarios it was assumed that the cooling demand is going to increase by 30% and 50%, respectively, while the maximum load of free cooling is going to be the same. Those two scenarios were compared with reference scenarios, where it was assumed that the increased cooling demand is met by compression cooling production.

In **Paper IV**, the way in which profitability of biofuel production through polygeneration would be affected by selling the excess heat from the production to a local DHS under the different EM conditions (EMS_{WEO-np} and EMS_{WEO-450}) was evaluated. The four technology

cases were included in the study (Table 12). All biofuel production plants included in the analysis have an input capacity of 300 MW (this choice is motivated in section 5.3.1). The sensitivity analyses were performed with respect to DH price levels (in both EMSs two different DH price levels were assumed; Section 5.2, Table 11), annual operating time of the plants (the annual operating time was assumed to be 5000 h or 8000 h, depending on the size of the DHS), and different discount rates (6% or 10%).

In **Papers III and V** cooperation between Stockholm's transport and DH sectors by introducing large-scale biofuel production into the DHS for purposes of using the biofuel in the local TS was suggested as a strategy for a reduction of global GHG emissions (Paper III) and for a reduction of DH production costs (Paper V). In both papers, the scenarios with the biofuel production introduced into the DHS were compared with reference scenarios, where only new CHP plants with a total heat capacity of 600 MW were introduced into the DHS; this heat capacity was chosen considering the future changes in the DHS presented in section 4.1.1.1.

The types of biofuel production plants introduced in the DHS in the scenarios with large-scale biofuel production in Papers III and IV were chosen based on assumptions regarding the development of the TS. Those assumptions have been established using trend information and data collected during literature and field studies (Hjalmarsson 2011; SEA, 2011). Three future scenarios have been developed to illustrate possible pathways of the TS: the "biogas", "electricity", and "diesel" scenarios. The choice of those pathways was motivated in the papers. In the "biogas" scenario it was assumed that the number of vehicles which run on biogas would increase. In the "electricity" scenario a large increase in the number of PHEV vehicles in the TS was assumed. It was assumed that hybrid electric cars would run on 50% electricity and hybrid electric buses would run on 30% electricity. The plants chosen to be introduced into the DHS are the ethanol production plants in which the by-product of raw biogas is directly used for CHP production (the "Ethanol 2 plant"). In the "diesel" scenarios it is assumed that the diesel fuel used in the sector would increase, and FTD and DME are suggested as replacements for fossil diesel. In all scenarios the electricity demand for the underground and local railways as well as for commuter trains, about 980 GWh (see section 4.1.3.1), was taken into account. In order to make the scenarios with the large-scale biofuel production in Papers III and IV comparable to each other and comparable to the reference scenarios, the total heat capacity of the new plants is 600 MW in all scenarios. Based on this, the capacities of the CHP plants that need to be introduced into the DHS were calculated. The reason for not introducing more than five new plants in any of the analysed scenarios is that only five locations in Stockholm were found to be suitable for building the large biomass-fuelled plants (see explanation in Papers III and V).

In Papers III and V different EMSs were considered (Table 11) and different approaches have been taken when deciding the capacities of the biofuel production plants. In Paper III two reference scenarios for TS without large-scale biofuel production have been assumed depending on the EM conditions. In the first reference scenario (when EMS_{level} were considered) it was assumed that the share of the fuels used for different types of vehicles

would remain the same as today (see Figure 2 in Paper III). In the second reference scenario (when EMS_{WWF} was considered) a strong electrification of road transport was assumed (see Figure 2 in Paper III); however this scenario is not included in this thesis. In both reference scenarios, biofuel is imported from other regions; only about 0.1 TWh of biogas is produced in one of the DH plants.

In Paper III the types and capacities of plants that need to be introduced into the DHS in the scenarios with large-scale biofuel production (Table 14) were decided depending on the biofuel demand in the TS. This biofuel demand was estimated based on the detailed assumptions regarding the future development of the TS presented in Figure 2 in Paper III and based on the data about the future TS presented in Tables 4 and 5.

Table 14. New plants introduced into the DHS.

	“reference” scenarios	“biogas” scenarios	“electricity” scenarios	“diesel” scenarios
Type	Base plant capacity (MW _{input})			
Paper III				
Ethanol 1	-	3×308	-	-
Ethanol 2	-	-	4×250	304
FTD	-	-	-	302
DME	-	-	-	259
CHP	4×220	2×250	235	2×300
Paper V				
Ethanol 1	-	3×300	-	-
Ethanol 2	-	-	3×300	300
FTD	-	-	-	300
DME	-	-	-	300
CHP	4×203	2×235	275	2×274

In Paper V it was assumed that all biofuel and electricity used in the local public TS would be produced in the DHS, and that the rest of the biofuel produced would be used in private cars. In the “biogas” scenario it is assumed that all public local buses and all local taxis and mobility services will run on biogas. The “electricity” scenario represents a future in which all local public buses, taxis and mobility services are run on ethanol PHEVs. In the “diesel” scenario all local public buses run on DME, and taxis and mobility services run on FTD. In all scenarios with large-scale biofuel production, three biofuel production plants, which have a biomass input capacity of 300 MW each, were introduced into the model of the DHS (Table 14). The biofuel and electricity used in the public TS are defined as demands in the model. However, an allowance is made for the model to produce even more biofuel if this would decrease the DH production costs.

In Paper V two different EMSs were considered (EMS_{WEO-np} and $EMS_{WEO-450}$; Tables 10 and 11), and sensitivity analyses of discount rate levels for the biofuel production plants have been performed as well.

In the rest of the thesis the scenarios from Paper V are denoted as follows:

- r-np, b-np, e-np, d-np (reference, “biogas”, “electricity” and “diesel” scenarios, respectively, in combination with EMS_{WEO-np});
- r-450, b-450, e-450, d-450 (reference, “biogas”, “electricity” and “diesel” scenarios, respectively, in combination with EMS_{WEO-450}).

In **Paper VI** the study aimed to analyse the possibilities of converting industrial processes to DH in manufacturing companies in three Swedish counties, and possible impacts on global GHG emissions and economic effects of the conversion considering two different EMSs for the year 2030 (EMS_{WEO-np} and EMS_{WEO-450}; Tables 10 and 11).

5.6 Estimating the possible reduction of fossil fuel consumption

In four papers the potential to reduce global fossil fuel consumption by applying different business strategies in DHSs was estimated. In Paper VI the potential to reduce fossil fuel use in the industrial sector by converting the industrial processes to DH was estimated. In Papers I, III and V it was calculated how the biofuel production in Stockholm’s DHS may reduce fossil fuel use in the local TS, assuming that all the biofuel produced would be used locally (the assumption is motivated in the previous section). The possible reduction of fossil fuel use in the TS caused by increased biofuel use was calculated considering the fuel economies (Table 5; section 4.1.3.1). Based on the fuel economies it was assumed that 1 MWh of gasoline can be replaced by 0.83 MWh of ethanol or by 0.81 MWh of biogas, and that 1 MWh of fossil diesel can be replaced by 1 MWh of FTD or by 0.98 MWh of DME. Since the scenarios in Papers III and V are almost similar, the results regarding the reduction of fossil fuel use from Paper III were not presented in this thesis.

The changes in fossil fuel consumption in the power sector caused by increased and decreased marginal electricity production were not analysed in the appended papers, nor were the changes in fossil fuel consumption in the power and transport sectors caused by changes in biomass use in the DHS when biomass is considered a limited resource (explained further in section 5.7). In this thesis those analyses are included as well (in section 6.2). When the influences on fossil fuel consumption in the power sector due to the changes in marginal electricity production were analysed, electricity efficiency for marginal production plants were considered. It was assumed that electricity efficiency in CCP in the year 2010 was 0.4, that the electricity efficiency in CCP plants in the year 2030 will be 0.55, and that the electricity efficiency in NGCC plants in the year 2030 will be 0.7. When the biomass is considered a limited resource the changes in global fossil fuel consumption due to the changes in biomass use in the DHS depend on the alternative use of biomass. If biomass use in the DHS increases by 1 MWh when the alternative for biomass use is in CCP plants, the coal use in the power sector increases by 0.9 MWh; when the alternative for biomass use is

for traditional FTD production, the fossil diesel use in the TS increases by 0.4 MWh. Those values are calculated from the biofuel efficiency of FTD plants and from the electricity efficiencies when the electricity is produced from coal and biomass in CCP plants.

5.7 Estimating the effects on global greenhouse gas emissions

In the appended papers two different approaches have been used when the impacts on global GHG emissions were analysed. In Papers I and II a simplified approach has been used. In those papers only the CO₂ emissions during the combustion processes in the DHS, and the changes of CO₂ emissions in the power sector due to the increase or decrease in marginal electricity production were included in the study. In Papers III and VI a comprehensive approach has been used. In those papers emissions during the whole life cycle of the fuels were considered and three GHG (CO₂, CH₄ and N₂O) were included in the analysis. The values of the GHG emissions are presented as CO₂ equivalent (CO_{2eq}) emissions. Moreover, possible effects on the GHG emissions in the power and transport sectors due to the increased or decreased biomass use in the DHS were estimated as well (explained later in this section).

The well-to-gate and combustion GHG emissions factors for the fossil fuels have been found in Edwards (2011). The combustion GHG emissions factor for waste has been found in Levinson and Freiman (2005). The GHG emissions from the waste landfills have not been considered in the present study. Data for GHG emissions during waste and biomass transportation are calculated based on the data presented in Börjesson and Gustavsson (1996). It is assumed that the waste is transported by truck with an average distance of 60 km. The assumptions regarding the transportation distance of biomass differ depending on the paper and on the scenario (for more detailed description see Papers III, IV and V). The values of the GHG emissions related to fossil fuel, biomass and waste use are presented in Table 15.

Effects on the power sector caused by changes in marginal electricity production were estimated considering the “operational” marginal power technology in the analyses performed for the year 2010 (Papers I and II), and considering the “build” marginal power technology in the analyses performed for the 2030s (Papers III and VI). The concepts “operational” and “build” marginal power technology, as well as the process of their identification were explained in sections 2.1.1 and 5.2. In Table 16 the GHG emissions factors used in different EMSs are presented (Axelsson and Harvey, 2010). The GHG emission factor for marginal electricity production in CCP plants differs depending on the EMS due to the different electricity efficiencies assumed for CCP plants for the years 2010 and 2030 (see the previous section).

The importance of applying a system approach when estimating the impact of biofuel use on global GHG emissions has been demonstrated in a number of previous studies (Melamu and

von Blottnitz, 2011; Khatiwada and Silveira, 2011; Sandén and Karlström, 2007). When the impacts on global GHG emissions due to the biofuel production in the DHS were analysed in Paper I, it was assumed that the biofuel produced will replace gasoline in the TS. When those impacts were analysed in Paper III, a different approach was used. In this case the whole TS was considered. Different future developments of the TS were assumed in different scenarios. In the reference scenario it is assumed that the biofuel used in the TS will be imported to the region. Data for well-to-tank GHG emissions for imported gasoline, diesel and biofuels (Table 15) have been found in Börjesson et al. (2010). The reason why the well-to-tank GHG emissions factor for biogas is negative is that Börjesson et al. (2010) applied a life cycle assessment methodology which includes the by-products' indirect effect on GHG emissions. In the scenarios with large-scale biofuel production in the DHS, the GHG emissions during the transportation of the biofuel produced to the filling stations are based on Wetterlund (2010). The assumed average distance between the production plants and filling stations is 50 km.

The GHG emissions factors of DH production in Paper VI for the year 2030 were calculated based on the fuel mixes in the DHSs (Figure 5; section 4.2.1.1) and the annual electricity and DH production in the DHSs (Table 6; section 4.2.1.1). It is assumed that the electricity produced would decrease marginal electricity production in the power sector. Since the future power-to-heat ratios are high in all DHSs (alfa-system in Table 6; section 4.2.1.1) due to higher CHP production, the GHG emissions factors of DH production are negative in most of the analysed cases (Table 17). This means that the DH production leads to a reduction of GHG emissions in the power sector, which is higher than the GHG emissions from the fuel combustion during the DH production. The only case where the GHG emissions of DH production are positive is when CCP plants are assumed to be the alternative for biomass use while at the same time the marginal electricity is produced in NGCC plants. In this case the increase in GHG emissions in the power sector due to the increased biomass use in the DHSs is higher than the reduction of the GHG emissions caused by the electricity production in the DHS.

When the possible influences of the changes in biomass use in the DHS on global GHG emissions were analysed, three different assumptions have been made. The first assumption was that biomass is an unlimited resource. Since biomass combustion can be considered carbon neutral (IPCC, 2001), in this case the only GHG emissions associated with the biomass use are the GHG emissions released during the transportation of biomass (Table 15). However, biomass will probably become even more subject to competition in the future. Thus, the second and third assumptions regard alternatives for biomass use. Increased biomass use in the DHS would lead to decreased biomass use in some other energy system, and consequently to increased GHG emissions in that system. The second assumption was that increased biomass use in the DHS will lead to decreased biomass co-firing in CCP plants and consequently to increased GHG emissions in the power sector (Table 15). The third assumption was that increased biomass use in the DHS would lead to decreased biomass use for traditional FTD production (FTD production that does not include co-production of heat).

This will result in lower FTD production and increased GHG emissions in the TS (Table 15). Those alternative forms of biomass use were identified by Axelsson and Harvey (2010).

A graphical description of the system approach used in this thesis when the effects on the GHG emissions were estimated is presented in Figure 7.

Table 15. GHG emissions factors (kg CO₂eq/MWh) used in the study.

GHG emissions during the whole life cycle of the fossil fuels	
Fuel oil	320
Coal	374
Natural gas	242
Diesel, gasoline	299
GHG emissions from waste combustion and transportation	
Waste	102
Well-to-tank GHG emissions for biofuels^a	
RME	95
Biogas	-70
Ethanol	64
GHG emissions from biomass transportation and marginal effects of biomass use	
Biomass transportation	8.3 – 10 ^b
Without marginal effects	0
CCP plants are the alternative users	336
FTD production plants are the alternative users	118 – 152 ^c
GHG emissions from transportation of biofuel from the plant to the filling station^d	
Ethanol	0.2
FT diesel	0.3
DME	0.3

^a Those well-to-tank GHG emissions for biofuels are used in the reference scenarios in Paper III where it is assumed that the biofuel used in the TS would not be produced locally, but instead would be imported.

^b Depending on the distance between the DHS and biomass producers.

^c Depending on the CO₂ emissions from the marginal electricity (since electricity is one of the by-products during FT-diesel production). For more details see the papers.

^d Considered for biofuel produced in the local DHS. GHG emissions from transportation of biogas were not included in the study since it was assumed that the filling points for biogas would be in the vicinity of the plants (see Papers III and V).

Table 16. GHG emissions factors (kg CO₂eq/MWh) for marginal electricity production.

	EMS ₂₀₁₀	EMS _{level-1,} EMS _{level-3,} EMS _{WEO-mp}	EMS _{level-2,} EMS _{level-4}	EMS _{WEO-450}
Marginal electricity	CCP	CCP	CCP + CCS ^a	NGCC
CO ₂ eq emissions of the marginal electricity	935	679	129	345

^a CCP + CCS = CCP plant with CCS.

Figure 7. A graphical description of the system approach used for analyses of energy flows and for evaluation of the impact on global GHG emissions.

Table 17. GHG emissions factors (kg CO₂eq/MWh) for DH production in Paper VI.

	WEO-np	WEO-450
DH production when biomass use is considered as CO₂ emissions neutral		
Västra Götaland	-164	-40
Östergötland	-192	-63
Jönköping	-134	-41
DH production when FTD production plants are the alternative users of biomass		
Västra Götaland	-118	6
Östergötland	-146	-17
Jönköping	-70	23
DH production when CCP plants are the alternative users of biomass		
Västra Götaland	-38	86
Östergötland	-66	63
Jönköping	44	137

5.8 Overview of the additional analyses presented per paper

Table 18. The additional analyses performed for purposes of this thesis presented per paper.

Paper	Additional analyses performed
I	The influences on global GHG emissions were analysed by taking the comprehensive approach (described in section 5.7; the results are presented in section 6.2.1). The changes in fossil fuel consumption in the power sector caused by the changes in marginal electricity production were analysed (see section 5.6; the results are presented in section 6.2.1). The changes in global GHG emissions and the changes in global fossil fuel consumption were analysed considering alternatives for biomass use (see sections 5.6 and 5.7; the results are presented in sections 6.2.1). Economic characteristics of the DHS were analysed considering annual average DH production costs instead of system costs (as was done in Paper V; the results are presented in section 6.1.1).
II	The electricity demand for pumping during the absorption cooling production is included in the calculations. It is assumed that it would be 10% of the absorption cooling production (see section 5.4.2). The influences on global GHG emissions were analysed by using the comprehensive approach (see section 5.7; the results are presented in section 6.2.2). The changes in fossil fuel consumption in the power sector caused by the decrease in electricity use for the current compression cooling production, and caused by the increased electricity production in the CHP plants were analysed (see section 5.6; the results are presented in section 6.2.2). The changes in global GHG emissions and the changes in global fossil fuel consumption were analysed considering alternative use of biomass (see sections 5.6 and 5.7; the results are presented in sections 6.2.2).
III	In order to make the results from Paper III comparable with the results from Paper I, the changes in global GHG emissions per scenarios from Paper III are presented in tonnes of CO ₂ eq (the results are presented in section 6.2.1).
IV	No new analyses were performed.
V	The changes of the fossil fuel consumption in the power sector caused by the changes in marginal electricity production were analysed. The alternative use of biomass was considered as well (see section 5.6; the results are presented in section 6.2.1).
VI	The changes in fossil fuel consumption in the power sector caused by the changes in marginal electricity production were analysed. The alternative use of biomass was considered as well (see section 5.6; the results are presented in section 6.2.3). Both types of alternative users for biomass (CCP plants and plants for FTD production) were considered in both EMSs (EMS _{WEO-np} and EMS _{WEO-450}).

To be able to compare the results from different papers and in order to improve the studies and to give more concrete answers to the research questions, some additional analyses were performed. Table 18 gives an overview of the additional analyses.

6 Results and analyses

In this chapter the results from the appended papers and from the additional analyses (described in section 5.8) are presented in relation to the research questions (see section 1.1).

6.1 Business strategies for district heating producers

This section presents the results which are in relation to the first research question:

1. *Can the following business strategies ensure profitable DH production and contribute to DH having an important role toward a future sustainable energy system?*
 - *introduction of biofuel production into DHSs*
 - *integration of DH-driven absorption cooling technology in DHSs*
 - *delivering industrial waste heat (from biofuel production industry) to DHSs*
 - *increasing DH use in industrial processes.*

This thesis includes analyses of these four business strategies for DH producers: introduction of biofuel production into DHSs (Papers I, III and V); integration of DH-driven absorption cooling technology in DHSs (Papers II and VI); delivering excess heat from biofuel production industry to DHSs (Paper IV); and increasing DH use in industrial processes (Papers II and VI). Since in the next section those business strategies are analysed as possible measures to help decrease global fossil fuel consumption and reduce global GHG emissions (section 6.2), in this section those viewpoints have not been discussed in detail. The focus of this section is mostly on economic aspects of different

business strategies and the effects which those business strategies would have on the DHSs regarding an efficient utilization of DH production plants.

Techno-economic analyses have been performed in four papers. As mentioned above at the beginning of section 5, two different viewpoints have been taken when the techno-economic analyses were performed. In Papers I and V it was analysed whether the suggested business strategy (the integration of biofuel production with DH production) would be profitable for DH producers. In papers IV and VI a different viewpoint has been taken. Those papers analyse whether cooperation between DH producers and industrial sector would be profitable for industry.

The fundamental idea of DH, according to Frederiksen and Werner (2013), is to increase energy efficiency of the energy system by utilizing heat losses from thermal power generation (CHP production), and excess heat from industrial processes (see section 3). Therefore, in this thesis, delivery of excess heat from the biofuel production industry to local DHSs was analysed as one of the business strategies which may ensure an important role for DH in a future sustainable energy system (Paper IV).

Climate change and energy efficiency measures in the building sector will probably lead to reduced DH demand in the existing DHSs in the future. Therefore, it is essential to expand the existing DH market by finding new purposes for DH use. The business strategy suggested in Paper VI is to increase DH use in manufacturing industry; Västra Götaland, Östergötland and Jönköping counties were used as the case studies. In Paper II a possibility to increase DH production during the summer by integrating DH-driven absorption cooling into Stockholm's DHS was analysed.

6.1.1 Integration of biofuel production into district heating – influences on district heating production costs

Possibilities to reduce DH production costs by introducing biofuel production into DHSs were analysed in Papers I and V.

Paper I evaluated profitability of introducing an “Ethanol 1 plant” (see section 5.4.1) into Stockholm's DHS. The plant has an input capacity of 279 MW. The profitability was evaluated by comparing the system costs (the term is explained in section 5.3.2) before and after the introduction of the plant, but for the purposes of this thesis the results are presented as annual average DH production costs instead (see section 5.8). The analyses were performed considering EMS₂₀₁₀ (Table 9; section 5.2).

After the introduction of the plant into the DHS the electricity production in the DHS increases from 2.30 TWh to 2.36 TWh annually, and annual ethanol and biogas production is 0.75 TWh and 0.55 TWh. This leads to an increase in revenues from the

by-products produced in the DHS from €122 million annually to €205 million annually. A third of the revenues comes from the income from the biofuel sold; €66 million is the revenue from the ethanol sold and €10 million is the revenue from the sale of biogas (see Paper I). As a result of the increased revenues, the annual average DH production costs decrease by 17% (from €23/MWh_{DH} to €19/MWh_{DH}; Figure 8). This happens despite the high investments in the “Ethanol 1 plant” and despite the fact that the costs for biomass increase due to the increased biomass use in the DHS; the biomass use increases from 6.5 TWh annually to 8.5 TWh annually. Even if the biomass price increases by 20% or the ethanol price decreases by 20% the annual average DH production costs are about 13% lower when the “Ethanol 1 plant” is introduced into the DHS (Figure 8). Due to the additional electricity production, the introduction of the “Ethanol 1 plant” into the DHS is more profitable when the electricity price increases to the European level (see section 5.2). In this case the DH production costs are 19% lower if the “Ethanol 1 plant” is introduced in the system (Figure 8).

Figure 8. The annual average DH production costs for different EM conditions (based on the results from Paper I and the additional analysis mentioned in section 5.8).

When the profitability for introduction of large-scale biofuel production into Stockholm’s DHS was evaluated (Paper V) this business strategy was compared with the usual business strategy for DH producers, which includes further investments in CHP production. The profitability was evaluated by comparing the annual average DH production costs when those two business strategies are applied.

If DH producers continue to invest only in CHP production, the investment required to build new CHP plants with a total heat capacity of 600 MW (the reference scenarios) is €645 million. The introduction of large-scale biofuel production into the DHS requires investments approximately two times higher. The required investments in the scenarios with the large-scale biofuel production are €1210 million (the “biogas” scenarios), €1089 million (the “electricity” scenarios) and €1355 million (the “diesel” scenarios). For a detailed description of the scenarios and new investments see sections 5.5 and 5.4.1.

Despite the higher investments required, the introduction of large-scale biofuel production into the DHS may still result in lower annual average DH production costs due to the higher revenues from the sale of by-products (Figures 9 and 10). Even if the RES-T support (see section 5.2) is not included, the revenues in the scenarios with biofuel production are between 35% and 130% higher than the revenues in the reference scenarios (Figure 9). If the DH producers invest in biogas and ethanol production (the “biogas” scenarios), the revenues would be highest. The revenues would be €631 million (b-np scenario) or €692 million (b-450 scenario) if the RES-T support is not included, and €783 million and €844 million if RES-T support is included (b-np + RES-T sup. and b-450 + RES-T sup. scenarios, respectively). RES-T support guarantees between 36% and 63% higher revenues from the biofuel produced in the “biogas” and “electricity” scenarios (Figure 9). Moreover, when RES-T support is included, the revenues from biofuel sales are higher than the revenues from electricity sales in all scenarios except in the “diesel” scenario in combination with EMS_{WEO-450} (d-450 + RES-T sup. scenario; Figure 9).

Figure 10 shows how the annual average DH production costs vary depending on the scenarios and EM conditions when the discount rate for the biofuel production plants is 6%. The RES-T support guarantees approximately €15/MWh_{DH} lower annual average DH production costs in the “biogas” scenarios (Figure 10), and approximately €9/MWh_{DH} and €7/MWh_{DH} lower annual average DH production costs in the “electricity” and “diesel” scenarios, respectively (Figure 10). The “biogas” scenarios are most profitable. The annual average DH production costs in the “biogas” scenarios are even negative when the RES-T support is included (Figure 10). It is less profitable to invest in ethanol plants in which the co-produced raw biogas is used for CHP production (the “Ethanol 2 plants”; the “electricity” scenarios), than to invest in ethanol plants in which the co-produced raw biogas is upgraded to be sold as fuel for vehicles (the “Ethanol 1 plants”; the “biogas” scenarios); for a detailed description of those plants see section 5.4.1 and Paper IV. This conclusion is in line with the conclusion drawn by Fahlén and Ahlgren (2009), who compared the profitability of selling SNG as fuel for vehicles with the profitability when the SNG is used for CHP production. However, even though the investment in the “Ethanol 2 plants” (the “electricity” scenarios) is less profitable than the investment in the “Ethanol 1 plants” (the “biogas” scenarios), when RES-T support is included, this business strategy may still be more attractive for DH producers than investments in CHP production only (the reference scenarios); see Figure 10. Even if the RES-T support is not included, the investments in the “Ethanol 2 plants” may result in profitability but only

when EMS_{WEO-np} is considered and if the discount rate is low (6% or lower; Figure 10). Investments in FTD and DME production (the “diesel” scenarios) are competitive to investment in CHP production only with the RES-T support included.

Figure 9. Revenues from the sale of by-products in different scenarios considering different EM conditions. (For explanation of how the different scenarios are denoted see section 5.5; RES-T sup. = RES-T support; WEO-np = EMS_{WEO-np} ; WEO-450 = $EMS_{WEO-450}$).

In Paper V sensitivity analyses of the discount rate were performed as well. The results showed that if the discount rate for the biofuel production plants is 10%, investment in the “Ethanol 1” plants (the “biogas” scenarios) instead of in CHP plants still results in profitability. When RES-T is not included, investment in the “Ethanol 2” plants (the “electricity” scenarios) is profitable only when EMSWEO-np is considered. When the discount rate is 10%, in order to make investment in FTD and DME production plants (the “diesel” scenarios) profitable the RES-T support must be higher than the RES-T support suggested in section 5.2. For a detailed overview of the results based on the higher discount rate (10%) see Figure 5 in Paper V.

Figure 10. Annual average DH production costs in different scenarios considering different EM conditions when the discount rate is 6%. (the scenarios are described in section 5.5; WEO-np = EMSWEO-np; WEO-450 = EMSWEO-450; RES-T sup. = RES-T support)

The higher Swedish energy prices in the EMSWEO-450, compared with the prices in the EMSWEO-np (see section 5.2), result in higher revenues from by-products in most of the analysed scenarios (Figure 9), but also in higher DH production costs (Figure 10) due to the higher costs for fuels and feedstock. The only scenario where the revenues are not higher in the EMSWEO-450 than in the EMSWEO-np is the “diesel” scenario when the RES-T support is included; this is due to the unprofitability of producing more FTD in this scenario than the amount that is needed for purposes of the public TS (for a further explanation see section 5.5). However, the increases in the revenues in the different scenarios differ significantly. The revenues from the by-products in the reference scenarios, which come mostly from the co-produced electricity, increase by 24% (the

reference scenarios in combination with $EMS_{WEO-450}$ compared to the reference scenarios in combination with EMS_{WEO-np} ; Figure 9). On the other hand, the increases in the revenues in the scenarios with the large-scale biofuel production (the “biogas”, “electricity” and “diesel” scenarios in combination with $EMS_{WEO-450}$ compared to the same scenarios in combination with EMS_{WEO-np} ; Figure 9) do not exceed 11%. The reason for this is that the electricity price is more sensitive to the CO_2 charge than the biofuel prices which are derived from the gasoline and diesel prices (since electricity use is associated with higher CO_2 emissions than gasoline and diesel use; see Tables 15 and 16). As a result, the 2.4 times higher CO_2 charges in the $EMS_{WEO-450}$ result in approximately 25% higher price ratios between electricity and biofuels in $EMS_{WEO-450}$, compared to EMS_{WEO-np} . Furthermore, since co-firing in CCP plants is the identified price-setting alternative use of biomass in the $EMS_{WEO-450}$ (see section 5.2), the higher CO_2 charge in this EMS also leads to higher biomass prices (see section 5.2). This makes it even less profitable for DH producers to invest in large-scale biofuel production instead of in CHP production, due to the higher biomass use in the scenarios with large-scale biofuel production than in the reference scenarios. Consequently, the annual average DH production costs in the reference scenarios are approximately €0.75/MWh higher when $EMS_{WEO-450}$ is considered, while in the scenarios with the large-scale biofuel production this increase varies within a range from €3/MWh to €4/MWh; Figure 10 (when the discount rate is 6%) and Figure 5 in Paper V (when the discount rate is 10%).

6.1.2 Delivering excess heat from biofuel production industry to local district heating systems – evaluation of biofuel production costs

In Paper IV, the profitability of biofuel production for four different biofuel production technologies (see section 5.4.1) was analysed considering different EMSs, different discount rates, and different DHS conditions. When the biofuel production costs were analysed the revenues from the heat and electricity co-produced were included. The profitability of the production was discussed by comparing the production costs with the gate biofuel prices presented in Table 11 (see section 5.2); those prices were calculated by assuming that the final biofuel price at filling stations is equal to the price of the fossil fuel replaced by that biofuel (for further explanation see section 5.2). According to the aim of this thesis, only results that concern influences of different DH prices and different annual operating times of biofuel production plants (which depend on the DH demand variation during the year) were presented in this section.

The biofuel production plants analysed in Paper IV show different sensitivities to the DH price level and to the annual operating time (see Figure 7 in Paper IV). While the sensitivity of biofuel production costs to the DH price depends on the heat efficiency of the plant, the sensitivity to the annual operating time depends on the total by-product (heat and electricity) efficiency and the investment costs. High heat efficiency implies

high economic benefit from introducing such a plant into a DHS. Since the “Ethanol 2 plant” is characterised by the highest heat efficiency compared to the other biofuel production plants included in the study (see section 5.4.1), the benefits (regarding the possibility of increasing the profitability and energy efficiency of the biofuel production) by introducing the “Ethanol 2 plant” into a DHS are most obvious. By utilizing the excess heat from the “Ethanol 2” production in a DHS the total energy efficiency of the plant increases by 95% (from 0.46 to 0.9; Table 12). Moreover, the “Ethanol 2” production costs show the highest sensitivity to the DH price level. If the operating time of the plant is 8000 h annually and the discount rate is 6%, the “Ethanol 2” production costs are €103/MWh when EMS_{WEO-np} is considered and €117/MWh when $EMS_{WEO-450}$ is considered (see Figure 7 in Paper IV). By selling the excess heat from the “Ethanol 2” production to a local DHS at a DH price which is set by BCHP production (Table 11) those costs may be reduced by 34% (see Figure 7 in Paper IV). By selling the excess heat at a DH price which is set by BHOB production (Table 11) the costs may be reduced by 51% compared to the production costs when the excess heat is not utilized (Figure 7 in Paper IV). When the annual operating time is only 5000 h, the “Ethanol 2” production costs are €124/MWh when EMS_{WEO-np} is considered and €138/MWh when $EMS_{WEO-450}$ is considered. The decrease of those costs after introduction of the plant into a DHS with a low DH price is 28%, and if the DH price in the DHS is high, it is 43% (see Figure 7 in Paper IV).

The simultaneous biogas and ethanol production (the “Ethanol 1 plant”; see section 5.4.1) is profitable for all EM and DHS conditions even without revenues from the heat co-produced (comparing the ethanol and biogas gate prices presented in Table 11 to the biogas and “Ethanol 1” production costs when the DH price is €0/MWh; see Figure 7 in Paper IV). Delivery of the excess heat from the “Ethanol 1” production to a DHS guarantees between 16% and 28% (depending on the EM conditions, the DH price level and the annual operating time) lower production costs. Furthermore, the utilization of the excess heat increases the total energy efficiency of the “Ethanol 1 plant” from 0.64 to 0.92 (Table 12).

Compared to the “Ethanol 1” and “Ethanol 2” production, the FTD and DME production are characterised by lower heat efficiencies, and because of this also by lower sensitivities to the DH price level (see Figure 7 in Paper IV). The benefits of introducing FTD and DME production into a DHS would be lower as well. The results showed that even if the DH price was high (set by DH production in BHOB), the FTD and DME production costs would decrease by less than 10% if the plants were introduced into the DHSs. The utilization of the excess heat from the biofuel production increases total energy efficiencies of the DME plant from 0.62 to 0.77 (Table 12), and of the FTD plant from 0.51 to 0.57 (Table 12).

6.1.3 Integration of district heating-driven absorption cooling technology in district heating systems

Paper II aims to assess the potential for reduction of global CO₂ emissions by converting from vapour compression chillers to DH-driven absorption chillers in Stockholm's DCS and in Stockholm's industrial sector. The part of the compression cooling production which should be converted to absorption cooling production was detected by comparing the cooling generation costs of these two technologies. The profitability of conversion has not been analysed in detail. The optimization model framework MODEST (see section 5.3.2) was used to determine the cooling technology with the lower cooling generation costs during the different periods of the year. In order to improve the research performed in Paper II new analyses which include electricity demand for pumping during absorption cooling production were performed (see section 5.8). Only the results from those analyses are presented in this thesis. The results showed that conversion from compression chillers to DH-driven absorption chillers in Stockholm's DCS and in Stockholm's industrial sector might imply an opportunity not only to reduce cooling generation costs but also to increase utilization of CHP plants in the DHS. The potential for the reduction of the cooling generation costs depends on the marginal DH production in the DHS. The DH-driven absorption cooling production was shown to be more cost-effective than vapour compression cooling production during the summer. The reason for this is the fact that during the summer the marginal DH production in Stockholm's DHS is usually DH production in CHP plants (the DHS was described in section 4.1.1), which is characterized by low DH production costs. The optimization results showed that about 89% of the cooling which is presently produced by vapour compression chillers during the months from April to October should be produced by DH-driven absorption cooling chillers (a result based on the additional analyses; see section 5.8). However, during the winter cooling production by compression chillers is more cost-effective than cooling production by absorption chillers since then the oil-fired plants work as the marginal sources of heat in the DHS. Finally, the results showed that about 72% of annual cooling demand in Stockholm's DCS and in Stockholm's industrial sector, which is currently met by compression cooling production, should be produced by DH-driven absorption chillers (a result from the additional analyses; see section 5.8).

In Paper VI, where the possibility to increase DH use in the industrial sector in three Swedish counties was analysed, a potential to increase DH production in the local DHSs by producing absorption cooling for industrial processes and comfort-cooling was found. The results from Paper VI also showed that compared to the other analysed industrial processes, DH-driven absorption comfort-cooling production has the highest potential to decrease seasonal variation of DH production in the DHSs, which would subsequently lead to a better utilization of the CHP plants in the local DHSs. This is due to the fact that the comfort-cooling demand is highest during the summer when the space heating demand is lowest. The results from Paper VI are discussed more in the next section.

In addition to this, another benefit of conversion from compression comfort-cooling production to absorption comfort-cooling production is the possibility to avoid the peak demand of electricity for compression-cooling production during the hottest summer days.

6.1.4 Increasing district heating use in industrial processes

In all three counties included in the study in Paper VI, a potential to increase DH use in the industrial sectors was found. The DH use in the analysed industrial companies has a potential to increase by four times in Västra Götaland (from 14 GWh to 58 GWh annually), by nine times in Jönköping (from 5 GWh to 45 GWh annually), and in Östergötland by two times (from 84 GWh to 168 GWh annually). Potential has been found for using the DH for:

- space heating;
- DH-driven absorption comfort-cooling;
- heating in production processes in the manufacture of food products and the manufacture of textiles;
- drying in production processes in the manufacture of food products, the manufacture of wood and of wood and cork products, the manufacture of fabricated metal products and the manufacture of machinery and equipment;
- DH-driven absorption-process cooling in the manufacture of chemicals and chemical products, the manufacture of basic pharmaceutical products and pharmaceutical preparations, and the manufacture of rubber and plastic products.

The results show that the conversion of industrial processes to DH in the analysed industrial companies leads to local DH demand curves which are less dependent on outdoor temperature; the load duration curves for DHSs in the analysed counties before and after the conversion to DH in industry are shown in Figures 9, 10 and 11 in the Appendix in Paper VI. This opens up a possibility for more efficient utilization of the DH production plants (above all of the CHP plants).

As previously mentioned, DH-driven absorption comfort-cooling production has the highest potential to decrease seasonal variation of DH production in the DHSs. This can be seen in Figure 4 in Paper VI, where comfort-cooling accounts for approximately 20% of the total DH use in the industrial companies in Västra Götaland.

The DH use in the industrial processes in the analysed industrial companies was also found to be competitive to the previous energy use, when an economic evaluation was performed. When the economic evaluation of conversion of industrial processes to DH was performed in Paper VI, only the energy cost changes for industrial companies were analysed (see Table 6 in Paper VI). Those costs were calculated based on the estimated

changes in energy use in the industrial companies, after the conversion of industrial processes to DH. The results showed that this business strategy leads to a decrease in energy costs for the industrial companies in all counties included in the study. Beside the EM conditions, a factor which has influence on the profitability is the type of process which is converted. For example, the conversion of compression cooling production to DH-driven absorption cooling production can result in higher energy costs because the COP of compression chillers is higher than the COP of absorption chillers (see section 5.4.2).

A potential to increase DH use through DH-driven absorption-cooling production for purposes of two industrial companies in Stockholm county has been detected in Paper II (see section 6.1.3). This has already been mentioned in the previous section.

All business strategies mentioned in this section are also analysed and discussed as business strategies which might lead to reduction of global fossil fuel consumption and of global GHG emissions. The results are presented in section 6.2.

6.2 Possibilities to decrease the global fossil fuel consumption and global GHG emissions

In this section the results which are in relation to the second research question are presented.

2. *How can heat production in DHSs contribute to reduction of global fossil fuel consumption and global GHG emissions?*

6.2.1 Possibility to decrease global fossil fuel consumption and global GHG emissions by integrating biofuel and district heating production

The possibility to decrease fossil fuel use in the TS by integrating biofuel production with DH production was analysed in Papers I, III and V. This possibility was motivated by an opportunity for development of a local biofuel supply infrastructure where the biofuel would be sold at a competitive price (due to the lower biofuel production costs when the excess heat is used for purposes of DH). In all three papers it is assumed that the by-produced biofuel would be used in the local TS and all three papers used the county of Stockholm as a case study. Since the analysed scenarios in Papers III and V are almost

similar, only the results from Paper V are presented when the effects on global fossil fuel consumption were analysed.

The possibility to decrease global GHG emissions by introducing biofuel production into DHSs has been analysed in Papers I and III. Influence on global GHG emissions was analysed considering not only the emissions during the combustion process in the DHS, but also considering the effects on global GHG emissions caused by by-production of electricity and biofuels in the DHS (see section 5.7). While in Paper I the only GHG which was included in the study was CO₂, and the life cycles of the fuels were not considered, in Paper III more comprehensive analyses were performed. In Paper III three GHGs were considered (CO₂, CH₄ and N₂O), as well as the emissions during the whole life cycle of the fuels and effects caused by increased biomass use in the DHS. For purposes of this thesis, additional analyses which include this comprehensive approach were performed on the results from Paper I as well (see section 5.8).

In Paper I an “Ethanol 1 plant” (see section 5.4.1) with input capacity of 279 MW was introduced into Stockholm’s DHS. Figures 11 and 12 (results from the additional analyses described in section 5.8) show how the potential for reductions in global fossil fuel consumption and global GHG emissions, after the introduction of the plant, varies depending on different EM conditions and different assumptions regarding alternative use of biomass. The variations due to the different EM conditions are caused by choosing different operation of existing plants in the DHS. Those variations are negligible in most of the analysed scenarios (Figures 11 and 12).

The results show that if the operating time of the plant is 8000 h/year the ethanol and biogas production in the DHS is about 0.75 TWh ($127 \cdot 10^6$ L) and about 0.55 TWh ($57 \cdot 10^6$ Nm³) annually. If the ethanol is sold as E85, i.e., ethanol that includes approximately 15% gasoline, the ethanol produced is enough to run 16.4% of the private cars in the region. The biogas production is enough to cover about 10% of the total fuel demand for the private cars in the region (see section 4.1.3). The gasoline use in private cars would be reduced by 1.58 TWh ($175 \cdot 10^6$ L) annually (Figure 11). Those values were calculated considering the fuel economies for those fuels (section 4.1.3.1). With the “Ethanol 1 plant” in the DHS, the electricity production would increase from 2.3 TWh/year to 2.36 TWh/year (scenarios based on Swedish electricity prices). At the same time the electricity use for the heat pumps and electrical boilers in the DHS would decrease from 1.37 TWh/year to 1.15 TWh/year.

The changes in electricity use and production would lead to a reduction of coal use in the power sector of 0.71 TWh annually and subsequently, to a reduction of GHG emissions in the power sector as well. Furthermore, the ethanol and biogas produced would reduce GHG emissions in the TS by replacing gasoline. The reduction in global GHG emissions caused by replacing gasoline in the TS with the ethanol and biogas produced is 0.48 million tonnes of CO_{2eq} annually. The changes in global fossil fuel consumption and global GHG emissions are also caused due to the changes in electricity and fuel use in the

DHS. The reduction in global GHG emissions is 0.85 million tonnes of CO_{2eq} annually if the biomass is considered an unlimited resource.

Since the electricity use and production and fuel use in the DHS depend on the EM prices, so do the reductions in global fossil fuel consumption and global GHG emissions. A higher European electricity price encourages 3% higher electricity production and leads to 9% lower electricity use in the DHS, compared with a scenario based on the Swedish electricity price. This leads to a reduction in coal use in the power sector of 0.86 TWh annually (Figure 11).

The results from the scenario which is based on higher biomass and electricity prices shows an increase in electricity use in the DHS equal to the increase in electricity production after the introduction of the plant into the DHS. The reason for the increase in electricity use is that due to the higher biomass price it becomes more profitable to produce DH by heat pumps or in electric boilers than to produce it in BHOB. As a result, no changes in coal use and GHG emissions in the power sector are found in this scenario, and this scenario is characterised by the lowest potential for reductions in global fossil fuel use (Figure 11) and global GHG emissions (Figure 12). This also makes the reduction in global GHG emissions independent of the type of the marginal electricity production plants. The reduction in global GHG emissions in this scenario is 0.57 million tonnes of CO_{2eq} annually, while in the other three scenarios this reduction is 0.85 million tonnes of CO_{2eq} (Figure 12).

When biomass is considered an unlimited resource, the introduction of the “Ethanol 1 plant” into Stockholm’s DHS results in a substantial reduction of global fossil fuel consumption and global GHG emissions (Figures 11 and 12). However, if biomass instead is considered a limited resource, the potential for reductions is not obvious (the additional analyses are described in section 5.8). Since the biomass use in the DHS increases after the introduction of the “Ethanol 1 plant”, the biomass use in some other energy sector decreases (see sections 5.6 and 5.7 for explanation). If the alternative use of biomass is traditional FTD production, when the “Ethanol 1 plant” is introduced into the current DHS (Paper I), gasoline use in the TS will increase by approximately 0.9 TWh annually. As a consequence, the annual reduction of GHG emissions is approximately 0.25 million tonnes of CO_{2eq} lower annually for all EM conditions (Figure 12). If the alternative use of biomass is co-firing in CCP plants, coal use in the power sector will increase by 2 TWh annually after the introduction of the “Ethanol 1 plant” into the DHS. Consequently, the potential for the reduction of global GHG emissions is lower. The introduction of the “Ethanol 1 plant” into the DHS even leads to an annual increase of global GHG emissions of 0.2 million tonnes of CO_{2eq} in the scenario when the biomass and electricity prices are higher (Figure 12). As previously explained, in this scenario the electricity production in the “Ethanol 1 plant” does not result in any reduction in GHG emissions since the electricity use in the DHS after the introduction of the plant increases just as much as electricity production in the DHS. Thus, the reduction of GHG emissions after the introduction of the “Ethanol 1 plant” into

the DHS is mostly caused by replacing the gasoline in the TS by ethanol and biogas. However, when CCP plants are assumed to be the marginal users of biomass, the increase of GHG emissions in the power sector due to the increased biomass use in the DHS is higher than this reduction of GHG emissions in the TS

Figure 11. The potential for reduction of global fossil fuel use, after the introduction of the "Ethanol 1 plant" into Stockholm's DHS, depending on the different EM conditions and different assumptions regarding alternative use of biomass (result from additional analyses described in sections 5.6 and 5.8).

Paper V analyses a possibility for cooperation between Stockholm's TS and DHS. The cooperation would be realised by introducing large-scale biofuel production into the DHS for purposes of TS use. According to a prerequisite in Paper V, the DH producers would be obligated to cover the total biofuel and electricity demand in Stockholm's public TS and the surplus of biofuel produced would be sold to the public filling stations. The types of biofuel production plants were chosen based on three assumed future developments of the TS. Three groups of scenarios with large-scale biofuel production were analysed: "biogas", "electricity" and "diesel" scenarios (for the description of the scenarios see section 5.5). When the changes in energy use and by-produced in the DHS were analysed these scenarios were compared with the reference scenarios in which it is assumed that the DH producers would invest in CHP production instead (see section 5.5). Figure 13 gives an overview of the changes in global fossil fuel consumption when the scenarios with large-scale biofuel production are compared with the reference scenario. Those changes are the results from the additional analyses described in sections 5.6 and 5.8.

Figure 12. The change of global GHG emissions, after the introduction of the “Ethanol 1 plant” into Stockholm's DHS, depending on the EM conditions and on the assumption regarding the alternative biomass use (result from additional analyses described in sections 5.7 and 5.8).

The previously mentioned cooperation would have a substantial influence on the fossil fuel use in the TS. The highest biofuel production, and subsequently the highest decrease in fossil fuel use in the TS, is found in the “biogas” scenarios. The annual biogas and ethanol production in this scenario are 1.89 TWh ($196 \cdot 10^6 \text{ Nm}^3$) and 2.46 TWh ($417 \cdot 10^6 \text{ L}$) (see Figure 1 in Paper V), which is enough to cover biofuel demand in the public TS and to cover 54% of the total fuel demand for local private cars. Compared with the reference scenario, in which only 0.09 TWh of biogas is produced annually, the biofuel production in the “biogas” scenario leads to an annual decrease in gasoline use in the TS of 5.17 TWh ($573 \cdot 10^6 \text{ L}$) (see Figure 13). When this decrease was calculated the fuel economies for biogas, ethanol and gasoline presented in Table 5 were considered. At the same time, the annual electricity produced in the DHS is approximately 0.5 TWh lower compared with the electricity produced in the reference scenario, which leads to an increase of fossil fuel use in the power sector. The results from the additional analyses (see sections 5.6 and 5.8) showed that in $\text{EMS}_{\text{WEO-np}}$, where CCP plants work as marginal producers of electricity, the coal use in the power sector would increase by approximately 0.92 TWh (Figure 13). When the marginal electricity is produced in NGCC plants ($\text{EMS}_{\text{WEO-450}}$), the decrease of electricity production in the DHS leads to an increase of NG use by 0.84 TWh annually (Figure 13).

In the “electricity” scenarios 2.46 TWh ($417 \cdot 10^6 \text{ L}$) of ethanol is produced annually (see Figure 1 in Paper V). After covering the energy demand in the public TS, the production surplus of ethanol in those scenarios is enough to cover 28% of the total fuel demand for private cars. If the ethanol is used in PHEVs, the production surplus may run 55% of the private cars in the region. The ethanol production leads to a decrease in gasoline use in the TS by 2.96 TWh ($328 \cdot 10^6 \text{ L}$) annually. The annual increase in fossil fuel use due to the decreased electricity production in the DHS is 0.78 TWh of coal ($\text{EMS}_{\text{WEO-np}}$) or 0.73 TWh of NG ($\text{EMS}_{\text{WEO-450}}$) (the results from the additional analyses described in section 5.6 and 5.8). When the biomass is considered an unlimited resource, the lowest potential for reduction of global fossil fuel use is found in the “electricity” scenarios (compared with the other scenarios with large-scale biofuel production; Figure 13).

In the “diesel” scenarios three types of biofuels are produced: FTD, DME and ethanol. The ethanol and DME production are 0.82 TWh annually and 1.49 TWh annually, independent of the EMSs (see Figure 1 in Paper V). The FTD production is 1 TWh annually in $\text{EMS}_{\text{WEO-np}}$. However, in the $\text{EMS}_{\text{WEO-450}}$ due to the unprofitability of producing more FTD the model chooses to produce only the amount which is required for use in the public TS (0.06 TWh annually; for a further explanation see section 5.5). The produced DME is used in the public TS. The ethanol produced is enough to run 15% of the private cars, and production surplus of FTD in $\text{EMS}_{\text{WEO-np}}$ (1 TWh annually) is enough to cover 20% of the fuel demand of private cars. Subsequently, the reduction of gasoline use in the TS (caused by the increase in ethanol use) is 0.98 TWh ($109 \cdot 10^6 \text{ L}$) annually, and the annual reduction in fossil diesel use in the TS (caused by the increased use of DME and FTD) is 2.60 TWh ($314 \cdot 10^6 \text{ L}$) when $\text{EMS}_{\text{WEO-np}}$ is considered and 1.58 TWh ($191 \cdot 10^6 \text{ L}$) when $\text{EMS}_{\text{WEO-450}}$ is considered; the fuel economies (Table 5)

were considered during the calculation. The electricity production in the “diesel” scenarios is only 7% lower than the electricity production in the reference scenarios. As a result, in those scenarios the increase in fossil fuel consumption for the marginal electricity production in the power sector (due to the differences in electricity production in the DHS) is lowest, 0.39 TWh coal annually (in EMS_{WEO-np}), and 0.52 TWh NG annually (in $EMS_{WEO-450}$) (the results from the additional analyses are described in sections 5.6 and 5.8).

When biomass is considered an unlimited resource, the integration of large-scale biofuel production with DH production may result in a significant reduction of global fossil fuel use. However, if biomass is considered a limited resource, the benefit of the large-scale biofuel production is not so obvious. The reason for this is the fact that the total biomass consumption in the DHS is between 3.12 TWh and 5.29 TWh (depending on the scenario) higher if DH producers invest in biofuel production instead of in CHP (the reference scenario).

When biomass is considered a limited resource, the increase in biomass use in the DHS leads to a decrease in biomass use in the power sector or in the TS. Compared with the results when biomass is considered an unlimited resource, the reduction of global fossil fuel consumption is significantly lower. If the alternative use of biomass is traditional FTD production the reduction of global fossil fuel consumption is between 60% and 66% lower in the “electricity” and “diesel” scenarios and between 42% and 44% lower in the “biogas” scenarios (see Figure 13; the results from the additional analyses are described in section 5.6 and 5.8). If the alternative use of biomass is electricity production the increased use of biomass in the DHS leads to an increase in coal use in the power sector of between 2.81 TWh annually and 4.77 TWh annually (depending on the scenario; see Figure 13) (the results from the additional analyses). Consequently, the large-scale biofuel production in the DHS leads to an increase of global fossil fuel consumption in most of the analysed scenarios (Figure 13).

If biomass is considered an unlimited resource, the investment in the large-scale biofuel production instead of in CHP production (Paper III) results in a considerable reduction in GHG emissions (Figure 14). The analyses in Paper III were performed considering three groups of scenarios with large-scale biofuel production (the “biogas”, “electricity” and “diesel” scenarios; see how those scenarios are denoted in section 5.5) and five EMS (four EMS_{levels} and EMS_{WWF} ; see section 5.2); the results where EMS_{WWF} is considered are not presented in this thesis. The greatest benefits are achieved in the “biogas” scenarios. In those scenarios three “Ethanol 1 plants” with a total input capacity of 924 MW are introduced into the DHS (see section 5.5). Investment in those plants instead of only in CHP plants results in a GHG emissions reduction of between 0.83 million and 1.25 million tonnes of CO_{2eq} annually (depending on the EM conditions; Figure 14). Depending on the EM conditions, the investment in FTD, DME and ethanol production (the “diesel” scenarios) instead of only in CHP plants results in between 8% and 21% lower reduction in global GHG emissions. The “electricity” scenarios are characterised by

the highest electricity production compared with the “biogas” and “diesel” scenarios. Because of this, the influence of the type of marginal electricity sources on the changes in GHG emissions is most noticeable. The annual reduction of global GHG emissions in those scenarios varies within a wide range between 0.4 million and 1.19 million tonnes of CO_{2eq}, if the biomass is considered an unlimited resource.

Figure 13. The changes global fossil fuel consumption when the scenarios with large-scale biofuel production (the scenarios are described in section 5.5) are compared with the reference scenarios where the investments are made in CHP production (the results from the additional analyses are described in section 5.6 and 5.8).

Figure 14. The reduction of global GHG emissions if DH producers in Stockholm's DHS invest in large-scale biofuel production instead of in CHP production (EMS 1-4 = EMS_{level-1-4}).

If biomass is considered a limited resource, the introduction of biofuel production into the DHS does not necessarily imply the potential for the reduction of global GHG emissions, since the increased biomass use in the DHS leads to decreased biomass use in some other energy system (explained in more detail in section 5.7). The results from Paper III showed that the "biogas" scenarios are not necessarily the best options if the alternative use of biomass is considered (Figure 14). The reason for this is that biomass use in the "biogas" scenarios is higher compared to the "electricity" and "diesel" scenarios. Consequently, the increase in global GHG emissions due to increased use of fossil fuel in the TS (if the alternative use of biomass is traditional FTD production) or in the power sector (if the alternative use of biomass is in CCP plants) is more noticeable (see section 5.7). If the alternative use of biomass is traditional FTD production, the annual reduction of global GHG emissions is considerably lower than in the case when the biomass is considered an unlimited resource; between 0.52 million and 0.69 million tonnes of CO_{2eq} in the "biogas" scenarios, and between 0.36 million and 0.55 million tonnes of CO_{2eq} in the "diesel" and "electricity" scenarios (Figure 14). The results also

show that as long as the production of marginal electricity results in high GHG emissions, an increased use of electricity in the TS is proven to be a worse strategy for GHG emission mitigation than an increased biofuel use (comparing the “electricity” scenarios with the “biogas” and “diesel” scenarios when $EMS_{level-1}$ and $EMS_{level-3}$ are considered; Figure 14).

If coal condensing power plants are assumed to be the alternative users of biomass, the investment in large-scale biofuel production instead of in CHP production would not signify a potential for reduction of GHG emissions (Figure 14). This is due to the decreased use of biomass in the power sector, which leads to increased coal use and consequently to an increase in GHG emissions (see section 5.7). The investments in biofuel production instead of in CHP production is especially poor strategy when the marginal electricity is produced in CCP plants ($EMS_{level-1}$ and $EMS_{level-3}$; Figure 14). In this case, replacing the marginal electricity with the electricity produced in the CHP plants in the reference scenarios results in higher benefits from a GHG emissions perspective than replacing the gasoline and fossil diesel with the biofuel produced in the scenarios which include large-scale biofuel production. When $EMS_{level-1}$ and $EMS_{level-3}$ are considered, the investment in large-scale biofuel production instead of in CHP production results in an increase in global GHG emissions, which is approximately 0.7 million tonnes of CO_{2eq} annually in the “biogas” and “electricity” scenarios, and approximately 0.4 million tonnes of CO_{2eq} annually in the “diesel” scenario.

In Paper III it was also analysed how the introduction of CCS technology would influence the changes in GHG emissions. The assumptions which were made when CO_2 capture potential for the new CHP and biofuel production plants were assessed are presented in section 5.4.3. Based on these assumptions it was calculated that the CCS potential in the scenarios with large-scale biofuel production is between 25% and 71% higher compared with the CCS potential in the reference scenarios (Table 19). This results in a considerable reduction of global GHG emissions if the DH producers invest in biofuel production instead of in CHP production even if the alternative use of biomass is co-firing in CCP plants (Figure 5 in Paper III).

Table 19. The CCS potential and electricity required for the CCS process in different scenarios.

	Reference	“Biogas”	“Electricity”	“Diesel”
Total CO_2 captured ($\times 10^6$ t)				
EMS 2	1.06	1.80	1.81	1.78
EMS 4	1.58	2.16	2.03	2.34
EMS 5	1.49	2.08	1.86	2.04
Electricity required (GWh)				
EMS 2	148	252	253	249
EMS 4	221	302	284	328
EMS 5	209	291	260	286

6.2.2 Possibility to decrease global fossil fuel consumption and global GHG emissions through district heating-driven absorption cooling production

The conversion from vapour compression chillers to DH-driven absorption chillers may lead to an increase in primary energy use. This is due to the fact that compression chillers are characterized by much higher COP than the absorption coolers. The ratio between the primary energy use for cooling production with DH-driven absorption coolers and the primary energy use for cooling production with electricity-driven chillers is highly dependent on the DH production and electricity production technologies considered.

As already mentioned in section 6.1.3, in order to reduce the cooling production costs, 72% (303 GWh annually) of the analysed compression cooling production in Paper II should be converted to DH-driven absorption cooling (the result from the additional analyses described in section 5.8). This would lead to an increase in DH production in the DHS of 760 GWh annually and subsequently to an increase in electricity production in the CHP plants of 110 GWh annually. At the same time, the electricity use for compression cooling production decreases by 86 GWh annually, while the electricity use for absorption cooling is only 30 GWh annually. Those changes in electricity use and production lead to a reduction of marginal electricity production in the power sector. As a result, assuming CCP plants as marginal electricity sources (see section 5.6) the reduction of coal use in the power sector is 420 GWh annually. This reduction is higher than the increase in fossil fuel use in the DHS due to the increased DH production (coal use increases by 101 GWh annually and oil use increases by 9 GWh annually). As a result of the reduction in fossil fuel use, the global GHG emissions decrease approximately 86 thousand tonnes of CO_{2eq} annually (a result from the additional analyses; see section 5.8). When biomass is considered a limited resource, a potential for reductions in global fossil fuel consumption and global GHG emissions still exists if traditional FTD production is considered to be the alternative use for biomass, but this potential is considerably lower. In this case, the fossil diesel use in the TS increases by 200 GWh annually due to lower FTD supply, which leads to increased GHG emissions in the TS. Because of this, the reduction in global GHG emissions after the conversion to DH-driven absorption cooling is lower, only 27 thousand tonnes of CO_{2eq} annually. If CCP plants are the alternative users for biomass, the conversion of compression cooling to absorption cooling leads to an increase in global fossil fuel consumption, since the increase in coal use in the power sector would be 450 GWh annually (the results from the additional analyses; see section 5.8), which is more than the 420 GWh reduction mentioned above. In this case, the conversion to DH-driven absorption cooling leads to an increase in global GHG emissions of 78 thousand tonnes of CO_{2eq} annually.

6.2.3 Possibility to decrease global fossil fuel consumption by increasing district heating use in industry

After the potential for conversion of industrial processes to DH was detected, the changes in energy use in the industrial companies were estimated (see Table 5 in Paper VI). Besides the possibilities of decreasing fossil fuel use in the industrial sectors (a possibility to decrease oil use has been found in all three counties, and a possibility to decrease NG use has been found in Östergötland; see Figure 15 in this thesis and Table 5 in Paper VI), a potential to decrease electricity use has been found in all counties as well, and a possibility to reduce biomass use has been found in Jönköping county.

The increased DH production in the local DHSs leads to a better utilization of the base-load DH production plants, including the CHP plants; see description of the DHSs in Västra Götaland, Östergötland and Jönköping counties in section 4.2.1.1. Subsequently, this leads to increases in the electricity production in the DHSs. When those increases were calculated the increase in DH demand was divided into two parts. From the first part of the DH demand, which load duration curves have the same form as the current DH load duration curves in the local DHSs, the increase in electricity production was calculated using the alfa-system of the DHSs (Table 6; section 4.2.1.1). From the second part of the DH demand, which causes the changes in the form of the DH load duration curves in the DHSs, the increase was calculated assuming that this DH would be produced only in CHP plants (in the NGCHP plant in Västra Götaland and in the BCHP plants in Östergötland and Jönköping counties). The estimated annual increases in electricity production are 28 GWh in Västra Götaland, 37 GWh in Östergötland, and 15 GWh in Jönköping county. This additional electricity production in the local DHSs and the reductions in electricity use in industry lead to decreased marginal electricity production in the power sector. For both EMSs considered in the study, the reduction in fossil fuel use in the power sector caused by the reduced marginal electricity production is higher than the reduction in fossil fuel use for the industrial companies (Figure 15). When the influence on fossil fuel use in the power sector is considered, and when biomass is considered an unlimited resource, the reduction in global fossil fuel consumption due to the conversion of the industrial processes to DH is substantial in all analysed counties (Figure 15), as well as the reduction in global GHG emissions. When EMS_{WEO-np} is considered (the marginal electricity is produced in CCP plants; see Table 11), the reduction of global GHG emissions achieved by the conversion of the industrial processes to DH in the studied counties varies between 22 thousand and 58 thousand tonnes of CO_{2eq} annually (Figure 16). When $EMS_{WEO-450}$ is considered (the marginal electricity is produced in NGCC plants; see Table 11), the reduction varies between 11 thousand and 29 thousand tonnes of CO_{2eq} annually (Figure 16).

When CCP production technology is assumed as marginal electricity production technology (EMS_{WEO-np}), the greatest benefits for GHG emissions reduction are achieved in Östergötland (Figure 16), where the decrease of electricity use in the industrial

processes (Table 5 in Paper VI), as well as the increase of electricity produced in the DHS are highest. Furthermore, the GHG emissions factor concerning DH production in DHS in Östergötland is lowest due to the highest share of DH production in CHP plants (Tables 6 and 17).

Figure 15. The changes in global fossil fuel consumption after the conversion of the industrial processes (in the analysed manufacturing companies in Västra Götaland, Östergötland and Jönköping counties) to DH, when the biomass is considered an unlimited resource.

Figure 16. The reduction in global GHG emissions achieved by the conversion of the industrial processes to DH in 83 manufacturing companies in three Swedish counties.

When biomass is considered a limited resource, the increased biomass use in the DHSs leads to a reduction of biomass use in some other energy system (see section 5.6). In

Jönköping county the decrease of biomass use in industry is equal to the increase of biomass use in the local DHS, so in this case study those effects are negligible. If CCP plants are the alternative for biomass use, due to the increased DH use in industry in Västra Götaland and in Östergötland, the annual coal use in the power sector increases by 15 and 29 GWh, respectively; if traditional FTD production is the alternative biomass use, the annual increases in fossil diesel use in the TS are 7 and 13 GWh, respectively. The results showed that even when those increases in coal and fossil diesel use are considered, the conversion of the industrial processes in Västra Götaland and in Östergötland still results in a reduction of global fossil fuel use and global GHG emissions (Figures 15 and 16). When the marginal electricity is produced in NGCC plants ($EMS_{WEO-450}$) the reductions in GHG emissions in the power sector due to the changes in marginal electricity production are approximately 50% lower because of a lower GHG emissions factor from the marginal electricity production (see Table 16). Therefore, when the $EMS_{WEO-450}$ is considered the potential for GHG emissions reduction is lower in all analysed cases (Figure 16).

7

Concluding remarks

This chapter contains a discussion of the results and conclusions in relation to the research questions.

7.1 Discussion

The aim of the thesis is to identify measures (that should be taken in DHSs) which contribute to the development of DHSs and other energy systems toward sustainability in a profitable way. The results in the thesis are presented as answers to two research questions. The first research question aims to identify business strategies for DH producers, which would ensure profitable DH production and contribute to DH having an important role in a future sustainable energy system. The second research question focuses on the *first and second principles of sustainability*, which refer to reduction of global fossil fuel consumption and global GHG emissions (see section 1). Through sensitivity analyses regarding the alternative use of biomass (these analyses are associated with the second research question) the *third principle of sustainability*, which refers to stopping the degradation of nature by physical means (see section 1) is discussed.

In those sensitivity analyses it is suggested that in order not to degrade nature by overusing the biomass, global annual biomass use should be limited. However, in order to limit the costs and environmental impacts during the transportation of the biomass this issue was not considered globally but instead on a European level. This means that increasing the biomass use in one energy system in Europe (e.g. a DHS) leads to decreased biomass use in some other energy system in Europe (e.g. power sector or industry), and consequently to an increased fossil fuel use in that other energy system. In order to include this important issue in the study, different assumptions about biomass availability and about the alternatives for biomass use have been made.

Using the sustainability principles during strategic planning is an effective way to handle possible trade-off situations which present risk of solving one problem by creating another one. One of the possible trade-off situations detected in this study is the problem

with increasing fossil fuel use in one energy system due to increased biomass use in some other energy system, as mentioned before. For the same reason it is important to apply a system approach as well as to look at the full life cycle of a product or a feedstock. Moreover, when the system approach is applied, selection of the system boundaries and surrounding may have large influence on the results. The studies presented in the thesis focus on environmental and energy issues and therefore largely do not consider the *fourth principle of sustainability* (see section 1), the so-called social principle of sustainability, which refers to the importance of not undermining people's capacity to meet their needs. Considering this principle of sustainability it must be mentioned that the biofuel production from lignocellulosic biomass (the type of biofuel production which is included in this study) reduces competition of biofuel production with food production (e.g. the competition between food production and ethanol production from sugarcane) because less biomass from arable land is required for biofuel production. On the other hand, the biofuel production from lignocellulosic biomass at the same time has a negative impact on raw material availability, for example, for the panel and pulp-and-paper industry. It is also important to consider other alternative ways for reaching the different goals of sustainability. For example, there are more types of energy sources that can be used to increase the share of renewable electricity in the power sector (e.g. solar, wind, hydro energy) than the types of energy sources which can be used to increase the share of renewable energy in the TS. This should be considered when the benefits of biomass use for biofuel production and of biomass use for electricity production (e.g. in BHP plants or co-firing in CCP plants) are compared.

When the conversions of compression cooling to DH-driven absorption cooling and the industrial processes from fossil fuels and electricity use to DH use are analysed, *exergy* (so-called *quality of the energy*) of different energy sources should be discussed as well. *Exergy* is the theoretical maximum of energy by work which can be obtained, and as such it can be used as a criterion to assess the efficiency of energy source utilization. For example, the *exergy factor* of electricity is, by definition, 100%, while the *exergy factor* of excess heat energy from thermal power generation and industrial processes is approximately 20% (Robèrt et al., 2007). From this viewpoint, excess heat energy should be used rather than electricity, for energy users that can use such heat energy. This is also, according to Frederiksen and Werner (2013), one of the main driving forces in the fundamental idea of DH (see section 3).

One of the issues which has been discussed through the results in this thesis is the profitability for DH producers (Papers I and V) or for their business partners (Papers IV and VI) when applying a new business strategy. This is a very important issue, since less profitable strategies may slow down further development of the DHSs. Thus, when starting with implementing new measures, the priority measures should be those that create adequate investment returns. For the same reason, those measures should also present flexible platforms for further actions. If a suggested strategy does not lead to profitability for DH producers, but on the other hand may contribute to development of society in the right direction when considering the principles of sustainability, policy

measures should be introduced to support those strategies, e.g. limited biomass resources increase the need for carefully designed policies which ensure that biomass is used in the most effective way while at the same time contributes to decreasing the impacts on the environment.

It is also important not to limit the actions based on current technologies, since new inventions are occurring all the time. For example, the studies in Papers I, III, IV and V are based on four different biofuel production technologies which are still in development. In Papers III and V the assumptions regarding future improvements of vehicle technology are included as well. However, even though the assumptions regarding the future technologies are necessary when long time frames are employed, those assumptions also include a high degree of uncertainty.

In four of the six appended papers Stockholm's DHS has been optimized by an optimization model framework called MODEST. In order to get more realistic output data, the model was calibrated according to detailed real production data (see section 5.3.2). However, despite this the output data are characterized by a certain degree of uncertainty. In all studies modelling is performed over a 10-year time period. Since it is difficult to predict potential variations in energy prices and DHS conditions (i.e., DH demand curve) from year to year, the input data to the model are assumed to be the same every year. There is also a risk in making analyses based on the future EMSs, especially since some sensitivity analyses performed in the studies (e.g. on energy prices and assumptions regarding the marginal electricity production) showed that the EM conditions may have a large effect on the results. Some energy prices in the EMSs are calculated (i.e., biofuel prices) based on the assumptions regarding people's willingness to pay by considering only economic aspects and without considering people's individual willingness to let their knowledge (e.g. about causes and consequences of climate change) influence their consumption patterns. Furthermore, every prediction regarding amount and composition of future waste fuel contains a degree of speculation. Through a literature review a number of different studies have been found which applied different assumptions. In some of them it has been predicted that the amount of waste in the future is going to increase due to increased urbanisation and a rise in population. On the other hand, in some other studies it is predicted that, despite increased urbanisation and a future rise in population, the amount of waste fuel is going to decrease due to increased recycling, which would be a result of a growing awareness about the consequences of climate change.

One important assumption in all papers included in this thesis is that the European electricity market is fully deregulated, and because of this the European and Swedish electricity markets are characterized by the same marginal electricity sources, CCP plants or NGCC plants (depending on the EM scenario assumed). In addition to this, there are many uncertainties regarding the future development of the power sector. With future marginal electricity sources not based on fossil fuels, the environmental benefits of electricity production in the DHSs and of reduction of electricity use in industrial

processes and for compression cooling production would be less obvious. This would make investments in large-scale biofuel production for DH producers more favourable compared to investments in CHP production, from an environmental viewpoint. This would also make DH-driven absorption cooling production less environmentally beneficial compared to vapour compression cooling production and conversion of industrial processes from electricity to DH less attractive from an environmental viewpoint.

Most of the business strategies suggested in this thesis are based on cooperation between DHSs and some other energy systems. The cooperation usually includes financial risks for both partners, mostly because of the new investments required. In some of the studies in this thesis those investment costs are not included in the analyses, which may cause some uncertainty concerning results; the investment costs for the energy demand-side measures (i.e., investments in the industrial sector in Paper VI and investments in TS in Papers III and V) were not included in the studies, nor were the investments in the DH-driven absorption chillers in Paper II. The investments in the DH-driven absorption chillers (Paper II), the industrial sector (Paper VI), and the TS (Paper III) were not included in the studies because the focus of those studies was more on the possible environmental benefits which may be achieved. The investments in TS were not included in the analysis performed in Paper V either because in this study only the profitability for DH producers was analysed.

Furthermore, social aspects of implementing the business strategies in the DHSs (e.g. social barriers and driving forces) were not included in the studies. In Papers III and V, where introduction of large-scale biofuel production into Stockholm's DHS for purposes of using the biofuel in the local TS was analysed, it was suggested that some agreements are required in order to secure a regular supply to biofuel users (TS) and to guarantee a possibility to sell by-produced biofuel for biofuel producers (DH sector). However, analyses of human factors which may have influence on these agreements between the DHS and TS were beyond the scope of this thesis.

In four papers (Papers I, II, III and VI) the issue of decreasing global GHG emissions by applying different business strategies in DHSs has been studied. Regarding this, it is important to mention that with a perfectly functioning EU Emissions Trading Scheme (mentioned in section 2.3) applying those business strategies will not have any impact on global GHG emissions in the systems included in the trading scheme; the GHG reduction in one part of the trading scheme would only result in increased GHG emissions somewhere else within the scheme (Dotzauer, 2010b). However, since the transport sector is not included in the trading scheme, there is still a large potential to decrease global GHG emissions by integrating biofuel production with DH production (Paper I and III). Furthermore, the suggested business strategies should also be considered as cost-effective measures which can contribute to future reduction of the CO₂ cap in the EU Emissions Trading Scheme, or as possibilities to adjust the analysed energy systems to a future cap in the EU Emissions Trading Scheme which will probably be lower than the current one.

In Paper III CCS technology has been recognized as a key option to significantly reduce GHG emissions caused by the DH and biofuel production in Stockholm's DHS. However, the utilization of this technology would require very capital-intensive investment for development of a large infrastructure for CO₂ transport from the capture location to storage sites, which most likely would be performed through pipelines. Furthermore, due to additional energy and water consumption, as well as to a potential risk of gradual or sudden CO₂ leakage which can endanger people and the climate system, in many studies the CCS technology has been recognized only as a possibility to exchange one problem for another; the temporary solution offered would have long-term negative consequences (Sprenga et al., 2007; Patil et al., 2010).

There is no single future solution which can be applied to all DHSs. The possible business strategies for DH producers, which may contribute to a sustainable development of energy systems, depend on a number of local conditions. This thesis includes only a few possible business strategies which may be applied in DHSs considering Swedish DH conditions and European EM conditions. Some other business strategies, not included in the thesis, are for example use of solar and geothermal energy for DH production, and an increased use of heat pumps. Finally, it is important to mention that although the results in this thesis are based on case studies, they can probably be useful for other regions with developed DHSs and with similar local climate conditions, as well as the industrial and transport sectors.

7.2 Conclusions

Finally, from the results presented in section 6 conclusions in relation to the research questions can be made.

1. *Can the following business strategies ensure profitable DH production and contribute to DH having an important role toward a future sustainable energy system?*
 - *introduction of biofuel production into DHSs*
 - *integration of DH-driven absorption cooling technology in DHSs*
 - *delivering industrial waste heat (from biofuel production industry) to DHSs*
 - *increasing DH use in industrial processes.*

When the possibility of integrating large-scale biofuel production with DH production in Stockholm's DHS was analysed, different scenarios with large-scale biofuel production introduced into the DHS were compared with a reference scenario, where the investments were made in CHP production. Three different scenarios with the large-scale biofuel production were analysed in combination with two energy market scenarios: (1) a scenario with biogas and ethanol production; (2) a scenario with ethanol production; and (3) a scenario with ethanol, Fischer-Tropsch diesel, and dimethyl ether production). Results showed that despite the fact that the introduction of biofuel production into the DHS is characterized by intensive capital investments, this business strategy may still result in lower DH production costs due to the higher revenues from the by-products in the DHS. The higher profitability would make DH production more competitive with other heating technologies in the future. However, in order to make the investments in ethanol, Fischer-Tropsch diesel, and dimethyl ether production more profitable than the investment in CHP production, support for transportation fuel produced from renewable energy sources is required. The investment in biogas and ethanol production was shown to be economically attractive for DH producers even if the support for transportation fuel produced from renewable energy sources is not included. If the support is included, and when the investments are made in biogas and ethanol production, the annual average DH production costs are even shown to be negative. The parameters which have influence on the profitability of the introduction of biofuel production into DHSs are the price ratio between electricity and biofuel (a higher ratio makes investments in CHP production more attractive for DH producers) and the biomass price (since the biomass use would be much higher if investments are made in biofuel production instead of in CHP production).

By buying excess heat from biofuel production industry DH may promote development of the biofuel production technologies which are not yet commercial. It was analyzed how this business strategy would affect the biofuel production costs for four biofuel production technologies:

- Ethanol production plant which includes co-production of biogas, electricity and heat;
- Ethanol production plant which includes co-production of electricity and heat;
- Fischer-Tropsch diesel plant which includes co-production of electricity and heat;
- Dimethyl ether production plant which includes heat co-production.

The technology cases showed different sensitivities to the DH price level. Due to the fact that the ethanol production plant, which includes co-production of electricity and heat, has the highest heat efficiency compared to the other technology cases, the costs of the ethanol production in this plant showed the highest sensitivity to the DH price level. Thus, the economic benefit of introducing such a plant into a DHS is most obvious. In addition to this, by utilizing the excess heat from the biofuel production plants the total energy efficiencies of the plants increase.

Climate change and energy efficiency measures in the building sector induce possible reduced DH demand in the existing DHSs. Therefore, in order to ensure a profitable role for DH in the future, it is important to expand the existing DH market by finding new purposes for DH use. Two of the possible purposes for DH use for the future are DH-driven absorption cooling production and DH use in industrial processes.

The comfort-cooling demand is highest during the summer when the space heating demand is lowest. Because of this, introduction of DH-driven absorption comfort-cooling production into DHSs would decrease seasonal variations of DH production in the DHSs. This would subsequently lead to a better utilization of the CHP plants in the local DHSs.

Converting from vapour compression chillers to DH-driven absorption chillers in Stockholm's district cooling system and in Stockholm's industrial sector is an opportunity for reduction of cooling generation costs and better utilization of CHP plants in the DHS. The absorption cooling production is more cost-effective than the compression cooling production during the summer, when the marginal DH production is characterized by low production costs (usually DH production in CHP plants). During the winter, when the oil plants serve as the marginal sources of the DH, cooling production by compression chillers is more cost-effective. This business strategy will become even more attractive for DH producers in the future, when summers become warmer because of climate change.

The conversion of industrial processes to DH leads to local DH demand curves which are less dependent on outdoor temperature, which subsequently opens up a possibility for more efficient utilization of the DH production plants by increasing base load production (above all of the CHP plants). Besides using DH for space heating and DH-driven absorption comfort-cooling, potential has been found for using the DH for following production processes:

- heating in production processes in the manufacture of food products and the manufacture of textiles;
- drying in production processes in the manufacture of food products, the manufacture of wood and of wood and cork products, the manufacture of fabricated metal products and the manufacture of machinery and equipment;
- DH-driven absorption process-cooling in the manufacture of chemicals and chemical products, the manufacture of basic pharmaceutical products and pharmaceutical preparations, and the manufacture of rubber and plastic products.

The results showed that these conversions of industrial processes to DH may also lead to lower energy costs in the industry.

The results also showed that all analysed business strategies imply a possibility for reduction of global fossil fuel consumption and for reduction of global GHG emissions. This is discussed further in the text below.

2. *How can heat production in DHSs contribute to reduction of global fossil fuel consumption and global GHG emissions?*

When biomass is considered an unlimited resource, the results showed that introduction of biofuel production into DHSs, introduction of DH-driven absorption cooling technology in DHSs, and increasing DH use in industrial processes may lead to reduction of global fossil fuel consumption and global GHG emissions.

The investments in biofuel production plants, instead of in CHP plants, would result in a decrease in electricity production in the DHS with CHP. As a consequence, the fossil fuel use for marginal electricity production (coal or natural gas) and GHG emissions in the power sector would increase. However, despite the increased fossil fuel use in the power sector, when the biomass is considered an unlimited resource the reductions in global fossil fuel consumption and global GHG emissions may still be significant due to the decreased gasoline and fossil diesel use in the transport sector.

Converting from vapour compression cooling to DH-driven absorption cooling is a measure which may contribute to avoiding the peak demand of electricity for compression-cooling production during the hottest summer days and also to increase electricity production in the DHS's CHP plants. Subsequently, despite the fact that the COP of compression chillers is lower than the COP of DH-driven absorption chillers, the conversion to DH-absorption cooling would still result in reduction of global fossil fuel consumption and global GHG emissions.

The conversion of industrial processes from fossils fuels and electricity to DH implies the possibility for better utilization of the base DH production plants. If the base plants are CHP plants the electricity production in the DHSs increases. This additional electricity production and the reduction of electricity use in the industry leads to a decrease in marginal electricity production in the power sector, which results in reductions in fossil fuel use and GHG emissions in the power sector. For the case studies analysed in this thesis, due to the decreased fossil fuel use and GHG emissions in the industrial and power sectors, the global fossil fuel consumption and global GHG emissions decrease as well.

However, after considering the third sustainability principle, the effects on other energy systems by increasing biomass use in the DHSs are included in the study. The results from those analyses showed that the environmental benefits, in terms of the reduction in global fossil fuel consumption and global GHG emissions, from implementing the suggested strategies are much less obvious, or do not exist at all. If the alternative users of biomass are plants for "traditional" biofuel production (which does not include utilization of the co-produced heat), an increased biomass use in the DHSs leads to an increase in gasoline and fossil diesel use in the transport sector. In this case, for all analysed business

strategies the environmental benefits exist but the benefits are much lower than when biomass is assumed to be an unlimited resource. If the alternative users of biomass are CCP plants, the investment in biofuel production instead of in CHP production and the conversion of compression cooling to DH-driven absorption cooling lead to increases in global fossil fuel consumption and global GHG emissions, due to the increased coal use in the power sector. When the conversion of the industrial processes to DH is considered for the analysed cases, the potential for reductions in global fossil fuel consumption and global GHG emissions still exists, but is much lower.

7.2.1 General conclusions

The hypothesis of the thesis is:

DH can contribute to a sustainable development of other energy systems, especially of the transport, industrial and power sectors.

Integrating biofuel and DH production in local DHSs enables development of local biofuel supply chains. This may facilitate the introduction of biofuel in the local transport sectors. DH may also reduce biofuel production costs in biofuel production industry, by buying excess heat from biofuel production, and in this way promote development of biofuel production technologies which are not yet commercial. This means that DH has possibilities to benefit the future sustainable development of the *transport sector*.

DH has possibilities to contribute to the sustainable development of the *industrial sector* by converting industrial processes from fossil fuels and electricity to DH (above all biomass and waste-based DH). This would make the industry less dependent on fossil fuels and fossil fuel-based electricity. Subsequently, this would lead to reductions in global fossil fuel consumption and global GHG emissions, associated with industrial production. Moreover, by buying excess heat from industrial processes, there is a possibility for DH to increase energy efficiency of the industrial sector and reduce production costs.

DH has a possibility to reduce fossil fuel consumption and subsequently GHG emissions in the *power sector* by producing electricity in biomass- or waste-fuelled CHP plants.

8

Further work

This section gives suggestions for further research.

The results in the five papers are based on case studies. Since DHSs are characterized by a number of local conditions, it is difficult to generalize the results and to accept them as valid for other DHSs. Therefore, there is a need to include more case studies in the research. Because of the uncertainty regarding the future contents and amounts of waste fuel, new analyses should be performed, in which other assumptions should be taken when those two parameters are considered. There is also a need to perform more sensitivity analyses on different EM conditions, such as EM prices, assumptions regarding the alternative users of biomass and assumptions regarding the parameters associated with the power sector. Also, in order to make the results which concern integration of biofuel production in DHSs more reliable, other technology cases for biofuel production should be considered.

The thesis aims to identify measures which should be taken in DHSs in order to contribute to the development of the DHSs and other energy systems toward sustainability. An interesting extension of this work would be to investigate whether DH technology has the potential to remain an important part of a sustainable energy system. Suggested further work is therefore to backcast from a situation with a sustainable energy system within a sustainable society, and study which measures would be necessary to implement. The sustainable energy system would be characterized by a power sector completely based on renewable energy, substantial reduction of waste fuel amount available for DH production due to increased recycling, substantial reduction in DH demand due to the energy efficiency measures in the building sector, and an increased utilization of the excess heat from industrial processes.

Due to the DH demand variations, the supply temperatures in Swedish DHSs are usually higher during the winter (120 °C) and lower during the summer (71 °C). The lower supply temperature during the summer decreases the heat distribution losses in the system and enables increased electricity efficiency (power-to-heat ratio) in the system's CHP plants. As mentioned earlier in this thesis, COP of DH-driven absorption chillers is highly dependent on the DH supplier temperature. Moreover, most of the industrial processes which can be converted to DH require temperatures higher than 71 °C. Therefore, the

supply temperature in the DHSs during the summer must increase in order to make the implementations of these measures more profitable. In order to make the results from the studies which include these two business strategies more reliable, the effects of the changes in DH supply temperature (regarding the performance of the CHP plants and the heat distribution losses) should be included in the study.

The further work should also include analysis of other business strategies (besides integration of DH-driven absorption cooling technology in DHSs and increasing DH use in industrial processes) which may improve utilization of the DH production plants. Some of the possible business strategies are e.g. drying wet fuels (biomass) during the summer when the DH demand is low and introducing thermal energy storages into DHSs.

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Appended Papers

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