DISTRICT HEATING AND CHP
– LOCAL POSSIBILITIES FOR GLOBAL CLIMATE CHANGE MITIGATION

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Kristina Difs

To my beloved husband Fredrik

Abstract

Global warming, in combination with increasing energy demand and higher energy prices, makes it necessary to change the energy use. To secure the energy supply and to develop sustainable societies, construction of energy-efficient systems is at the same time most vital. The aim of this thesis is therefore to identify how a local energy company, producing district heating (DH), district cooling (DC) and electricity in combined heat and power (CHP) plants, can contribute to resource-efficient energy systems and cost-effective reductions of global carbon dioxide (CO_2) emissions, along with its customers. Analyses have been performed on how a local energy company can optimise their DH and DC production and what supply-side and demand-side measures can lead to energy-efficient systems in combination with economic and climate change benefits. The energy company in focus is located in Linköping, Sweden. Optimisation models, such as MODEST and reMIND, have been used for analysing the energy systems. Scenario and sensitivity analyses have also been performed for evaluation of the robustness of the energy systems studied. For all analyses a European energy system perspective was applied, where a fully deregulated European electricity market with no bottlenecks or other system failures was assumed.

In this thesis it is concluded that of the DH-supply technologies studied, the biomass gasification applications and the natural gas combined cycle (NGCC) CHP are the technologies with the largest global CO_2 reduction potential, while the biomass-fuelled plant that only produces heat is the investment with the smallest global CO_2 reduction and savings potential. However, the global CO_2 reduction potential for the biomass integrated gasification combined cycle (BIGCC) CHP and NGCC CHP, the two technologies with highest electricity efficiencies, is highly dependent on the assumptions made about marginal European electricity production. Regarding the effect on the DH system cost the gasification application integrated with production of renewable biofuels (SNG) for the transport sector is the investment option with the largest savings potential for lower electricity prices, while with increasing electricity prices the BIGCC and NGCC CHP plants are the most cost-effective investment options. The economic outcome for biomass gasification applications is, however, dependent on the level of policy instruments for biofuels and renewable electricity. Moreover, it was shown that the tradable green certificates for renewable electricity can, when applied to DH systems, contribute to investments that will not fully utilise the DH systems' potential for global CO_2 emissions reductions.

Also illustrated is that conversion of industrial processes, utilising electricity and fossil fuels, to DH and DC can contribute to energy savings. Since DH is mainly used for space heating, the heat demand for DH systems is strongly outdoor temperature-dependent. By converting industrial processes, where the heat demand is often dependent on process hours instead of outdoor temperature, the heat loads in DH systems can become more evenly distributed over the year, with increased base-load heat demand and increased electricity generation in CHP plants as an outcome. This extra electricity production, in combination with the freed electricity when converting electricity-using processes to DH, can replace marginal electricity production in the European electricity market, resulting in reduced global CO_2 emissions.

Demonstrated in this thesis is that the local energy company, along with its customers, can contribute to reaching the European Union's targets of reducing energy use and decreasing CO_2 emissions. This can be achieved in a manner that is cost-effective to both the local energy company and the customers.

Sammanfattning

Den globala uppvärmningen i kombination med ett ökat energibehov och stigande energipriser gör det nödvändigt att förändra energianvändningen. Energieffektiva system är samtidigt en förutsättning för att kunna säkra energitillförseln och utveckla hållbara samhällen. Fjärrvärme har en viktig roll att fylla i den här omställningen. I fjärrvärmesystemen kan värmeresurser som annars kan vara svåra att nyttiggöras, som till exempel spillvärme och förbränning av avfall tas tillvara. Fjärrvärme kan även bidra till elproduktion i kraftvärmeverk där totalverkningsgraden är högre än vid separat el- respektive värmeproduktion. En omställning av energisystemet till en ökad användning av fjärrvärme och minskad användning av el genom effektiviseringar och konverteringar från olja och el till fjärrvärme kan bidra till att skapa energieffektiva system.

Syftet med den här avhandlingen är att identifiera hur ett lokalt energibolag som producerar fjärrvärme, fjärrkyla och el i kraftvärmeverk kan bidra till att skapa energieffektiva system och kostnadseffektiva globala koldioxidreduktioner tillsammans med sina kunder. Det energibolag som framförallt har studerats i den här avhandlingen är Tekniska Verken i Linköping AB. För att optimera energibolagets fjärrvärme- och fjärrkylaproduktion har energisystemanalyser genomförts, där både åtgärder på tillförsel- och användarsidan har studerats. Genom att se energiförsörjningen ur ett systemperspektiv kan man undvika att ekonomiska och miljömässiga vinster vid en anläggning ersätts av förluster någon annanstans. Optimeringsmodeller, som MODEST och reMIND, har använts för energisystemanalyserna där även scenarier och känslighetsanalyser har inkluderats. För alla energisystemanalyser har ett europeiskt energisystemperspektiv använts där en totalt avreglerad europeisk elmarknad utan flaskhalsar eller andra systemfel antagits.

Slutsatser från analyserna är att det lokala energibolaget kan bidra till kostnadseffektiva globala koldioxidreduktioner genom ett effektivt nyttjande av bränslen i kraftvärmeanläggningar och i bioraffinaderier. Speciellt kraftvärmeanläggningar med hög elverkningsgrad, som t.ex. biomasseförgasning- och naturgaskombianläggningar, har en betydande global koldioxidreduktionspotential. Även biomasseförgasningsanläggningar som är integrerade med produktion av förnybara drivmedel för transportsektorn har visat sig kostnadseffektiva med stor potential att reducera de globala koldioxidutsläppen. Styrmedel har dock en stor påverkan på det ekonomiska utfallet för förgasningsanläggningarna.

Dessutom har studierna visat att energibesparingar kan åstadkommas genom att konvertera el- och fossilbränsledrivna industriella processer till fjärrvärme och fjärrkyla. Eftersom fjärrvärme framförallt används för lokaluppvärmning är värmelasten i fjärrvärmesystem säsongsbetonad. Genom att konvertera industriella processer som inte är utetemperaturberoende till fjärrvärme kan fjärrvärmelasten bli mindre säsongsbetonad och mer jämt fördelad över året. En jämt fördelad värmelast är fördelaktig för driften av fjärrvärmeanläggningar och kan bidra till mer elproduktion i kraftvärmeanläggningar. Den extra elproduktionen, tillsammans med den el som blivit tillgänglig efter konvertering av eldrivna processer till fjärrvärme, kan ersätta europeisk marginalelsproduktion vilket kan reducera de globala koldioxidutsläppen.

Det som har framkommit av dessa studier är att det lokala energibolaget, tillsammans med sina kunder, kan bidra till att uppfylla de mål den Europeiska Unionen har angående reduktionen av energianvändningen och koldioxidutsläppen. Dessutom kan detta ske på ett kostnadseffektivt sätt för både energibolaget och dess kunder.

Acknowledgement

List of appended papers

Paper I
Kristina Difs, Louise Trygg
Pricing district heating by marginal cost
Energy Policy, 37 (2009) 606-616, Elsevier

Paper II
Kristina Difs, Elisabeth Wetterlund, Louise Trygg, Mats Söderström
Biomass gasification opportunities in a district heating system
Biomass and Bioenergy, 34 (2010) 637-651, Elsevier

Paper III
Louise Trygg, Kristina Difs, Bahram Moshfegh
Absorption Cooling in CHP systems – old technique with new opportunities
Proceedings of the Xth World Renewable Energy Congress, Glasgow, Scotland, 21-25 July, 2008.

Paper IV
Kristina Difs, Maria Danestig, Louise Trygg
Increased use of district heating in industrial processes – Impacts on heat load duration
Applied Energy, 86 (2009) 2327-2334, Elsevier

Paper V
Kristina Difs, Louise Trygg
Increased industrial district heating use in a CHP system – economic consequences and impact on global CO_2 emissions
Proceedings of the 5th European Conference on Economics and Management of Energy in Industry, Vilamoura, Portugal, 14-17 April, 2009.

Paper VI
Kristina Difs, Marcus Bennstam, Louise Trygg, Lena Nordenstam
Energy conservation measures in buildings heated by district heating – A local energy system perspective
Energy, 35 (2010) 3194-3203, Elsevier

Paper VII
Kristina Difs
National energy policies: obstructing the reduction of global CO_2 emissions? An analysis of Swedish energy policies for the district heating sector
Accepted for publication in *Energy Policy*

Thesis outline

This thesis starts with an introduction of the field studied and continues with important background and assumptions related to the research papers. Thereafter, the methodology and cases studied are discussed. The thesis ends with a summary of the results from the appended papers and conclusions, as well as suggestions for further work.

Chapter 1 includes a brief introduction to the research field; in this section the importance of studies in this area is also discussed. In this chapter the hypothesis and research questions are stated, along with a brief description of the appended papers.

Chapter 2 provides an overview of district heating and combined heat and power, discusses their potentials and challenges, and describes policy instruments affecting the Swedish district heating sector. This chapter also includes a literature review of district heating studies.

Chapter 3 gives a short presentation of the European electricity market and barriers to its becoming a fully integrated market. This chapter also assesses the impacts of electricity supply and use.

Chapter 4 deals with CO_2 emission abatement instruments, such as the Kyoto Protocol and the European Union's emission trading scheme. The method used in this thesis to account for local and global CO_2 emissions is also described.

Chapter 5 discusses the methodology applied in this thesis.

Chapter 6 includes a description of the cases studied and a compilation of the energy prices used in the different studies.

Chapter 7 provides a summary of the results obtained from the research papers and an analysis of the results. The results are presented in order according to the research questions.

Chapter 8 discusses the research results and presents conclusions drawn from them. Last of all, some suggestions for further work are pointed out.

Chapter 9 contains references.

Abbreviations

AC	Absorption chiller
BIGCC	Biomass integrated gasification combined cycle
Bio CHP	Biomass-fuelled combined heat and power
Biofuel	Renewable transportation fuel
Bio HOB	Biomass-fuelled heat-only boiler
CC	Compression chiller
CCS	Carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
DC	District cooling
DH	District heating
ECM	Energy conservation measure
EU ETS	The European Union emission trading scheme for GHG
GHG	Greenhouse gases
HOB	Heat-only boiler
MIND	Method for analysis of industrial energy systems
MODEST	Model for optimisation of dynamic energy systems with time-dependent components and boundary conditions
NGCC	Natural gas combined cycle
TEP	EU tradable CO_2 emission permits
TGC	Tradable green certificates for renewable electricity
TPA	Third-party access
TVAB	Tekniska Verken Linköping AB (local energy company in Linköping)
SNG	Synthetic natural gas
Waste CHP	Waste-fuelled combined heat and power

TABLE OF CONTENTS

1. Introduction

This chapter includes a brief background and introduction to this thesis. The aim and research questions are stated, as well as the scope and delimitations. Furthermore, an overview is given of the appended papers in combination with a short summary of the papers and co-author statements. Other publications not included in the thesis are also presented in this chapter.

One of mankind's major environmental challenges today is to tackle anthropogenic global warning. In order to manage global warming, it is vital to reduce the emissions of greenhouse gases (GHG) by, for example, decreasing the use of fossil fuels and eliminating inefficient resource use. By an efficient utilisation of energy, both on the supply and demand sides, primary energy use can be reduced and hence also the emissions of GHG. Efficient use of resources is of utmost importance, since the population of the world puts higher demand on the biosphere than the earth can provide in terms of the area of biologically productive land and sea. The global ecological footprint, i.e. the land and sea area required to provide the resources needed and the area for assimilated waste is 2.7 global hectares (gha) per person, while the total productive area is only 2.1 gha per person. In Sweden the ecological footprint is over 5 gha per person (WWF, 2008).

The fourth assessment report from the Intergovernmental Panel on Climate Change (IPCC) states that 11 of the 12 years during 1995-2006 rank among the 12 warmest years of global surface temperatures since 1850. Furthermore, the global average sea level is increasing, while at the same time the Northern Hemisphere snow cover is decreasing (see Figure 1.1). IPCC also states that it is likely that the frequency of heat waves, heavy rainfall and high sea levels have increased in intensity and frequency for the past 50 years (IPCC, 2007).

The drivers of climate change are mainly the emissions of GHG and aerosols, changes in land cover and solar radiation, each of which has the potential to alter the energy balance of the climate system. From pre-industrial times the anthropogenic emissions of GHG[1] have steadily

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[1] The GHG considered are those covered by the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6).

been increasing; between 1970 and 2004 the anthropogenic GHG emissions increased by 70%. The most important GHG is CO_2, which represented 77% of the anthropogenic GHG emissions in 2004 (IPCC, 2007).

Changes in temperature, sea level and Northern Hemisphere snow cover
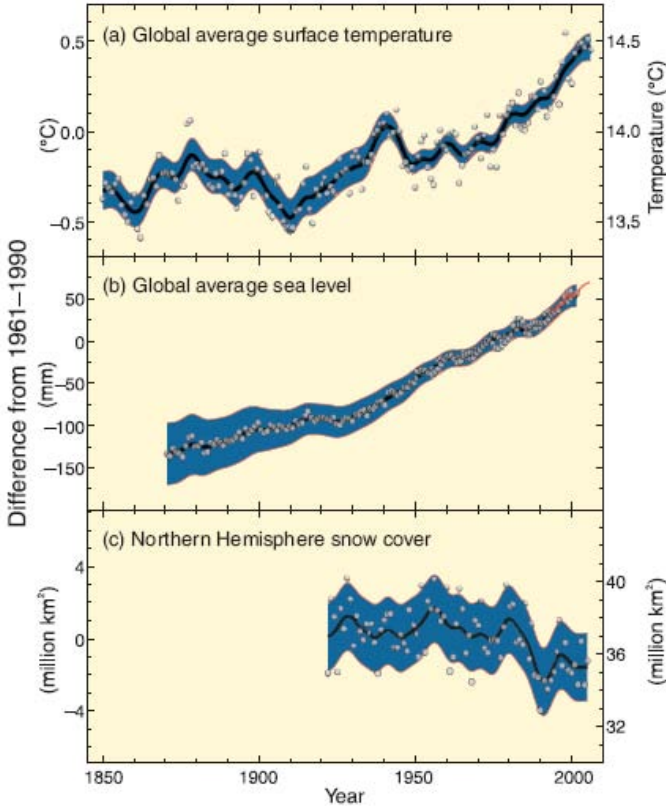
Figure 1.1. Observed changes in a) global average surface temperature; b) global average sea level from tide gauge (blue) and satellite (red) data; and c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from comprehensive analysis of known uncertainties (a and b) and from the time series (c) (IPCC, 2007).

For the European Union's 27 member countries (EU-27) the emissions of GHG were just above 5,000 million tonnes of carbon dioxide equivalent in 2007, of which almost 60% came from energy supply and use (see Figure 1.2). However, the combustion of fossil fuels represents 93% of the emissions of GHG in EU-27, where CO_2 accounts for 83% of the GHG emissions (EEA, 2009). Moreover, the International Energy Agency (IEA) predict that with current policies the energy demand of the world will be 40% higher in 2030 compared to 2007, and 77% of the energy demand increase will be supplied by fossil fuels. Additionally, they forecast that energy-related CO_2 emissions will increase by 40% in 2030 compared to

2007. Overall, this increase in energy demand and fossil fuel use will also lead to increased energy prices (IEA, 2009).
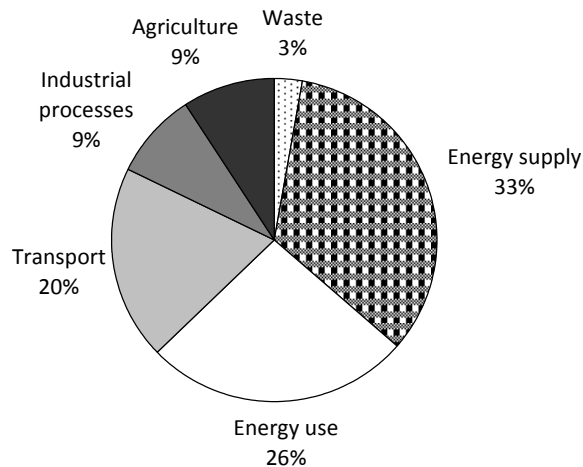
Figure 1.2. Total greenhouse gas emissions by sector for EU-27 in 2007 (EEA, 2009).

Thus, urgent measures are required to tackle this increase in energy use and CO_2 emissions. In the European Union (EU), targets have been established to reduce the emissions of GHG by, for example, increasing the energy efficiency and the share of renewable energy sources. One technology that has been identified by the EU as energy efficient is the combined heat and power (CHP) technology (EC, 2004). The CHP technology, which can be used in district heating (DH) systems for production of both heat and electricity, can utilise a variety of fuels and has higher overall efficiency than condensing power plants. Sweden has a well-built-out DH system that can be utilised for efficient electricity production in CHP plants. Although the utilisation of CHP plants in Swedish DH systems is relatively low, there are expansions plans, where the installed electricity output from CHP plants is predicted to increase by 40% between 2006 and 2015 (SDHA et al., 2008). At present, DH in Sweden is mainly used for space heating and domestic hot water in the residential and service sectors, where DH accounts for about half of the heating demand. On the other hand, for the industrial sector the utilisation of DH is almost unnoticeable, accounting for only 3% of the Swedish industrial energy use. Instead, electricity is extensively used in the industrial sector (SEA, 2009). From an economical viewpoint a reduction in industrial electricity use is essential. Since the deregulation of the Swedish electricity market in 1996 electricity prices have increased for Swedish industries. From January 1997 to January 2007 the electricity prices increased by 30-65%, depending on the size of the industry (SCB, 2008). Maintaining high electricity use will be unsustainable for Swedish industries, in terms of both economic and CO_2 aspects. Hence, there is potential for implementing energy efficiency measures and converting industrial processes, such as heating, cooling, drying etc., from electricity to DH for Swedish industries. Furthermore, decreasing the electricity use by conversion to DH will not only reduce electricity demand but could also lead to more electricity production if the DH is produced in CHP plants. In other words, conversion of electricity-using processes to DH has the potential to reduce the electricity demand while electricity production can at the same time increase in

CHP plants. When considering a fully deregulated European electricity market, the extra electricity produced in Swedish CHP plants and the electricity freed when converting industrial processes to DH can thus replace marginal electricity production in continental Europe.

In this thesis energy system analyses have been performed that take into account measures and investments applied on both the energy demand and supply sides. The analyses have included both the economic and global CO_2 aspects. The results from the studies can be used as decision support for the management of the local energy companies and for the industries, as well as for the design of policy tools.

1.1. Aim and research questions

The aim of this thesis is to identify how a local energy company, producing DH, district cooling (DC) and electricity, can contribute to energy-efficient systems and cost-effective reductions of global CO_2 emissions along with its customers.

The hypothesis is that in a local energy system, measures can be identified both for the local energy company and its customers that will lead to more energy-efficient systems in combination with cost-effective global climate change mitigation when using a European energy systems approach.

The hypothesis is evaluated in the following four research questions:

1. Which investments in a local DH system can lead to decreased global CO_2 emissions in combination with reduced costs for the DH system?

2. What effect will energy demand-side measures have on the local energy system in terms of energy usage, end-user energy costs and DH system costs, as well as on climate change mitigation potential?

3. How will the pricing of DH affect the DH system and its customers regarding end-user energy costs, DH system costs and global CO_2 emissions?

4. How do energy policy instruments influence the choice of investments in the DH sector and the reduction potential of global CO_2 emissions?

Table 1.1 illustrates which research questions are explored in which of the appended papers.

Table 1.1. Schematic overview showing in which appended papers the research questions are explored.

Research question	Paper
1	II, III
2	I, IV, V, VI
3	I, VI
4	II, V, VII

1.2. Scope and delimitations

The focus of this study is DH systems, where the term DH system corresponds to the whole DH arrangement, including production facilities, transmission and distribution networks, as well as subscribers. In particular the DH system in Linköping, which is managed by Tekniska Verken AB (TVAB), has been studied. A smaller study of E.ON's DH system in Örebro was performed in paper III. The technical measures of the DH systems were considered in combination with different fuel and electricity prices. A fully deregulated European electricity market with no bottlenecks or other system failures was assumed; thus, restrictions on power transmission capacity were not considered. Consequently, the electricity produced and utilised locally in Sweden is considered to affect the marginal source of electricity in Europe. Due to the fully integrated European electricity market, European electricity prices are assumed to level out to an equilibrium price, which in the long run is equivalent to the marginal cost of electricity production in the European electricity system. This will lead to increased electricity prices in Sweden with daily variations.

The industrial energy audits analysed in this thesis comprise small and medium-sized industries located in various municipalities in Sweden. For analyses of the residential energy demand, statistics about multi-dwelling buildings located in Linköping were considered.

For the climate impact only the emissions of CO_2 were considered, since they represent the major part of GHG emissions (see Introduction). Furthermore, biomass was regarded in this study as CO_2 neutral and the alternative use of biomass was not addressed, which of course can be a subject for discussion, see for example Holmgren et al. (2007) and Wetterlund et al. (2009).

1.3. Paper overview

This thesis is based on the following seven papers.

Paper I
Kristina Difs, Louise Trygg
Pricing district heating by marginal cost
Energy Policy, 37 (2009) 606-616, Elsevier

In this paper the focus is on how eight industrial customers, located in the Linköping area, can change their energy use by implementing energy efficiency measures and by converting electricity-using support processes to DH. Industrial energy audits were studied to analyse the industrial energy use. However, conversion to DH must always be an attractive choice; hence, the effect of electricity and DH pricing is also analysed in combination with a changed industrial energy use. Outcomes from the analyses show that the companies can reduce their annual electricity use by 30% when implementing energy efficiency measures and converting to DH. In the paper it is demonstrated that the industries can reduce their energy costs when converting industrial processes to DH and when marginal DH prices are applied. Furthermore, the effect of an increased DH demand for the DH supplier in Linköping, TVAB was analysed by using an optimisation model (MODEST). The study showed that the there could be reduced DH system costs along with reductions of the global CO_2 emissions when industries convert industrial processes to DH.

Paper II
Kristina Difs, Elisabeth Wetterlund, Louise Trygg, Mats Söderström
Biomass gasification opportunities in a district heating system
Biomass and Bioenergy, 34 (2010) 637-651, Elsevier

This paper analyses whether biomass gasification applications are economically interesting investments for DH systems. In this study the DH system in Linköping is modelled in an optimisation model (reMIND) along with different biomass gasification applications. The gasification applications are evaluated in six scenarios, employing two time perspectives – short and medium term. The scenarios differ in economic input data, technical system and investment options. Results from the study indicate that biomass gasification applications, such as biomass integrated gasification combined cycle (BIGCC) CHP and production of synthetic natural gas (SNG), can be profitable investments for the DH supplier. Besides being more cost-effective than conventional combustion technologies (biomass-fuelled CHP), biomass gasification applications can also contribute to a larger CO_2 emission reduction potential than the reference scenario without gasification applications. Moreover, with the biomass gasification applications the production of high value products (electricity or SNG) can increase. Which of the biomass gasification applications is the most profitable one is, however, dependent on the level of policy instruments for biofuels and renewable electricity.

Paper III
Louise Trygg, Kristina Difs, Bahram Moshfegh
Absorption Cooling in CHP systems – old technique with new opportunities
Proceedings of the Xth World Renewable Energy Congress, Glasgow, Scotland, 21-25 July, 2008.

In this paper the economic and climate impacts of implementing heat-driven absorption cooling in the DH system in Örebro, Sweden, are analysed. The optimisation model MODEST is utilised for the energy system analysis. When introducing absorption chillers (ACs) in the district cooling system the potential for increasing electricity production in the local CHP plants increases in combination to a reduction of the electricity use for existing chillers. With a projected increased cooling demand in combination with electricity prices corresponding to European electricity prices, the system costs can be reduced in combination with decreased global CO_2 emissions compared to the cooling system without ACs.

Paper IV
Kristina Difs, Maria Danestig, Louise Trygg
Increased use of district heating in industrial processes – Impacts on heat load duration
Applied Energy 86 (2009) 2327-2334, Elsevier

The aim of this paper was to find energy conversion measures that allow industrial processes to utilise DH instead of electricity or fossil fuels. In this paper the industrial processes that are potentially convertible to DH are mapped out and the effect on the DH heat load after the conversions is analysed. In the study 34 industrial energy audits and seven industrial cooling audits were examined in order to characterise the heat load profile for respective industry and process. It is concluded in the study that conversion of industrial processes to DH can result in a DH load profile that is less outdoor temperature-dependent and more evenly distributed over the year. Moreover, by converting processes to DH the industrial electricity and fossil fuel use

can be reduced in combination to an overall energy saving. Additionally, by converting electricity and fossil fuel-driven processes to DH the electricity production can potentially increase in CHP plants, which altogether can lead to reduced global CO_2 emissions.

Paper V
Kristina Difs, Louise Trygg
Increased industrial district heating use in a CHP system – economic consequences and impact on global CO_2 emissions
Proceedings of the 5th European Conference on Economics and Management of Energy in Industry, Vilamoura, Portugal, 14-17 April, 2009.

In this paper the heat load profiles obtained in Paper IV were utilised to analyse the effect on different DH systems when changing the heat load profile. Two perspectives have been applied, representing the DH heat load profile before and after converting industrial processes to DH. This change in DH heat load profile was analysed for three types of base load CHP plants, each utilising a different fuel (biomass, waste and natural gas). The DH system analyses were performed in MODEST. Moreover, five scenarios were employed to illustrate the effect of energy prices and policy instruments for the DH system when changing heat load profile. The changed heat load profile after implementation can increase the operating of the present CHP base load plants but can also make it possible to invest in larger CHP plants, which altogether can increase the electricity production in the DH system by almost 20%, regardless of the employed scenario. Moreover, a changed heat load profile has the potential to reduce the system costs as well as to reduce global CO_2 emissions.

Paper VI
Kristina Difs, Marcus Bennstam, Louise Trygg, Lena Nordenstam
Energy conservation measures in buildings heated by district heating – A local energy system perspective
Energy, 35 (2010) 3194-3203, Elsevier

This study focuses on how energy conservation measures (ECMs), implemented in multi-dwelling buildings heated by DH, will affect the energy costs and demand for the residences as well as the DH production and revenue for the DH supplier. The local energy system in Linköping was used as a case study. Three ECMs, all with specific and diverse heat load profiles, were included in the analysis: heat load control, attic insulation and electricity savings by changing to new household appliances. The capital costs of the ECMs and the changed energy costs due to implementation of ECMs were calculated for the residences. For analysis of the ECMs' effect on the local DH system the optimisation model MODEST was used. Besides analysing the changed heat load profile of the DH system when residences implement ECMs, the study explores the economic effect for the residences and the DH supplier as well as the effect on global CO_2 emissions when ECMs are implemented in the local energy system. Results from the study show that the electricity savings measure is the most beneficial measure, from both an economic and global CO_2 perspective. Attic insulation was shown not to be profitable to invest in for the local energy system.

Paper VII
Kristina Difs
National energy policies: obstructing the reduction of global CO$_2$ emissions? An analysis of Swedish energy policies for the district heating sector
Accepted for publication in *Energy Policy*

This study analyses the effect national energy policy instruments have on investments in Swedish DH systems. In this study national energy policy instruments, such as energy taxes and tradable green certificates for renewable electricity production (TGC), are included as well as the EU emission trading scheme for GHG. The local DH system of Linköping was modelled in MODEST and the effect of the policies was analysed for three plant investments: biomass-fuelled CHP (bio CHP), natural gas-fuelled combined cycle CHP (NGCC CHP) and biomass-fuelled heat-only boiler (bio HOB). Results from the study indicate that national energy policies, such as the TGC, can contribute to investments that will not fully utilise the DH systems' potential for global CO$_2$ emissions reductions. However, the CO$_2$ emission reduction potential is highly dependent on the assumptions made about the marginal electricity production technology in use in Europe.

1.4. Co-author statement

In Paper I the author of this thesis did the model simulations, analysis of the results and wrote most of the paper except a section of the introduction. Louise Trygg contributed with discussions and valuable comments on the paper.

Paper II was planned and written by Elisabeth Wetterlund and the author of this thesis. Elisabeth Wetterlund was responsible for most of the modelling, but the results were analysed together and the model development was a joint work. Elisabeth Wetterlund wrote the part about biomass gasification and the scenarios, whereas the author of this thesis was responsible for the section about the DH system and the collection of input data for the DH system. All authors contributed with discussions and comments on the paper.

In Paper III the author of this thesis did the modelling and analysis of the results as well as wrote about the case study, method (except the first part of the method) and the results. Concluding discussions were written in collaboration with Louise Trygg. All authors contributed with discussions and comments on the paper.

Paper IV was planned by the authors together, where the author of this thesis was responsible for the development of the method and also wrote most sections except part of the introduction and the concluding discussions, which were written jointly. All authors contributed with discussions and comments on the paper.

The author of this thesis was responsible for the model run as well as the writing of Paper V. Louise Trygg commented on the paper.

Paper VI was a collaboration between the Division of Energy Systems at Linköping University and the local district heating supplier in Linköping, TVAB. Marcus Bennstam had the main responsibility for the modelling, whereas the author of this thesis structured the study, collected input data for the multi-dwelling buildings, analysed the results and wrote the paper. All authors contributed with discussions and comments on the paper.

1.5. Other publications not included in the thesis

Trygg, L., Difs, K., Wetterlund, E., Thollander, P., Svensson, I-L. Optimala fjärrvärmesystem (Optimal district heating systems). Report No 2009:13, Swedish District Heating Association, 2009.

Wetterlund, E., Difs, K., Söderström, M. Energy policies affecting biomass gasification applications in district heating systems, First International Conference on Applied Energy (ICAE 09), 5-7 January 2009, Hong Kong.

Difs, K. Revised structure for energy recovery from agricultural, waste and the wastewater sectors in the GAINS model, YSSP Interim Report, IIASA, Laxenburg, 2008.

Difs, K. Kraft att förändra – En studie om miljövärdering av el (Power to change – A study of the environmental assessment of electricity), Karlsson, M. and Palm, J. (eds.), Omställning för uthållighet – essäer om energisystem i utveckling. Arbetsnotat nr 34, Programme Energy Systems, Linköping University, 2007.

Difs, K. Energisystemmodellen MODEST – ett verktyg för analys av energisystem (The energy system model MODEST – A tool for analysis of energy systems), Karlsson, M. and Palm, J. (eds.), Att analysera system – reflektion och perspektiv. Arbetsnotat nr 35, Programme Energy Systems, Linköping University, 2007.

2. District heating and CHP

This section starts with a short introduction to district heating, district cooling and combined heat and power (CHP). After that challenges and potentials for district heating and CHP are discussed, along with the heat load duration and pricing of district heating. Economic policy instruments presently affecting the Swedish district heating sector are also pointed out. The section ends with a literature review of district heating studies.

The energy demand in the residential and service sectors corresponds to over one-third of the Swedish energy use. Of the energy demand for the residential and service sectors over 60% is used for space heating and domestic hot water. The most common heating applications for space heating and domestic hot water for the residential and service sectors are illustrated in Figure 2.1, where DH is shown to be a common space heating alternative, especially for multi-dwelling buildings and the service sector. Overall, in 2008 Swedish DH delivery was about 48 TWh, where 60% was delivered to multi-dwelling buildings and houses, 30% to the service sector and 10% to industries (SEA, 2009).
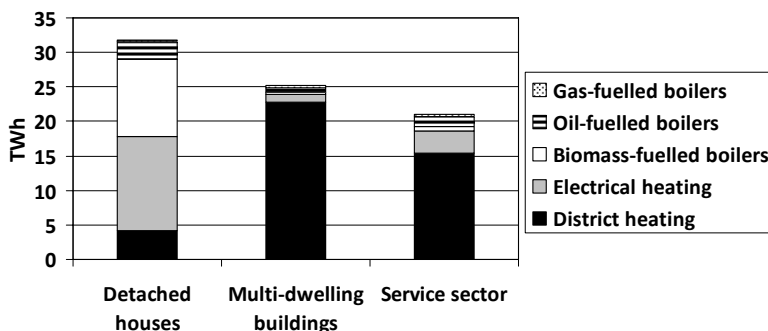
Figure 2.1. Heating applications utilised for space heating and domestic hot water in Sweden, 2007 (SEA, 2009).

In a DH system a hot medium, often water, is distributed in pipelines for supplying cities and other densely populated areas with heat. The medium is heated, for water to about 70-120°C, in large production facilities that are situated in one or several places near the distribution system. DH is mainly utilised for space heating and domestic hot water but can also be utilised in industrial processes. For the Nordic countries DH is a common heating option, but DH is also widely spread in East Europe and Russia. There are other regions where DH exists, such as North America, parts of Western Europe and China. In Sweden DH was already on the agenda in the beginning of the 20th century, but it took until 1948 before the first DH system was built in Karlstad (Fredriksen and Werner, 1993).

Besides distributing a hot medium, cold water can also be distributed in pipelines for cooling purposes. District cooling (DC) was first introduced in 1992 in Sweden when the city of Västerås developed a DC network. DC can be supplied from, for example, free cooling (sea and river water), compression chillers (CCs) or heat-driven absorption chillers (ACs), or a combination of the three technologies (SEA, 2009). In heat-driven ACs the compressor has been replaced by a generator and absorber, which reduce the required amount of electricity considerably compared to CCs. ACs require a water temperature of about 70-150°C (SDHA, 2007), which makes them suitable to incorporate in a DH system. DC is mostly used for air conditioning in the service sector and is hence predominantly concentrated in the city centre. This can be noticed in Stockholm, which has one of Europe's largest DC networks. In 2008 the DC production in Sweden was about 0.8 TWh, which is an increase of 13% compared to 2007 (SEA, 2009).

To construct a DH system a production facility, a distribution network and subscribers are required. In the production facilities, which can be fuelled by different fuels such as biomass, oil or coal, the water is heated and depending on the facility even converted to steam with high temperature and pressure. The most commonly used DH production facilities are heat-only boilers (HOB), CHP plants and electricity-driven heat pumps. Industrial waste heat can also be utilised in a DH system if the industrial facility is relatively close by. For a schematic overview of how the different DH plants operate during the year, see Figure 2.2, where the heat load duration curve for a DH system is illustrated. The base load DH plants are in this example waste incineration plants or industrial waste heat. Base load plants have low operating costs due to inexpensive fuels, which make them suitable for long operating hours. The higher up in the heat load curve, the more expensive are the fuels, where electricity and oil-fuelled boilers cover the peak loads. Heat loads in DH systems are further discussed in section 2.2.
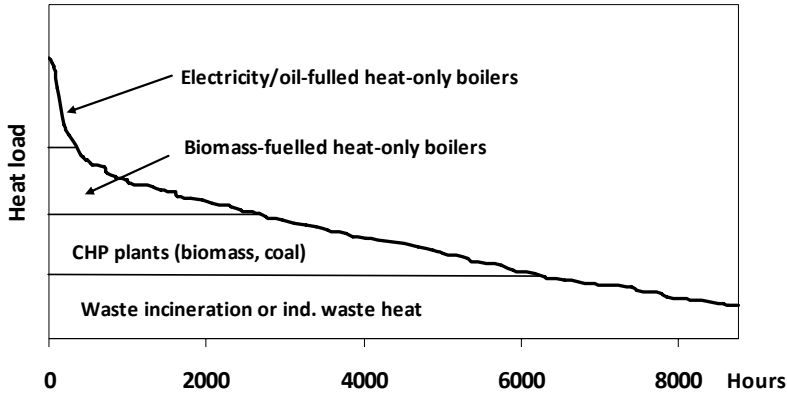
Figure 2.2. Schematic heat load duration curve for a DH system including different DH plants.

CHP plants, which cover base and seasonal heat loads, produce both heat and electricity and are consequently an energy-efficient technology for electricity production compared to condensing power plants. However, CHP plants require a DH system that can utilise the excess heat. Even though CHP is an energy-efficient technology, Swedish DH systems have a relatively low proportion of CHP plants compared to other countries. In 2008 the share of DH supplied by heat from CHP plants was about 47% in Sweden (SDHA, 2008), which can be compared to Denmark and Finland, where the share of DH supplied by heat from CHP plants is 80% (Energiateollisuus, 2010; ENS, 2008). The low share of heat from CHP plants in Swedish DH systems can be explained by the nuclear programme in the 1970s, which resulted in overbalanced electricity production and hence made the DH systems electricity consumers, utilising heat pumps and electric boilers, instead of electricity producers (SEA, 2009). Consequently, the types of plants supplying DH have changed since the introduction of DH systems in Sweden. The main fuel used in the beginning was heavy oil (90% of the energy supplied) but after the two oil crises in the 1970s and 1980s the DH plants were converted to instead handle solid fuels such as biomass and coal (SEA, 2009). Today, biomass, peat and waste constitute over 70% of the energy supplied to the Swedish DH plants, see Figure 2.3. The high share of renewable and non-fossil energy sources has resulted in the low local CO_2 emissions of 72 kg/MWh DH from the Swedish DH plants (Euroheat & Power, 2010).
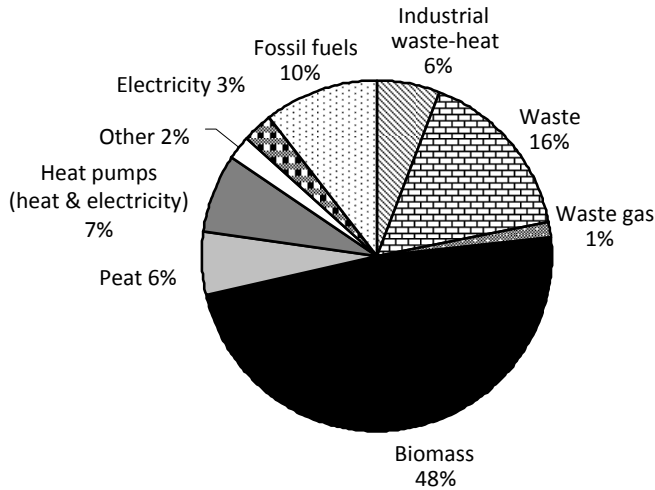
Figure 2.3. Supply of fuels and electricity for heat and CHP production in Swedish district heating systems in 2008 (SDHA, 2008).

2.1. Challenges and potentials for district heating and CHP

DH has many benefits compared to local heating systems utilising small-scale boilers. In a DH system the production facilities are large units that are placed centrally, which results in higher efficiencies and hence less usage of primary energy as well as better flue gas cleaning compared to locally placed boilers. DH systems can also contribute to electricity production if the DH system contains CHP plants. Moreover, DH production facilities have better fuel flexibility and can utilise poorer, less clean fuels (such as waste and recycled wood) than the locally placed boilers. DH plants can also benefit from economy of scale, which results in lower specific heating costs for DH plants than for smaller boilers. However, there are drawbacks to DH. The construction of the DH distribution network requires substantial underground work which will have impacts on a city's functioning and is capital intensive. The distribution networks also have heat losses of about 10%, which lowers the efficiencies. In addition, one of the most important aspects for the DH customer to consider is the lack of influence on their heating supply, for example, the customer has no say regarding price increases. If the DH supplier decides to increase the DH price the customer has little influence on this unless the DH customer chooses to change heating system or implement measures to reduce the DH demand (Fredriksen and Werner, 1993).

Today, the DH distribution systems in Sweden are natural monopoly markets, but this can change if third-party access (TPA) is implemented. If TPA is introduced the DH distribution networks will open up for competition and as a consequence, any company with heat to deliver will be able to access the DH distribution network to sell heat to DH customers. TPA would make DH systems similar to the deregulated electricity market, where the customer can choose who to buy electricity from. An introduction of TPA for the DH systems could affect the pricing of DH since the natural monopoly would dissolve, and by exposing the DH market to competition the DH prices could potentially be lowered. On the other hand, introducing TPA could affect the operation of CHP plants negatively and the incentives to invest in new CHP plants and the distribution network could decline. Consequently, there are some aspects

to consider before introducing TPA for the DH systems; TPA is currently under investigation by the Ministry of Enterprise, Energy and Communications (MEEC, 2009).

Other challenges that the DH suppliers face are reduced heat demand due to implementations of energy conservation measures (ECMs), the building of low-energy houses and the warmer climate (Carlson, 2009). The EU has, for example, set targets to increase energy efficiency where a directive promoting energy efficiency in buildings has been established (EC, 2002). In Sweden there is considerable room for ECMs in the building sector, since little has been done since the oil crisis in the mid 1980s (Nässén and Holmberg, 2005). Hence, if energy and DH prices are starting to increase, ECMs might be implemented in the building sector, which will affect the sales of DH. However, raising the DH prices may not be an effective way of increasing profit, since an increased DH price will in the long term lead to implementation of energy efficiency measures that will also affect the operation of CHP plants and electricity production. A study by Werner (2009) has shown that the long-term price elasticity of DH can result in a profit that is only half of the price increase, especially if the DH systems contain CHP plants.

Since the residential heating demand can be reduced due to ECMs and warmer climate, it is important for the DH supplier to focus on new applications where DH can be utilised. Since DH is mainly used for space heating, the heat load in DH systems is strongly dependent on seasonal variations. Hence, the heating demand during the summer months is relatively low compared to the winter months, and therefore technologies such as heat-driven absorption cooling could be interesting options for the DH supplier. By introducing DC networks or locally placed absorption cooling machines driven by DH, the heat demand can increase mainly during the summer months, which could increase the operation of base load plants such as CHP plants. Furthermore, by introducing DH in industrial processes, heat demand can increase. This increase in heat demand is not primarily season dependent but rather dependent on the processes and operating hours of the industry. Table 2.1 lists industrial production and support processes that potentially could be converted to DH. However, the processes that can be converted to DH are dependent on several conditions, such as required temperature levels, process design and location. Also, by installing household appliances such as dishwashers and washing machines that run on DH the heat demand can increase. These measures could have a positive effect on the operation of the DH plants by increasing the base load. By converting electricity-using processes to DH, the resource utilisation could be reduced as well as the emissions of CO_2.

Table 2.1. Production and support processes potentially convertible to DH.

Production processes	Support processes
heating	space heating
drying/concentration	space cooling[a]
cooling[a]	hot tap water

[a] DH-driven absorption cooling

DH systems could also be suitable to incorporate with various types of biorefineries. DH systems could, besides distributing heat and electricity, also be integrated with, for instance, lignocellulosic ethanol production. With the introduction of biorefineries and polygeneration in DH systems, the overall efficiencies could increase due to the exchange of resources, see for example Leduc et al. (2010) and Starfelt et al. (2010). DH systems could also be integrated

with other production processes requiring heat or steam, such as drying biomass feedstock for producing pellets (Wahlund et al., 2002). Moreover, by introducing biomass integrated gasification combined cycle (BIGCC) CHP plants in the DH system, the power-to-heat ratio could increase compared to conventional biomass steam turbine plants. An introduction of biomass gasification in a DH system could also lead to production of valuable transportation fuels based on biomass, such as Fischer-Tropsch diesel, dimethyl ether or synthetic natural gas (Börjesson and Ahlgren, 2010).

2.2. Heat load duration

The challenges and potentials mentioned in the previous section can result in very different effects on the heat load of the DH systems. The heat load of the DH system, i.e., how the total DH demand of the consumers varies over the year, determines how the DH plants are operated but also what type of investments should be made. If, for example, ECMs such as insulation and replacement of windows are implemented in the building stock, the peak heat demand will be affected, which in turn can change the operation of DH plants. A decreased heat demand will decrease the operation of DH plants, but depending on what measures are implemented the operation of CHP plants can also be influenced, with decreased electricity production as a result. Reductions in the operation of HOBs or heat pumps are positive, since these plants only produce heat. However, reduced electricity production in CHP plants can be counterproductive since electricity production in less energy-efficient condensing power plants in continental Europe, which only produce electricity and where the heat is wasted, can instead increase.

However, by converting industrial processes and household appliances, such as washing machines and dishwashers, to DH in combination with implementation of DH-driven absorption cooling and combinations of DH systems and biorefineries the heat demand can instead increase. Besides the increase in heat demand by conversions of these applications to DH, the profile of the heat load duration curve can change, since the heat demand of these applications is not outdoor temperature-dependent. This can lead to an increased base heat load which can, in the long term, result in the potential to invest in larger CHP plants. This conversion to DH can hence lead to more electricity production in the present CHP plants but also in the potential future, bigger CHP plants.

2.3. Pricing of district heating

As mentioned in section 2.1, the pricing of DH is important for the implementation of demand-side measures. In a report from Avgiftsgruppen (2009) the costs of different heating alternatives are compared, among them DH. In the report a typical multi-dwelling building[2] was "moved" around in the Swedish municipalities to evaluate the costs for heating, electricity, water etc. From this study it is concluded that in the municipalities that supply DH, 10% of the DH suppliers have increased the DH prices by at least 30% in the last five-year period (2003-2008). Furthermore, if the DH price for this typical building is compared to the heating costs of alternative heating sources (including capital costs), such as biomass-fuelled (pellet) boilers and heat pumps, the outcome shows that it is profitable to change to the alternative heating sources in 40% of the municipalities with DH (Avgiftsgruppen, 2009). It can be complicated to compare DH prices between different DH suppliers since the pricing systems are very dissimilar, but this could be an indication that Swedish DH suppliers need to

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[2] A multi-dwelling building of 1000 m^2 with 15 apartments and an annual DH demand of about 0.2 GWh.

examine the DH pricing system. The pricing structure of Swedish DH system varies, where pricing structures of 3-4 components are common. Usually the pricing structures consist of a variable heating cost, a flow cost and an additional fixed charge, but other components such as seasonal price setting could also be included in the price structure (SDHA, 1999). According to Fredriksen and Werner (1993) the pricing structure of DH should:

- be competitive
- be predetermined
- be easy to understand
- cover the costs
- be designed to give correct price information

However, it can be complex to combine all these requirements. To design a pricing structure that gives correct price information to the customers, the variable heating cost should be based on the factual marginal DH costs. Such a price structure would give the DH customers an indication of what the costs are for increasing or decreasing DH usage. The marginal costs for one DH production facility can easily be calculated based on the fuel price and plant efficiency, but since most DH systems contain several plants with different operating hours, the marginal costs can be difficult to estimate and the costs can also vary over the year (Fredriksen and Werner, 1993). For CHP plants there is also the issue of allocation of joint costs, depending on what the by-product of CHP generation is (electricity or heat). For example, Sjödin and Henning (2004) suggest that heat should be considered the main product since a DH system has a DH demand to fulfil. Then the heat costs are calculated as the DH production costs less the value of produced electricity. Hence, with an ideal price structure of DH where the variable heating costs are based on the factual marginal costs, it can be difficult for the customer to predetermine the DH costs. Therefore, the variable heating costs are sometimes divided into seasonally dependent tariffs (Fredriksen and Werner, 1993).

2.4. *Economic policy instruments affecting the district heating sector*

The economic policy instruments discussed in this section are (1) the energy taxes, such as energy, CO_2 and sulphur taxes which are applied on fossil fuels and the NO_x levy, (2) tradable green certificates for renewable electricity (TGC), (3) the European Union emission trading scheme for GHG (EU ETS) and (4) grants for conversion of heating systems. Besides economic policy instruments there are also other policy instruments such as administrative policy instruments, information and research activities, but these policy instruments are not considered here.

National energy taxes were originally introduced to finance the public spending requirements. In recent years there has on the other hand been a shift, and now the energy taxes are also used to control the supply and utilisation of energy, in order to achieve energy and environmental policy goals. However, taxes still contribute to a large part of the Swedish state finances; in 2008, the revenue from energy taxes constituted almost 9% of the Swedish state revenue (SEA, 2009).

In order to control the supply of energy, and in particular to promote indigenous electricity production, there are several tax exemptions for production. For example, there are no energy and CO_2 taxes applied to electricity production, only to heat production. The tax exemptions

on electricity production are explained by electricity use is taxed instead, while there is no tax on heat use. On the other hand, heat produced in CHP plants has tax exemptions just as the heat produced in industrial facilities does (see Table 2.2).

Table 2.2. Energy tax levels for heat and electricity production (SEA, 2009).

Production	Tax levels (%)		
	Energy tax	**CO_2 tax**	**Sulphur tax and NO_x levy**
Heat[a]	100	100	100[c]
CHP heat	0	7[b]	100[c]
Industrial heat	0	7[b]	100[c]
Electricity	0	0	100[c]

[a]Heat from heat-only boilers.
[b]For facilities covered by the EU ETS.
[c]Depending on the production facility.

In addition to the taxes there is also a nitrogen oxide (NO_x) levy, which was implemented in 1992 for stationary plants producing more than 25 GWh heat and/or electricity annually. This levy is fiscally neutral. The assimilated fees are repaid to the plant operators in proportion to their production and NO_x, meaning that only the plants with highest NO_x emissions are net payers (Ministry of the Environment, 1990).

Energy taxes have been part of the Swedish policy instruments for some years now, but a relatively newly implemented policy instrument is the TGC, which was implemented in 2003. The TGC system is a market-based system supporting the production of electricity from renewable energy sources[3] and peat. As the system is constructed it will be in force to 2030 and its aim is to increase electricity production from renewable energy sources and peat by 17 TWh between 2002 and 2016. The government has suggested an expansion plan for the system where the goal is to increase the electricity production from renewable energy sources by 25 TWh by 2020. One certificate is issued per MWh of electricity produced from approved electricity suppliers; the certificates are then traded between the suppliers and the consumers, who are required to buy certificates in relation to a certain proportion (quota) of their electricity use. The quota obligation varies during the period of the certificate system to increase the demand for certificates and to enhance the incentives for renewable electricity production. Newly approved electricity suppliers will receive certificates for 15 years, whereas approved electricity production plants put into operation before 1 May 2003 will receive certificates to the year 2012 or 2014 (SEA, 2009; Swedish Parliament, 2003). A number of European countries have established some sort of support system to increase renewable electricity production. These support systems include feed-in tariffs, variants of certificate systems and various tax incentives (SEA, 2008a).

However, the TGC seems to promote mature technologies, such as biomass-fuelled CHP, since the production costs are lower for mature technologies than for newer technologies, such as wind power and solar energy (Wang, 2006). From the start of the certificate system in 2003 the electricity production from biomass fuels has increased by over 5 TWh from 4.2 TWh to 9.6 TWh, which is almost four times more than the increase in electricity production from wind power (SEA, 2009). Hence, the implementation of TGCs has changed the fuels

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[3] Wind power, solar energy, geothermal energy, certain biomass fuels and certain hydropower.

utilised in the DH systems, where biomass and peat presently represent the majority (see Figure 2.3).

Furthermore, the EU has established the ETS for GHG in order to meet the goals in the Kyoto protocol[4]. The EU ETS was introduced for the member countries in 2005 and the scheme is based on grandfathering, where the allocation of tradable emissions is distributed according to historical emissions (EC, 2003b). The idea of implementing the EU ETS is to cost-effectively reduce the emissions of GHG, since the EU ETS will promote measures where the mitigation cost is lowest. The EU ETS is further discussed in section 4.1.

Finally, the Ministry of Enterprise, Energy and Communications (MEEC) has implemented grants for conversion of heating systems. The grant presently affecting the DH sector is the one for conversion of resistance heating in residential buildings (MEEC, 2005). The grant has been established in order to decrease the use of electricity for heating proposes and consequently to enhance the energy efficiency for heating applications. It will continue to the end of 2010. For example, in detached houses about 5 TWh electricity was used for resistance heating in 2007 (SEA, 2009). In the ordinance (MEEC, 2005), grants are available for those converting their resistance heating systems to DH, heat pumps and biomass-fuelled boilers.

2.5. Related literature

DH systems have been analysed in numerous previous studies, some of which are briefly discussed in this section. Since the studies performed in this thesis have focused on Swedish DH systems and their conditions, mainly studies analysing Swedish DH systems are included in this section. These studies are included to provide an understanding of what has been performed in this research area as well as to provide context for this thesis. Many of the studies contributed with valuable input for the analyses performed in this thesis. Since the optimisation model MODEST has been used in this thesis for analyses of DH systems, previous studies where MODEST has been utilised are included as well.

Some of the earlier works that focus on Swedish DH systems are, for example: Werner (1984), Gustavsson (1994a; 1994b) and Henning (1997; 1998; 1999). In Werner (1984) daily heat loads in six Swedish DH systems were analysed. By using daily heat load observations a heat load model was developed that can be utilised for simulation of various heat loads and also for analysis of the impact different measures have on the heat load. Werner has also co-authored a textbook on DH that includes the DH production facilities, heat load, distribution system, and economic as well as historical aspects (Fredriksen and Werner, 1993).

The energy conservation potential for five district-heated buildings of three types (industrial, school and residential) was analysed in Gustavsson (1994a). In the study the cost of conserved energy is related to the avoided costs for DH production for different scenarios (with and without energy taxes and capital costs for investments). Results from the study indicate an energy-conservation potential of 30-60% of final energy use. While Gustavsson (1994a) focuses on the energy conservation potential for buildings, Gustavsson (1994b) analyses the impact of the ECMs for the DH system of Lund, Sweden. Gustavsson concludes that ECMs in buildings heated by DH can lead to higher utilisation of base load DH plants if additional buildings are also connected to the DH system. Other conclusions from the study are that biomass-fuelled CHP plants in combination with ECMs can contribute to reduced CO_2

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[4] The goal is a GHG reduction of 8% for EU-15 from 1990 to 2008-2012.

emissions compared to production systems based on fossil fuels where no ECMs have been implemented. Other studies where Gustavsson has examined energy conservation and energy efficiency in buildings are for example Gustavsson and Joelsson (2007) and Joelsson and Gustavsson (2008; 2009).

Henning has used the energy system optimisation model MODEST for analysing different DH systems. The MODEST model has thoroughly been described in Henning (1997; 1999). In Henning (1998) the MODEST model was used for analysing a municipal electricity and DH system, where the electricity demand can be reduced by ECMs, load management and when replacing electric heating. In the study the profitability of load management and CHP is analysed with and without heat storage for different electricity prices. Conclusions from the study are that heat storage could be used to cover heat demand peaks, increase CHP production and run heat pumps during the night when the electricity price is lower.

Additional studies where MODEST has been used for analyses of DH systems are, for example, Danestig (2009), Gebremedhin (2003), Sjödin (2003), Sundberg (2001) and Trygg (2006). In Danestig (2009) MODEST was used for several analyses of DH systems, such as assessment of the CHP potential for the DH systems in Stockholm and evaluation of the benefits from cogeneration in Örnsköldsvik for the local DH system, which is a cooperation between the local DH supplier and a pulp industry. She concludes that there is a significant CHP potential in the DH systems in Stockholm, which also can lead to a potential reduction in CO_2 emissions. Overall, Danestig shows that heat demands in DH systems can be seen as a resource that can contribute to resource-efficient systems and climate change mitigation. The main focus in Gebremedhin's thesis is regional and industrial cooperation in DH systems; the energy system analyses were performed with MODEST (Gebremedhin, 2003). By using a systems approach and extending the system boundaries he concludes that cooperation between different DH systems and industries is an unexploited potential, which can lead to more energy-efficient heat supply systems. Sjödin (2003) used MODEST to analyse Swedish DH systems in combination with a fully integrated European energy market. Sjödin's main focus has been on the supply side of DH and assessment of CO_2 emissions. He demonstrates in his thesis that CHP generation in Swedish DH systems can reduce global CO_2 emissions. Sundberg (2001) analyses, with the help of MODEST, what technical and economic parameters are the most important when investing in a CHP plant for a DH system. The conclusion from the analyses is that the factors that affect the CHP investment the most are: fuel prices, taxation, operation and maintenance costs, electricity price, investment cost and overall efficiency. Trygg (2006) uses MODEST for analysing the cooperation between an industry and a local DH system, for assessment of absorption cooling in Norrköping and for evaluating the impact on the national power supply when reducing electricity use in Swedish industry. The study shows, among other things, that cooperation between an industry and a local DH system can reduce the energy system cost by half in combination with global CO_2 reduction potential.

Other studies worthy of mentioning regarding heat supply and demand are Karlsson et al. (2009), Knutsson (2005) and Rolfsman (2003). Karlsson et al. and Knutsson have a heat supply perspective, while Rolfsman considers both the heat supply and demand perspectives. In Karlsson et al. (2009) the economic potential of creating a regional heat market, consisting of three industrial plants and four energy companies, is studied. Results from the study indicate that by connecting the separate units to a larger energy system, economic profit can be achieved. Depending on the scenario the payback times vary between 2 and 11 years.

Moreover, by combining the units CO_2 emissions can be reduced. Knutsson analyses to what extent the Swedish DH sector can fulfil the Swedish and international energy policy targets. With help of the developed simulation tool HEATSPOT, the Swedish DH systems' response to various policy instruments was studied (Knutsson et al., 2006a). Knutsson concludes that the Swedish DH sector has great potential for CHP generation and that the combination of TGCs and the EU tradable CO_2 emission permits (TEPs) almost doubles the renewable electricity generation in Swedish CHP plants (Knutsson, 2005). Rolfsman (2003) focuses on the energy systems of buildings and their impact on the surrounding energy system. All studied buildings are located within a DH network; thus, measures applied to the buildings will affect the DH system. Measures applied include wall insulation, new windows and the introduction of heat pumps. He also compares the life cycle cost of applying demand-side measures relative to investments on the supply side. In his results he concludes that when it comes to implementing measures there is a conflict between the present DH tariff and a tariff based on short-range marginal costs.

Some studies have evaluated, among other things, the environmental aspects of DH systems. The assessment of CO_2 emissions for DH systems is discussed in Grönkvist et al. (2003). Grönkvist et al. (2003) analyse four models for assessing the net CO_2 emissions: marginal coal, limited biofuel, price flexibility and marginal new technology. Included in all models are the local CO_2 emissions from the DH plants and the CO_2 emissions originated from emission sources influenced by the project in question. In the study it is demonstrated that the choice of model is crucial for assessing the net CO_2 emissions; depending on the model selected, the results can vary considerable. Torchio et al. (2009) analyse energy and environmental aspects for DH systems, where not only CO_2 emissions are considered but also other pollutants, such as SO_x, NO_x and particulate matter. The study analyses the energy and environmental impacts of replacing local heating systems (natural gas and oil boilers) in a town in Northern Italy with a DH system with natural gas-fuelled CHP plants. Conclusions reached in the study are that not only can the primary energy use and the CO_2 emissions be reduced, but the other pollutants as well when substituting the local heating systems with DH. Eriksson et al. (2007) performed life cycle assessment of fuels for DH, where waste incineration and combusion of biomass and natural gas were included. In the study both CHP production and DH production alone were considered. The study shows that biomass utilised in CHP plants can be considered the most environmentally favourable technology and that waste incineration is usually preferred over landfill disposal of waste. However, the study indicates that recycling is a better choice than incineration. Natural gas fired in CHP plants can be an interesting alternative when the marginal electricity production is fossil fuel intensive, yet if the marginal electricity production is fossil fuel lean, biomass is a better option. The study also showed that the fuels waste and natural gas are very sensitive to external factors (waste management and energy policies), while biomass utilised in CHP plants is less sensitive to these factors.

Other studies not focusing on Swedish DH systems relevant to mention are, for example, Grohnheit and Gram Mortensen (2003), Lund et al. (2010), Rentizelas et al. (2009), Rosen et al. (2005) and Xu et al. (2009). Grohnheit and Gram Mortensen (2003) discuss the liberalisation of DH systems and analyse competition in the space heating market, where TPA and unbundling between heat producers, transmission and distribution companies for DH systems are included. Grohnheit and Gram Mortensen conclude that a community policy will be needed for support of the infrastructure required to increase CHP production. The community policy should include a framework of conditions for DH distribution networks compatible with national traditions of regulation of real property. They further suggest

creating a community policy that supports and regulates the development of procedures for international tendering for operation of DH networks. In Lund et al. (2010) an energy system analysis of Denmark's energy system was performed in order to evaluate the impact of different heating alternatives on the fuel demand, costs and CO_2 emissions. In the study DH and different individual heating alternatives were evaluated in the present energy system as well as in the potential future energy system, where the energy system is converted to 100% renewable energy sources. Results from the study are that the best solution, both in the present and in the future energy system, is to combine a gradual expansion of DH with individual heat pumps in the rest of the areas. Rentizelas et al. (2009) analysed the financial and GHG emissions impacts for a biomass district energy trigeneration system producing heating, cooling and electricity, located in Greece. The trigeneration system contains a biomass-fuelled CHP plant and ACs. Results from the study showed that the trigeneration system can achieve a GHG emissions reduction of almost 80% compared to a cogeneration system, due to longer operating hours. The trigeneration system is also financially favourable to the cogeneration and electricity only systems. Rosen et al. (2005) studied a district energy system in Edmonton, Canada, where DH and DC are supplied. Rosen et al. performed an efficiency analysis, including both energy and exergy analyses, of producing DC in CCs and examined both single-effect and double-effect ACs. From the analysis it is concluded that exergy analyses provide important insights into the performance of the overall system efficiency compared to energy analysis. Exergy analysis can identify the locations and causes of inefficiencies more accurately than energy analysis for systems containing different forms of energy, such as district energy systems producing electricity, heat and cooling. The development of a combined cooling, heating and power (CCHP) system in China was analysed in Xu et al. (2009). An analysis of combining the CCHP system with a desalination plant was also performed. Xu et al. conclude that CCHP systems will be important supplements to large-scale centralised power systems in China and that by extending distributed systems there is potential to reduce coal consumption and CO_2 emissions. Compared with the single system, the CCHP system with desalination has an annual energy saving ratio of over 30%.

3. The deregulated European electricity market

This chapter begins with an introduction to the deregulated European electricity market and points out the barriers to a fully integrated electricity market. Next, the assessment of electricity production regarding environmental aspects is discussed, along with present and potential future marginal electricity production.

The European Union has had a deregulated electricity market since 1 July 2004 for non-household customers and since 1 July 2007 for all customers. The objective of a common and deregulated electricity market for the member countries was to construct a competitive, secure and environmentally sustainable market in electricity (EC, 1996, 2003a, 2009c). However, the member countries have adopted the electricity market directives to various extents. For example, the Nordic countries have had a common electricity market, Nord Pool, for some years now. Norway was first to deregulate their electricity market and on 1 January 1996 Norway and Sweden established a common electricity market and power exchange. In 1998 Finland was integrated and in 2000 the Nordic market was complete when the last part of Denmark was integrated. Nord Pool accounts for over 70% of the total value of electricity consumption in the Nordic market (Nord Pool, 2010a). Other countries and regions have achieved market integration to a lesser extent. Even though the traded volumes on the power exchange markets are increasing, investments in cross-border and internal power transmission capacity must be realised in order to achieve a fully integrated market (EC, 2009a).

3.1. Obstacles to a fully integrated electricity market

The full potential of a common deregulated European electricity market has not yet been recognised, since there are still obstacles to overcome before a completely integrated market can be achieved. A report from the European Commission on a study of the progress in creating an internal electricity and gas market states that the electricity market is far from fully integrated and that there still exist national and regional electricity markets (COM, 2008). For example, several member countries have still not implemented the existing legislation (the second internal market package). In particular, core aspects of market

deregulation, such as effective separation of supply and production activities (unbundling), regulatory oversight and abolition of regulated supply tariffs, have not been carried out. Furthermore, the lack of market integration has resulted in, for instance, price differences, regional monopolies and continual cross-border congestion. Regarding the price differences, the electricity prices are starting to converge for industries, especially in central and northwestern EU, but there are still areas where the difference is over 100% (COM, 2008). The differences in electricity price for companies are demonstrated in Figure 3.1.
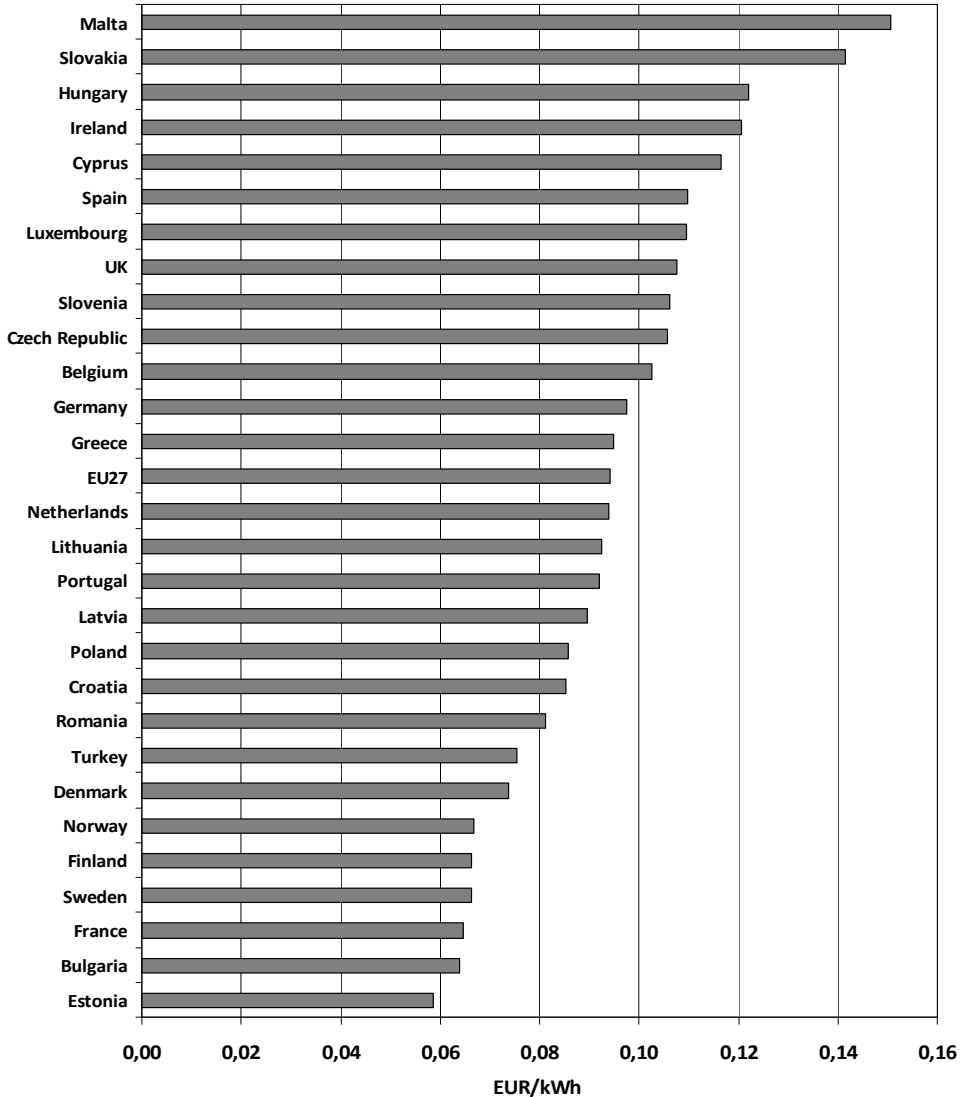

Figure 3.1. Electricity prices (without taxes, first half-year prices in 2009) for companies with an electricity consumption of 500 MWh – 2,000 MWh (Eurostat, 2010).

One solution to the problem of price differences is to increase the power transmission capacity, both nationally, within the countries, as well as transnationally. Concluded in the report is that the transnational power transmission capacity in relation to installed capacity is below 10% in five member countries and between 10% and 30% in an additional 10 member countries. Moreover, the concentration in the market structure on a national scale is still very high, with a few dominant suppliers, many also in control of the infrastructure, which further increases their market power. Unbundling has hence not yet been implemented effectively: in about half of the member countries power supply and production have thus far not been separated (COM, 2008).

To come to terms with these obstacles that prevent the electricity market from becoming fully integrated, the EU has launched a third legislative package (EC, 2009c, d). In this package the Commission proposes:

- effective separation of supply and production activities (unbundling)
- independent and effective national regulators
- promotion of cross-border collaboration and investment
- greater market transparency on network operation and supply
- cooperation between transmission system operators
- implementation of an Agency for Cooperation of Energy Regulators (ACER)
- increased solidarity among the EU countries

In the legislative package the EU has addressed the fundamental issues and in March 2011 the new legislative package will come into force. It is expected that with the implementation of this package a fully integrated European electricity market can be a reality in the future.

3.2. Assessing impacts of electricity supply and use

Assessment of environmental impacts when changing electricity utilisation is important in order to grade and compare alternative courses of action. The emissions from electricity can be hard to comprehend since there are often no signs of emissions where the electricity is utilised. Electricity production, including fuel extraction and transportation, can however give rise to considerable emissions and impacts on the environment, depending on the electricity production technology. The EU member countries have different electricity production technologies; consequently, the GHG emissions from power production vary. For instance, in Sweden only a minor share of the electricity production is based on fossil fuels, so the GHG emissions from this sector are low. On the other hand, electricity used in Sweden can be produced in Germany or Denmark, where the use of fossil fuels for electricity production is dominant, due to Sweden's power transmission connections with surrounding countries (see Figure 3.2) and the deregulation of the European electricity market. The Swedish transnational power transmission capacity exceeds 8,000 MW (Nord Pool, 2010b), which can be related to the total installed electrical production capacity in Sweden of nearly 35,000 MW (SCB, 2010). Hence, the transnational transmission capacity constitutes almost 25% of the Swedish installed electrical capacity. In 2009 the maximum power supply output was about 23,500 MW, the maximum power import was about 4,000 MW and the maximum power export about 4,500 MW (SvK, 2009). Consequently, due to the transnational transmission capacity, changing electricity production and use in Sweden has the potential to affect electricity production in the European electricity market.

Regarding the assessment of impacts for changed electricity production and use, many suggestions and methods for how to evaluate the environmental impacts have been considered. For example, Sjödin and Grönkvist (2004) discuss different methodologies for how to assess electricity production and use. Assessments according to eco-labelled electricity, average electricity production and marginal electricity production will be discussed in this section, as well as the time perspective. Depending on how the system boundaries are drawn for the electricity market studied, i.e. if Sweden, Nord Pool or the European electricity market are considered as the electricity market, the CO_2 emissions from average and marginal electricity production vary extensively. The CO_2 emissions from electricity production can vary from 20 kg CO_2/MWh for average Swedish electricity production up to almost 1000 kg CO_2/MWh for marginal electricity production in Europe (Engström et al., 2009). There is no consensus on how to assess changes in the electricity production and use but, for example, the Swedish Environmental Research Institute (IVL) recommends that the marginal electricity production method is used (Engström et al., 2009) and the Swedish Energy Agency (SEA) used the marginal method for assessing electricity use in its report about assessment of CO_2 emissions in energy utilisation (SEA, 2008b). In the following sections the different methods of assessing the impacts of electricity production and use will be discussed.
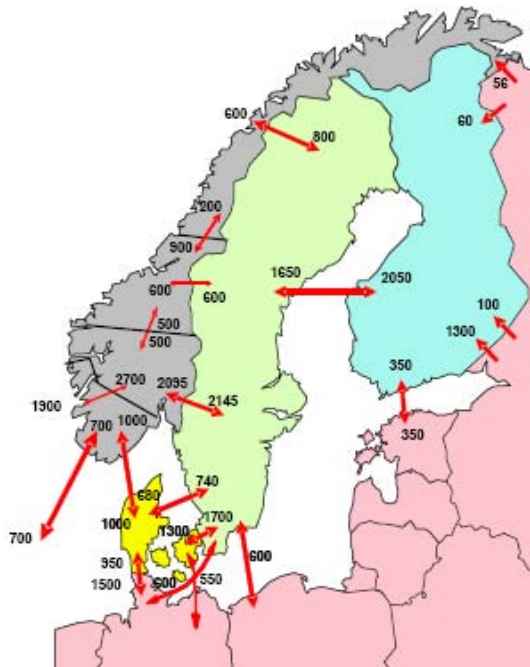

Figure 3.2. Power transmission capacities, in MW (Nord Pool, 2010b).

3.2.1. Origin of electricity and eco-labelled electricity

Electricity suppliers offer customers a variety of alternatives regarding the choice of electricity production technologies. Swedish electricity customers can, for example, choose to

buy only wind, hydro or nuclear power or CO_2-neutral electricity. The price difference for choosing these alternatives varies for different companies as well as for the alternatives. For instance, at E.ON and Vattenfall hydropower can be chosen free of charge, but Fortum charges extra for hydropower. However, Fortum offers CO_2-neutral electricity at no extra cost (EON, 2010; Fortum, 2010; Vattenfall, 2010). When the customer decides to buy production-specific electricity, the amount and type of electricity is registered for this specific customer. Nonetheless, this electricity would have been produced anyway; in the short term, there are no extra value or environmental benefits for choosing this production-specific electricity (Gode et al., 2009).

On the other hand, electricity customers can choose to buy electricity that is eco-labelled with The Swedish Society for Nature Conservation's (SSNC) "Good Environmental Choice" (Bra Miljöval). In order to acquire the eco-labelling, the electricity must come from renewable energy sources, such as hydro, wind, wave and solar power, or from combustion of biomass or biogas. Another criterion that has to be fulfilled is that a maximum of 10% non-renewable energy can be used during the life cycle of the eco-labelled electricity for extraction, transportation etc. Furthermore, the electricity supplier must finance different environmental projects related to hydropower, renewable power and energy efficiency (SSNC, 2009). Consequently, when the electricity customer chooses to buy electricity that is eco-labelled or chooses to buy shares in wind-power projects that invest in new wind-power plants, there can be environmental benefits and progress in the power system (Gode et al., 2009).

3.2.2. Average electricity production

When using the average electricity production method, the environmental impacts for all electricity production technologies for a defined area are accounted for. Some spokespersons think that this is the most rational method to use since all electricity utilisation should bear the responsibility for the last produced unit of electricity. Besides, it is uncomplicated to obtain electricity statistics for a certain area and hence a summarisation of all environmental effects for electricity production can be considered but, on the other hand, it can be complex to decide where to draw the boundaries for the electricity system (Engström et al., 2009).

However, when using the average electricity production method changes in the electricity use can be difficult to account for. In the average electricity production method a reduction in the use of electricity assumes a reduction in production in all power plants by the same amount, hence also the base power plants. Consequently, the use of average electricity production is recommended for accounting records where the total amount of emissions is calculated for a certain area and not when assessing the environmental impacts due to changed electricity production and use (Gode et al., 2009; Sköldberg et al., 2006).

3.2.3. Marginal electricity production

For the marginal electricity production method, the last production unit is assumed to be affected by an increase or decrease in the electricity demand. In a well-functioning market production should always be covered by the production technology with the lowest marginal costs. In Figure 3.3 the merit order curve for the total power production in the Nordic electricity system is illustrated, where the production technologies are arranged according to their increasing marginal costs. Different supply curves are also included to demonstrate the dependence on water supply. The graph shows the merit order over one year; since some of the power technologies are more flexible, they can change their production according to electricity prices and hence the merit order can be adjusted. Since the electricity demand varies continuously, the marginal production technology can vary during the year. On an

annual basis the marginal source of electricity in the Nordic electricity system is presently coal condensing power (SEA, 2008b; Sköldberg et al., 2006). However, when considering a longer time perspective additional production technologies can be included and hence the technology used for the build-margin must be integrated for a comprehensive study of the future electricity system. The build-margin technology has been studied in, for example, Axelsson et al. (2009) and Sköldberg and Unger (2008). Since the marginal electricity production technology in the future depends on the electricity system of today as well as the build-margin it is difficult to estimate the long-term marginal electricity production technology. Natural gas combined cycle (NGCC) condensing power plants, efficient coal condensing power plants, renewable electricity and power plants with carbon capture and storage (CCS) are some potential future marginal electricity production sources.
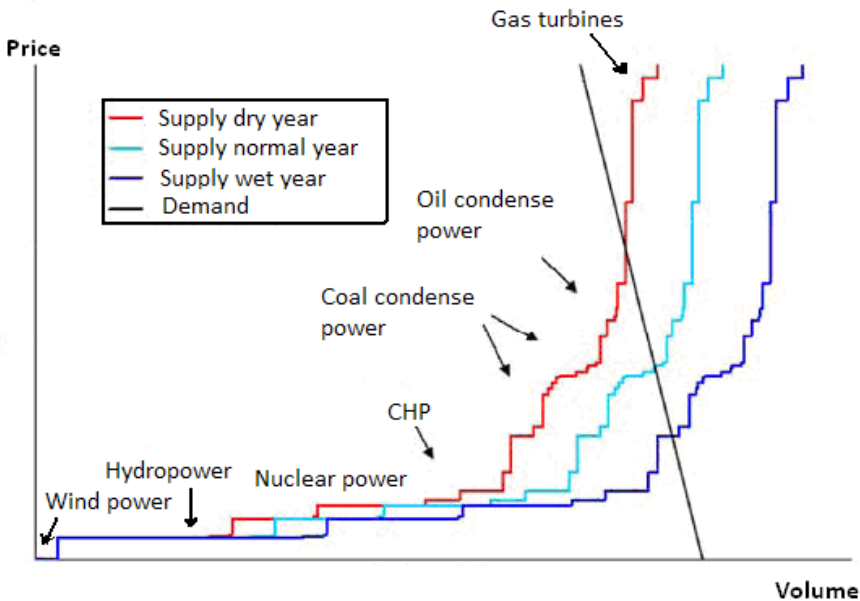
Figure 3.3. Merit order curve for power production in the Nordic electricity system, with a variety of supply curves (translated from Sköldberg et al. (2006)).

Assessing electricity production according to the marginal electricity production method is a commonly used approach; see for example Danestig et al. (2007), Knutsson et al. (2006b), Trygg and Karlsson (2005) and Wahlund et al. (2004). This method is also recommended when performing studies of changed electricity production and use (Dotzauer, 2010; Engström et al., 2009; Gode et al., 2009; Sköldberg et al., 2006). This method has also been applied in this thesis when accounting for CO_2 emissions from changed electricity production and use.

4. CO$_2$ emission abatement and accounting instruments

The following section raises the important subject of mitigation of greenhouse gases and consequently CO$_2$ emission abatement and accounting instruments, such as the carbon emission trading schemes initiated by the Kyoto Protocol and the European Union, are discussed. Next the calculation method for local and global CO$_2$ emissions used in this thesis is stated and the CO$_2$ emissions from changed electricity production and use are demonstrated.

Since pre-industrial times the global atmospheric concentration of CO$_2$ has increased from 280 ppm to 379 ppm in 2005 and the annual CO$_2$ concentration growth rate for the years 1995-2005 was 1.9 ppm (IPCC, 2007). Hence, in order to reduce the CO$_2$ emissions and curb the atmospheric concentration of GHG, CO$_2$ emission abatement instruments, such as the Kyoto market mechanism and emission trading schemes, must be implemented and applied on a global scale.

4.1. The Kyoto protocol and the European Union emission trading scheme

In 1997 the Kyoto Protocol was adopted in Kyoto, Japan, but it took until February 2005 before the Protocol entered into force. To date 184 parties have ratified the Protocol, which calls for binding targets of an average GHG emission reduction of 5% of 1990 levels over the five-year period 2008-2012. For the EU the GHG emission reduction is 8% of 1990 levels for the period 2008-2012. Each country has its own national GHG emission reduction target and these targets should primarily be met by national measures. However, there are three additional mechanisms included in the Protocol to help achieve the targets: (1) international emission trading (IET), (2) a clean development mechanism (CDM) and (3) joint implementation (JI). With the IET, countries that have excess emission allowances can sell the allowances to countries deficient in emission allowances. Both the CDM and JI are project-based mechanisms. CDM enables countries that ratified the Protocol to invest in sustainable development projects that reduce GHG emissions in countries without quantified commitments, i.e. generally the developing countries. JI is joint GHG reduction investments in countries that have ratified the Protocol. These market-based mechanisms are creating a

carbon market where CO_2 emissions can be reduced in a cost-effective way. This carbon market was worth 30 billion USD in 2006 and this market is growing (UNFCCC, 2010).

In the European Climate Change Programme the EU ETS is the most important climate policy instrument. Three periods have been established for the EU ETS (2005-2007, 2008-2012 and the post-Kyoto protocol). The EU ETS is an EU internal market where CO_2 emissions are traded, a so-called cap and trade system, i.e. there is a cap for the overall CO_2 emissions allowed and within that limit the participants can buy and sell allowances as they require. All of the 27 member countries take part in the EU ETS and a national allocation plan, assessed and approved by the Commission, is stated for each respective country. When considering all the member countries' allocation plans the cap for the entire EU can be determined. The emission reduction targets are a 20% reduction in GHG emissions by 2020 and a 50% reduction in GHG emissions by 2050 compared to the 1990 emission levels (EC, 2009b).

The majority of allowances in EU ETS were also allocated free of charge in the first and second periods, but from 2013 full auctioning will be implemented. However the auctioning will come with many exceptions. From the beginning of the EU ETS in 2005 only selected sectors were included, such as the energy sector and energy-intensive industries but in a newly developed directive there were suggestions to also include air and sea traffic when the second period ends in 2012 (EC, 2009b). When only including the original sectors about 40% of the GHG emissions in EU are covered; for Sweden that figure is 35%. Additionally, in the first period only CO_2 emissions were included but some countries have extended the EU ETS to also include nitrogen oxides in the second period (SEA, 2009).

As mentioned previously, the EU ETS is currently in its second period, which will continue until 2012. Studies have analysed the outcomes from the first period, which ended in 2007. One conclusion that can be drawn is that the allowance prices have varied tremendously, from under 1 euro to over 30 euro per tonne of CO_2 (see Figure 4.1). Since the allowances in the first period were distributed rather generously, the allowance prices were expected to be low. No obvious reasons can be recognized for the high allowance prices. However, the price crash in April 2006 can most likely be explained by the emission verification which revealed that the 2005 emissions were below the cap (Hintermann, 2010). The volatility of the allowance prices has led to hypothesis that electricity producers, with their market power, can act strategically and hence influence the prices of the allowances (Jaehn and Letmathe, 2010).
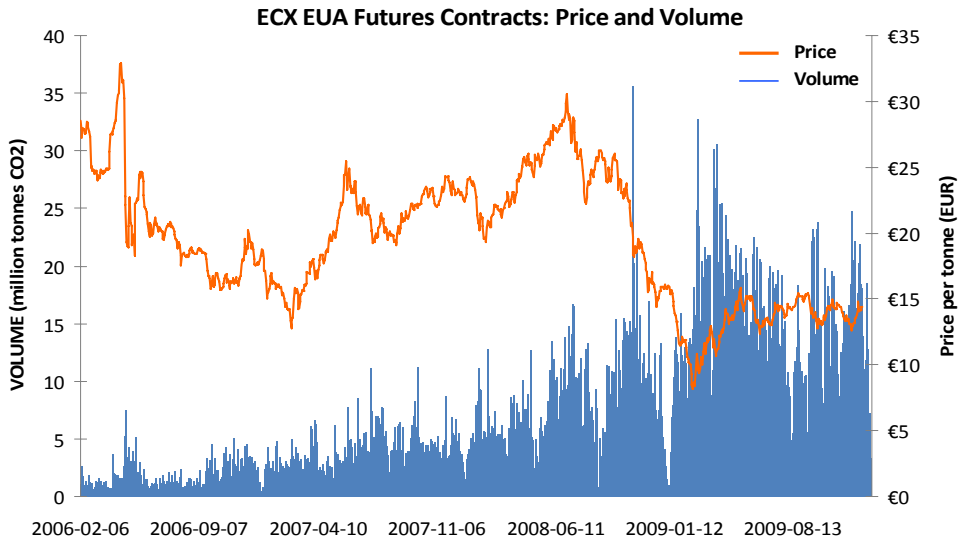
Figure 4.1. EU emission allowance prices (orange line) and volume (blue bars) (ECX, 2010).

Furthermore, a study of 221 companies that are included in the Swedish emission trading sector examined the potential problems with making informed decisions, which are vital for an efficient emission trading scheme. Results from the study show that more than half of the respondent companies believe that the routines of the EU ETS could be simplified and that few companies seem to take an active interest in the trading of the allowances. The lack of interest in the allowance market could be explained by the fact that many companies have an allowance surplus and that the allowances had no initial cost. However, half of the respondents considered the impact of the EU ETS as a key issue when taking long-term decisions and that the long-term price of allowances is very important or important for their investments. Moreover, management plays a central role in the company's allowance administration, which indicates the EU ETS importance and status. The introduction of the EU ETS has raised awareness of the importance of reducing GHG emissions. Many companies have already taken action or plan to take action to reduce GHG emissions, but surprisingly this has been done without close attention to the market mechanism (Sandoff and Schaad, 2009).

The importance of an emission trading scheme has also been noted in the USA. In a survey conducted by Point Carbon, 90% of the US respondents thought that the USA will introduce a GHG cap-and-trade system by 2015. In addition, even though the respondents of Point Carbon's survey forecast instability in the carbon market and the climate policy in the near-term they are confident in a well-functioning GHG emission trading market in the medium to long term, with a long-term equilibrium carbon price (Point Carbon, 2009).

Consequently, there are still imperfections in the carbon market, but this is a relatively recently implemented system with large potential. In order to minimise information asymmetry Jaehn and Letmathe (2010) recommend that regular reporting of actual emission levels should be implemented. They also propose that limitations in banking allowances and restrictions in the validity of allowances can prevent negative side effects of market failures. In a study conducted by Schleich et al. (2009) it is stated that the allowance budget for the

second period for the EU ETS is 13% lower than the historical emissions in 2005 and the budgeted emission for the first period. Thus, the emission cap for the second period in the EU ETS is much stricter than for the first test period. With a tightening cap and price stability on the allowances, incentives for an efficient carbon market can be projected. The market can also be extended to include more countries and additional emissions and sectors. More important, the emission trading scheme has put the abatement of GHG on the agenda, and the scheme also enables cost-efficient reduction of GHG and on the contrary of taxes, a set target for GHG reductions. As of 2008 the current progress towards reaching the EU-15 Kyoto target was 6.2% below the base-year emissions, see Figure 4.2. However, the financial crisis may have had an impact on the reduction of GHG for 2007-2008.
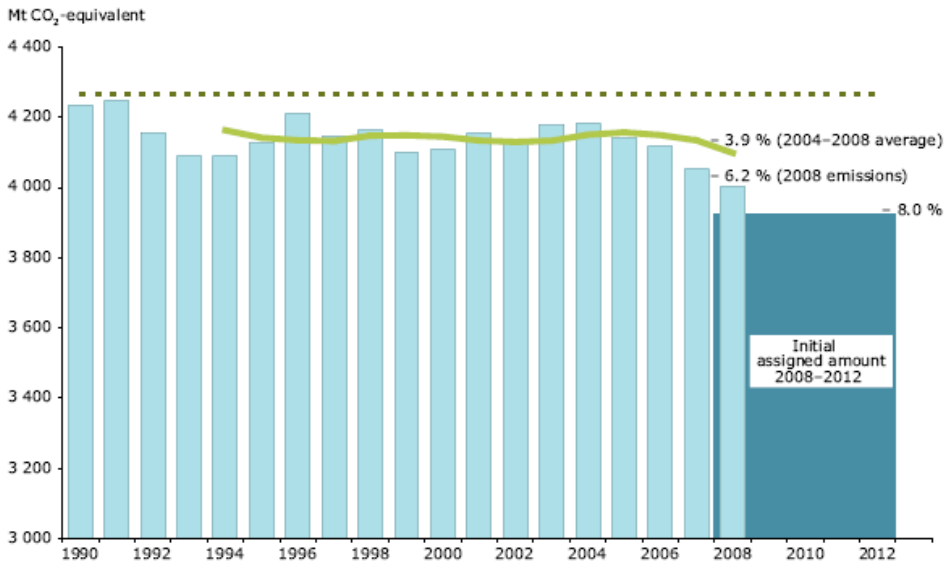
Figure 4.2. Current progress towards EU-15 Kyoto targets, where the bars are annual values and the green line is a five-year average plot (EEA, 2009).

4.2. Assessment of local and global CO₂ emissions

Since the emissions of CO_2 have a global effect, the impact of CO_2 emissions should be assessed with a system perspective and an extension of the system boundaries. When calculating the CO_2 emissions from changed energy demand, the system boundaries must not be too narrow, only including the local and region area. Instead the system boundaries should be extended to also include the European electricity system. Hence, it is important to include not only the local CO_2 emissions due to changed DH production and use but also the potential effect on global CO_2 emission due to changed electricity production and use. In this thesis the net effect on global CO_2 emissions due to changed use and production of electricity and DH for a specific region has been calculated as:

$$Net\ global\ CO_2\ emissions = \underbrace{\sum_{k=1}^{n} \Delta DH_k F_k}_{local\ CO_2\ emissions} + \underbrace{(\Delta Electricity_{use} - \Delta Electricity_{CHP})F_{electricity}}_{global\ CO_2\ emissions}$$

where ΔDH_k is the change in DH production (including plant efficiencies) for the specific fuel k and F_k is the fossil CO$_2$ emissions for that specific fuel (see Table 4.1), $\Delta Electricity_{use}$ is the change in electricity use while the $\Delta Electricity_{CHP}$ is the change in electricity production in the CHP plants and $F_{electricity}$ represents the fossil CO$_2$ emission factors for European electricity production. Due to the deregulated European electricity market the change in electricity production and use in Sweden is assumed to affect the European marginal electricity production (see section 3.2).

Table 4.1. Fossil CO$_2$ emission factor for fuels (life-cycle emissions; Uppenberg et al (2001)).

Fuel	Fossil CO$_2$ emission factor (kg CO$_2$/MWh)
Waste	90[a]
Coal	340
Biomass	N/A[b]
Natural gas	220
Oil	300

[a] CO$_2$ emissions from fossil-based fraction of waste.
[b] Biomass is considered to be CO$_2$ neutral, since the IPCC guidelines do not include CO$_2$ emissions from biomass in the national totals of GHG emissions (IPCC, 2006).

Consequently, when assessing the CO$_2$ emissions for different heating alternatives it is vital to also include the impact on the European electricity system. The net global CO$_2$ emissions for some heating alternatives can be viewed in Figure 4.3, where the European marginal source of electricity is assumed to be coal condensing power, with a fossil CO$_2$ emission factor of about 1000 kg/MWh of electricity (electricity efficiency of 0.33). The black bars represent the local CO$_2$ emissions for the different heating alternatives, whereas the red bars illustrate the total global CO$_2$ emissions (including local CO$_2$ emissions), when the electricity produced by the CHP plants has been accounted for. Hence, when considering the marginal European electricity production, the produced heat from resistance heaters affects the net global CO$_2$ emissions by over one kg per kWh heat even though the local CO$_2$ emissions in Sweden from resistance heaters are nonexistent. As can be seen in the figure, CHP contributes to none or negative net emissions of global CO$_2$ because the electricity generated in the CHP plants is considered to replace marginal European electricity production.
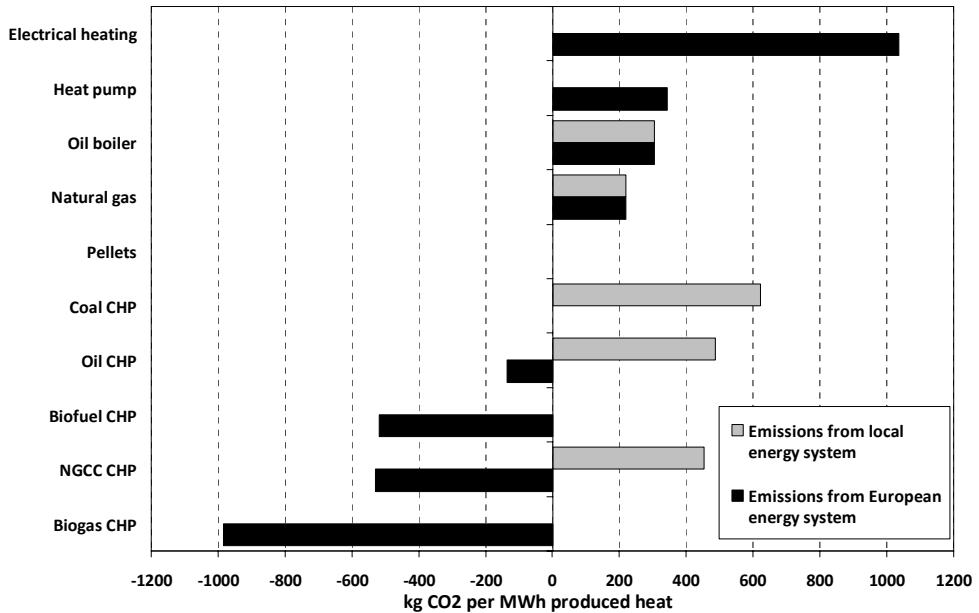
Figure 4.3. Net global CO₂ emissions per MWh produced heat (red bars) for different fuels and technical solutions when coal condensing power is marginal electricity production in the European electricity system (Werner, 2001; Werner and Karlsson, 2010).

4.2.1. CO₂ emissions from changed electricity production and use

In this thesis the marginal electricity production method has been applied where different marginal electricity production technologies were considered. In the short term coal condensing power was used as the marginal electricity technology. The EU recommends using a default coefficient for electricity generation of 2.5, which corresponds to an average EU electricity generation efficiency of 40% (EC, 2006). However, since it is the coal condensing plant with the poorest efficiency that is last to be utilised, an electricity efficiency of 0.33 was assumed, which releases about 1 tonne of CO_2 per MWh electricity produced (Sjödin, 2003). Over the longer term different power production technologies were assumed, normally NGCC condensing power but also efficient coal condensing power plants and coal condensing with CCS (Paper II and Paper V). All changes in electricity production and use were assessed according to the equation in section 4.2 but with various fossil CO_2 emission factors for European marginal electricity production.

Since the EU has established a cap for emissions in the emission trading scheme for GHG, reduced CO_2 emissions from the energy sector can lead to increased CO_2 emissions somewhere else in the system. However, the net global CO_2 emission calculations performed in this thesis estimate the potential reduction. In the short term reduced electricity use might not lead to reduced global CO_2 emissions, unless there is an oversupply of the emission allowances. But in the long term the electricity reduction measures implemented today can have an effect on the future prices of allowances, on technology development and hence on the future emission cap (Gode et al., 2009).

5.   Method

This section includes a presentation of the methods used in this thesis, first discussing the systems approach and system boundaries as well as the climate change mitigation perspective. After that, the basis for industrial energy audits is explained. Finally, the structure of energy system modelling is outlined, along with a discussion about sensitivity analysis.

5.1. Systems approach

When evaluating complex energy systems such as DH systems, it is important to consider both the components obviously included (DH plants, DH customers, fuels, distribution networks etc.) and surrounding elements and their interactions with the DH system. System theory or the systems approach has been discussed in, for example, Ingelstam (2002), where some of the most prominent researchers and spokesmen in this field are portrayed. There is no universal definition of system theory or consensus on how a system should be defined. Ingelstam (2002), however, defines a system as follows: a system (a) includes components and the relationships between them; (b) has a set of components and relations that are rationally chosen as a system, in that they represent a whole; (c) can be separated from the rest of the world by a system boundary, but is not closed except in exceptional cases; and (d) has a surrounding that can interact with the system. The relations between the surroundings and the system are vital to study, according to Ingelstam. As mentioned earlier, numerous researchers have touched upon the field of system theory and systems approach. One of the most well-known spokespersons for system theory is Churchman, who wrote *The Systems Approach* (Churchman, 1968). Churchman thought that a systems approach should be used to avoid sub-optimisations, i.e. by analysing the system as a whole drawbacks associated with analysis of separate units could be avoided. Also, Churchman considered that by using a systems approach and widening the system boundaries, synergies could be detected. For energy systems the synergetic effects can be detected, for example, in CHP technology, where the surplus heat from electricity production can be utilised for DH production and in biorefineries where the total efficiency can increase due to resource optimisation of several processes (see section 2.1). Operational research (OR) can

also be mentioned when discussing Churchman. OR was developed during World War II to integrate methodologies from different research areas to solve military problems. After the war OR was further developed and integrated in civilian organisations (Ingelstam, 2002). The OR technique used in this thesis is linear programming, which here has been used for optimising energy systems.

5.1.1. System boundaries for district heating systems

A systems approach has been applied to the energy system analyses included in this thesis. When using a systems approach the system boundaries and the connections to the surroundings have to be determined: here a local DH system was analysed in combination with the surrounding energy system. Besides the technical features of the DH system, economic aspects and policy instruments were included as well as studies of synergy effects when implementing DH systems with a biorefinery. Optimisation models were used for evaluation of economic consequences and changes in plant operations when varying the input data. For all energy system analyses included in this thesis, the impacts on CO_2 emissions were studied. For the performed energy system analyses the potential outcome when implementing different measures was studied, with the exception of human behaviour. For example, this thesis does not analyse what the barriers and driving forces are for implementing different measures.

An attempt to describe the local DH system and its connections to the surrounding energy system and hence the system boundaries is illustrated in Figure 5.1. In the surrounding energy system, of which the local DH system is part, heating, cooling, electricity, transportation fuels and other fuels are supplied to the residences and industries. In the DH system the fuels' CO_2 emissions from the whole fuel cycle (raw material extraction and distribution) are considered; data are taken from Uppenberg et al. (2001). The electricity produced and consumed has an international character, due to the deregulated European electricity market, and hence the electricity produced and used in the region can be substituted for marginal European electricity production. Moreover, in Paper II a biorefinery with potential to produce the transportation fuel synthetic natural gas (SNG) has been included in the analysis of the local DH system. The SNG produced in the biorefinery is assumed to replace gasoline in the transport sector. Additionally, factors that constitute the surrounding system and that affect the local DH system, e.g. fuel and electricity prices and various policy instruments, were studied in different scenarios (Paper II and Paper V) and in sensitivity analyses. Besides the supply-side energy, demand-side measures were considered and conversions from electricity or other fuels to DH or DC were included in the energy system analyses. Other changes in DH demand associated with demand-side management, such as ECMs, were considered in Paper VI.
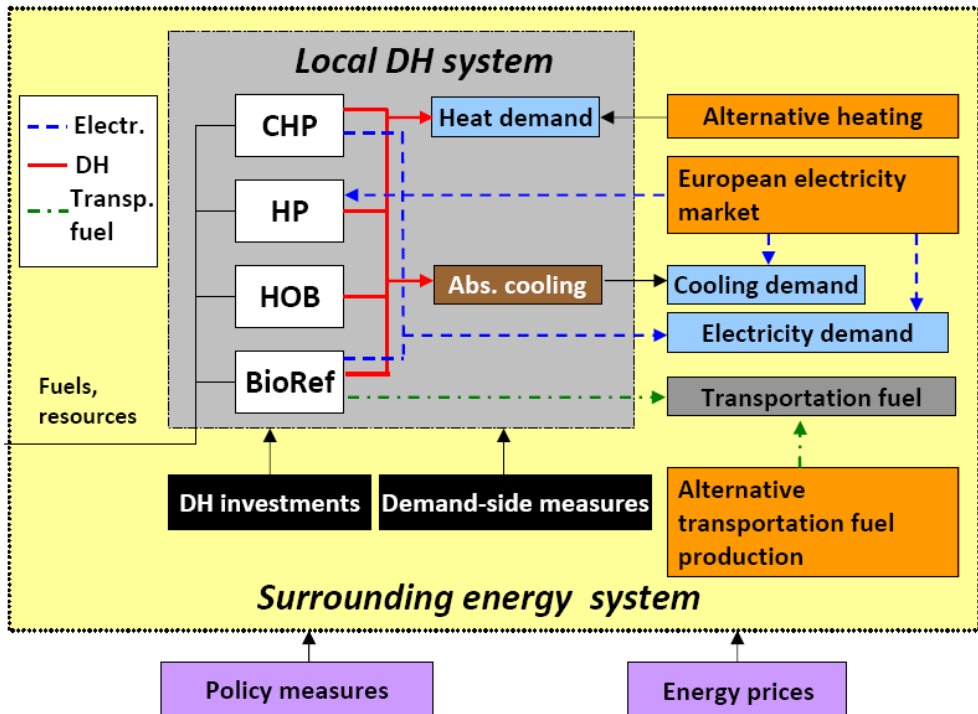
Figure 5.1. System boundaries for the local DH system (HP = heat pump, HOB = heat-only boiler, BioRef = biorefinery, Abs. cooling = absorption cooling).

5.2. Industrial energy audits

In papers I and IV, industrial energy audits were analysed in order to assess the companies' potential for reducing their energy demand and altering their use of energy towards less dependence on electricity. The energy audits analysed have mainly been performed by Linköping University and the Energy Agency of Southeast Sweden and they are based on the methodology of the Analysis tool. The Analysis tool is a strategic method for system changes in industrial energy use that has been developed to help industries analyse their energy use with the aim of reducing electricity use. This analysis tool applies a top-down perspective and a systems approach to detect system errors, the main focus of the Analysis tool. By identifying system errors, such as heating and cooling installations that can operate simultaneously or the use of electricity for non-electricity-specific processes, for example space heating or drying, the industries can reduce their overall energy demand but more importantly decrease their use of electricity (Karlsson, 2001). In papers I and IV the main aim of the industrial energy audit analyses was to identify processes convertible to DH and system errors that could decrease the electricity use. Naturally, determining what process could be fuelled by DH instead of electricity or fossil fuels has to be assessed on a case-by-case basis depending on temperature level of the process or other circumstances. The companies represented are small and medium-sized. For more information about industrial energy audits, see for example Franzén (2005), Thollander (2008) and Trygg (2006).

5.3. Energy system analysis and modelling

When performing energy system analysis, various tools and models can be helpful depending on the complexity of the system. For an overview of energy models, see for example Jebaraj and Iniyan (2006). Varying different parameters in an energy system model can increase the understanding of the interactions between the components and help in the evaluation of future conditions' impact on the energy system. Moreover, by using models for analysis of complex systems, suboptimisation can potentially be avoided since the whole system is analysed and not one subsystem at a time. However, it is important to remember that models are reproductions of the real system and the reliability of the model is dependent on the modelled components and input data as well as the on the system boundaries. In this thesis two energy system models were used, the MODEST model and the reMIND model (based on the MIND method). Both models are optimisation models, where mainly the system cost is minimised. MODEST is designed for analysis of local and regional energy systems, whereas the main application of the MIND method is analysis of industrial energy systems. However, both models are flexible and can be used for other applications as well. For analysis of energy systems on their own, such as DH and electricity systems, the MODEST model has been used in this thesis, while when gasification applications were included (Paper II) a reMIND model was instead constructed. The models are more thoroughly described in the following sections.

5.3.1. The MODEST model

The MODEST model was used for energy system analysis in papers I, III, V, VI and VII. MODEST is an acronym for Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions. Based on linear programming, MODEST was developed to optimise DH and electricity production in local, regional and national energy systems. The objective function is to minimise the system cost, which is calculated as the present value for each given time period. In the system cost all the costs associated with DH and electricity production can be included, for example fuel costs, maintenance costs, investment costs, taxes and fees. In addition to all the costs, the income from selling electricity generated in the CHP plants is also included in the system cost. For an overview of the information flow in the model see Figure 5.2, which shows how information is processed and what kind of input data is needed. The input data that need to be defined for the model are costs and what different components the energy system consists of. Examples of input data for the components are maximum capacity, efficiency, investment cost, power-to-heat ratio (for CHP plants), fuel and maintenance cost, as well as technical and economic lifetime. Other essential input data to define are the energy demand that the plants in the system need to fulfil and a suitable time division, which divides the energy demand appropriately over the year. Results from the optimisation show which investments are economically beneficial, marginal costs for supplying the energy demand and how existing plants should operate to minimise the system cost. For more information about the MODEST model, see Gebremedhin (2003), Henning (1998; 1999) and Henning et al. (2006).

One of the benefits of MODEST is the flexible time division. For the studies performed in this thesis, each year was divided into 88 time steps to illustrate how heat demand varies over the year. On winter days, from November to March, when heat demand peaks and the heat variations are significant, the time division is at its finest, sometimes modelled hour by hour. During the remaining part of the year, from April to October, longer time divisions were used, since the variations in heat demand are smaller. Due to the flexible time division, the large number of plants and components that can be modelled at one time and the negligible computation time, the model can be used for many applications. However, there are some limitations to the model. Since MODEST does not implement integer variables the model

cannot, for example, consider start-up costs allow for smaller units having higher investment costs per MW than larger units (this has to be modelled manually, as does the minimum operation capacity of the plants).

The MODEST model has been used in many studies and applied to over 50 local DH systems. The model has also been used to analyse cooperation between local energy companies and industries as well as the potential profitability of connecting local DH systems (Henning, 1999; Sundberg and Sjödin, 2003).
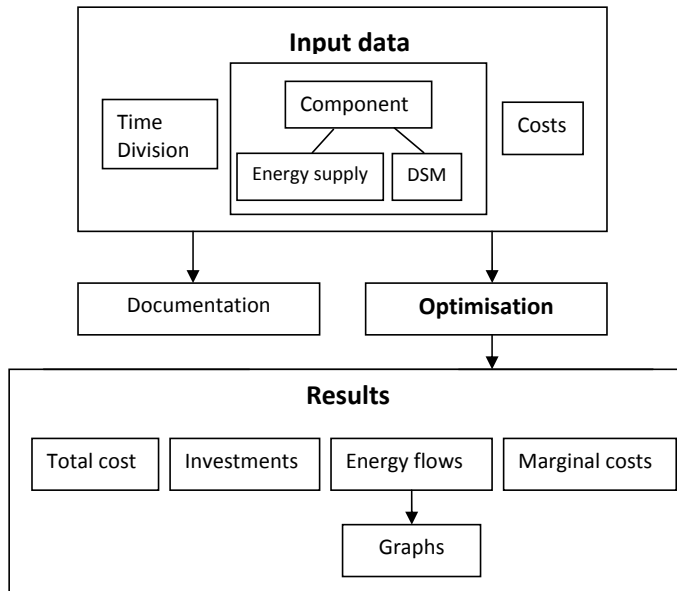
Figure 5.2. The main flow of information in MODEST; DSM = demand-side management (Henning, 1999).

5.3.2. The reMIND model

In Paper II a reMIND model was constructed of the local DH system in Linköping for analysis of the profitability of investing in gasification applications. The reMIND model, based on the MIND method (Method for analysis of INDustrial energy systems), is an optimising tool for dynamic energy systems. The MIND method is based on mixed integer linear programming (MILP) and like MODEST the objective function is mainly to minimise the system cost. Included in the system cost are fuel and maintenance costs, investment costs, costs associated with taxes and fees and the revenue for electricity and other products sold. Just as for MODEST, input data that need to be defined are maximum capacity, number of time steps, efficiencies, power-to-heat ratio (for CHP plants), capital costs and flow dependency for industrial processes. In the reMIND model 29 time steps were applied, divided as follows: November to March had three time steps: (1) days, (2) nights along with weekends and (3) one peak day per month. For the remainder of the year each month was divided into two steps: (1) days and (2) nights along with weekends. With fewer time steps,

the heat and steam demand was not described as precisely as in MODEST, but additional time steps would probably have increased the computation time considerably. Outcomes from the model are optimal operation strategies and investments profitability. Furthermore, the model can be used for analysis of material flows and their dependency on boundary conditions. More thorough descriptions of the MIND method can be found in Karlsson (2002), Nilsson (1993), Sandberg (2004) and Thollander et al. (2009).

The MIND method has a broad range of application areas due to its flexible mechanism and time division. For example, analyses of the pulp and paper industry (Gong and Karlsson, 2004; Klugman et al., 2009), steel industry (Ryman and Larsson, 2007) and DH systems (Wetterlund and Söderström, 2010), as well as analyses of cooperation between industries and DH companies (Karlsson et al., 2009; Klugman et al., 2009) have been performed with the MIND method. The possibility of modelling material flows and the benefits of MILP were reasons why a reMIND model instead of a MODEST model was built in Paper II. In Paper II gasification applications were included in the DH system; because reMIND is based on MILP, gasification plants could be modelled where smaller units had higher investment costs per MW than larger units. The minimum operation capacity, which is a main factor for gasification plants, could also be considered as well as that only one of the gasification types could be chosen in the model at each optimisation run.

5.3.3. Validation

When performing energy system modelling it is vital that the model is accurately built so the behaviour of the real system can be appropriately illustrated in the model. To ensure that the model describes the real system correctly, validation of the model must be performed.

The MODEST model has been tested and applied in numerous DH studies (see section 2.5). For example, the calculation method for marginal DH costs in MODEST was validated in Sjödin and Henning (2004), where the marginal DH costs obtained from two other methods were compared to the marginal DH costs from MODEST and they all showed similar results. Furthermore, MODEST has proven to be a valuable method for supporting strategic decisions in local energy systems (Byman, 1999). Byman performed an energy system analysis with MODEST and at the same time an experienced consulting firm performed an analysis of the energy system with manual calculations. The two studies were performed under the same conditions and both studies showed almost identical results.

The MIND method has mainly been tested for industrial purposes. However, some studies of the cooperation between industries and DH systems have been performed. Since a MODEST model of the Linköping DH system had previously been built, a comparison of the Linköping MODEST model and the reMIND model could be performed and they showed similar results. However, the time division was not the same in the two models, which prevented a complete comparison. For all studies performed in this thesis the results from the models were validated against real operating data for the local DH systems. Also, to ensure that the behaviour of the energy system was appropriately illustrated, sensitivity analyses were performed, varying key parameters. The results from the sensitivity analyses were then checked to identify out-of-the-ordinary behaviours of the system.

5.4. Sensitivity analysis

In energy system analyses with optimisation models the output from the models is highly dependent on the input data, such as different price levels. To evaluate the robustness of the

optimal solutions, sensitivity analysis can be performed where fundamental parameters are varied. There are different methods to perform sensitivity analysis, such as one-factor-at-a-time, factorial design and scenarios. They all have different benefits and drawbacks, see e.g. Sundberg (2001) and Darton (2003). The one-factor-at-a-time method, where only one factor is varied at a time, is easy to use but could be time-consuming for systems containing many parameters. Also, the method does not consider the interaction effects of different parameters. For the factorial design method the aim is to identify the parameters and what combination of parameters has the most impact on the system; hence, the interaction effects are considered. The method can however be very time-consuming for large systems. When performing scenario analysis central parameters are considered to be related. For example, if the fossil fuel price increases the electricity price will be affected, and hence the interaction effects are included in the scenarios. However, it can be difficult to evaluate how the different parameters are related. One advantage is that the number of scenarios can be predefined, which reduces the number of extra optimisation runs. In this thesis energy market scenarios with interdependent parameters were used in papers II and V, the one-factor-at-a-time method was applied in Paper VII and in Paper III the electricity prices were varied.

The energy market scenarios used in papers II and V are based on the ENPAC tool (Energy Price and Carbon Balance Scenarios). An overview of the calculation flow in the ENPAC tool is illustrated in Figure 5.3. Input data for the tool are prices of fossil fuels and policy instruments such as the fee for tradable CO_2 emissions permits. Outcomes from the tool are marginal energy conversion technologies (build-margin) in key energy markets, which in turn yield consistent values for energy prices (fossil fuels, electricity, biomass fuels and heat for DH) and CO_2 emissions associated with marginal use of key energy carriers. For more information about the ENPAC tool, see Axelsson and Harvey (2010) and Axelsson et al. (2009).
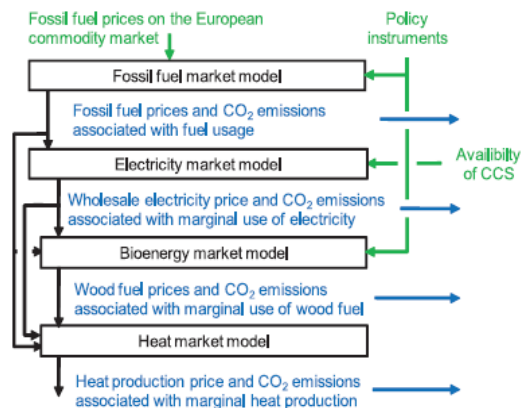
Figure 5.3. Overview of the calculation flow in the ENPAC tool. Green arrows represent required input to the tool. Boxes represent calculation units for the different energy markets. Black arrows represent information flow within the tool. Blue arrows represent output from the tool, i.e. energy market parameters (Axelsson and Harvey, 2010).

When determining the future build-margin for electricity production in the different scenarios, investment and fuel costs as well as cost for policy instruments are considered. The electricity production technology with the lowest cost is selected as the future build-margin electricity

technology for each scenario and this determines the future electricity prices and the CO_2 emissions. The electricity prices originating from the build-margin electricity technologies are used in papers II and V as future base load electricity prices. Build-margin technologies included are coal condensing power, coal condensing power with CCS and NGCC condensing power. Moreover, the price setting on biomass is based on the high volume users' willingness to pay for biomass. In the scenarios the price of biomass is set by coal due to co-firing of biomass in coal power plants and large-scale renewable transportation fuel (biofuel) production.

Since the tool was originally developed to create scenarios for energy-intensive industry the tool has been adjusted here for the Swedish DH sector (for example taxes and other fees have been included). The policy instruments considered in the scenarios are energy taxation, TGC, the EU ETS CO_2 charge and biofuel certificates (for the transportation sector, only considered in Paper II). Four energy market scenarios were applied in papers II and V. Figure 5.4 shows how the policy instruments and the fossil fuel prices vary in the scenarios. Two levels of fossil fuel prices were used, low in scenarios 1-2 and high in scenarios 3-4. Furthermore, two levels of CO_2 charge were used, which demonstrates different CO_2 reduction ambitions. Also, two price levels of TGC are included, where a high CO_2 charge is assumed to correspond to a low TGC price (Tolonen et al., 2006). In the two papers where the energy market scenarios were used, scenarios using present fuel prices and policy instruments were also included and therefore the numbering of the scenarios in Figure 5.4 is not consistent with the numbering of the scenarios in the two papers.
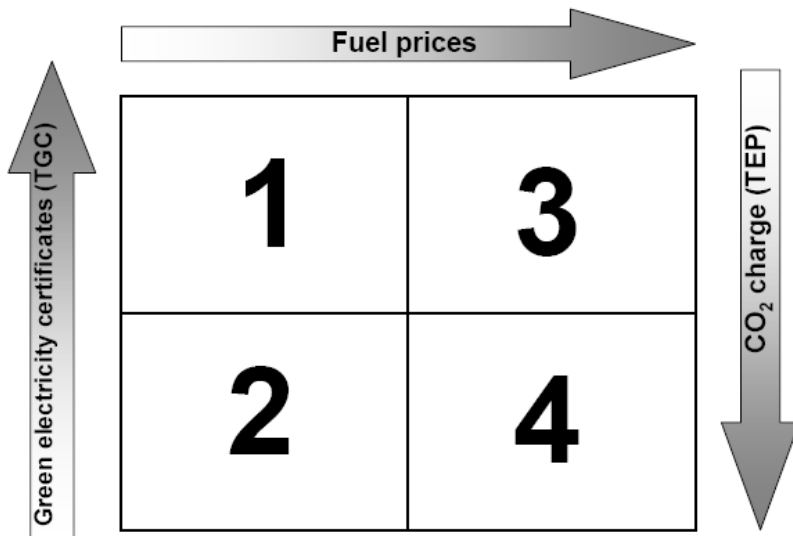

Figure 5.4. Schematic description of the energy market scenarios used in papers II and V, where the arrows represent how the prices go from low to high levels

6. Case studies

This chapter presents the district heating systems studied, describing the heat production, district heating plants and recent or planned investments in the district heating systems. Moreover, the energy prices used in the studies are defined along with the scenario and sensitivity analyses used in the different cases.

6.1. Description of the district heating systems studied

Two DH systems were studied in this thesis, the systems in Linköping and Örebro. Besides distributing DH, both systems manage a DC network as well. The system in Linköping produces more DH; the electricity production in the two DH systems is however about the same. Both DH systems contain CHP plants and HOBs, which results in flexible systems.

6.1.1. Linköping

Linköping, located about 200 km southwest of Stockholm, has about 140,000 inhabitants, making it the fifth largest city in Sweden. Linköping has an extensive DH system, which is managed by the municipally owned Tekniska Verken Linköping AB (TVAB). The local DH network system in the Linköping area is also connected to the adjacent community of Mjölby via a DH transmission pipeline. Overall, these combined DH systems represent one of the largest DH systems in Sweden. Besides distributing DH, TVAB can also supply steam to industrial businesses and DC to the service sector. In 2008 the production of DH and steam for the combined DH systems of Linköping and Mjölby was about 1,700 GWh, with a maximum heat demand of about 500 MW. The DC demand in 2008 was about 30 GWh with a maximum cooling demand of 30 MW. A majority of the DC (60%) is supplied by heat-driven absorption cooling, which utilises heat from the DH production. During the winter, free cooling from a river nearby is utilised for the DC production, while CCs are required to supply enough DC for peak days during the summer.

The DH production in Linköping is supplied by a number of different plants, both CHP plants and HOBs. The base load plants in the system are the two waste incineration facilities,

consisting of the older waste hybrid CHP plant and the newer waste CHP plant. These two facilities supply about 60% of the DH demand. The older waste hybrid CHP plant was originally constructed to produce electricity through operation of an oil-fired gas turbine, where the steam from the waste incineration was superheated by the flue gases from the gas turbine and then expanded through a steam turbine. However, oil prices have increased since the installation of the hybrid CHP plant and the gas turbine has hardly been operated at all during the last years. Consequently, this hybrid CHP plant has recently been updated with a new low-pressure steam turbine, which enables electricity production without operating the oil-fired gas turbine. For both of the waste incineration facilities, a direct condenser can be used for heat-only production.

Besides the waste incineration plants, there are both CHP plants and HOBs that can be fuelled by coal, oil and biomass. The DH system also contains electric boilers. Hence, the DH system contains a variety of plants and fuels, giving the DH system a high degree of fuel flexibility.

Moreover, by cooling the DH network supply line in the nearby river and in cooling towers (recoolers) extra electricity can be produced in the CHP plants when the DH demand is low and when it is profitable to sell electricity. The cooling capacity is 45 MW and the annual electricity generation in all the CHP plants is about 325 GWh.
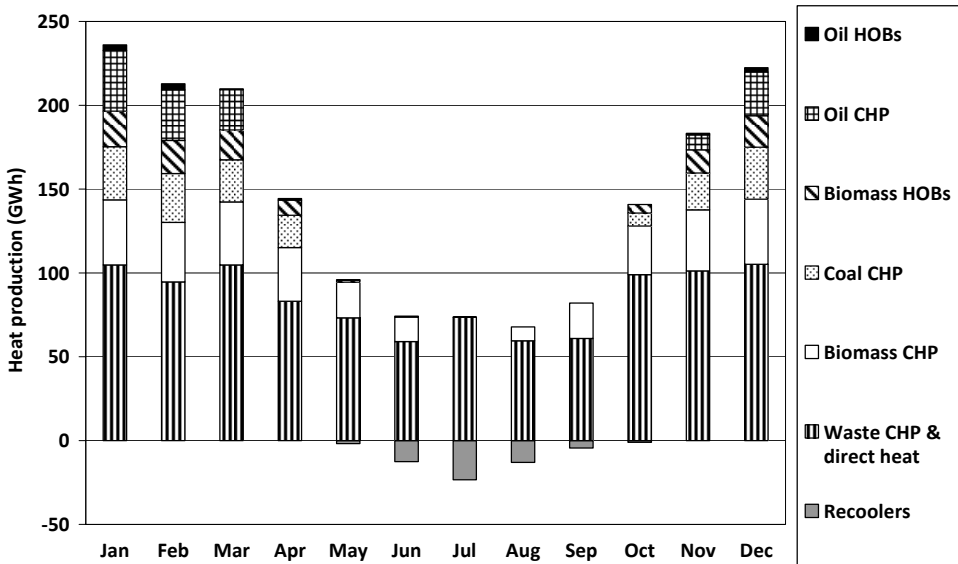
Figure 6.1. Annual heat production (in GWh) in 2008 for the combined DH systems of Linköping and Mjölby.

6.1.2. Örebro

Örebro, with its population of about 135,000 inhabitants, is about the same size as Linköping regarding residents. Örebro is located about 200 km west of Stockholm and about 120 km north of Linköping. The DH system in Örebro has been managed by E.ON since 1997; before that the municipality owned the DH system. In 2000 the Örebro DH system became

connected to the neighbouring communities of Hallsberg and Kumla. In 2008 the combined DH system of Örebro, Hallsberg and Kumla was the seventh largest DH system in Sweden in terms of DH production (SDHA, 2008) and the production in 2008 was about 1,250 GWh DH, 12 GWh DC and about 320 GWh electricity. The maximum heat demand of about 350 MW is supplied by a number of different plants. Excess heat from a nearby waste incineration plant (SAKAB), where toxic waste and waste from households and industries are incinerated, covers most of the base load heat demand. The remaining heat demand is mainly covered by a CHP plant fuelled by peat and wood. Other plants supplying DH are biomass-fuelled HOBs, an oil-fuelled CHP plant and heat pumps. To further increase electricity production E.ON is planning to invest in a new CHP facility for mixed waste in 2012.

In addition to DH, E.ON distributes DC where the main customer today is the University Hospital. The DC is presently supplied by free cooling during the winter months, November to March, while the remaining cooling demand is supplied by modified heat pumps. The heat pumps are utilising purified wastewater from a nearby wastewater treatment plant along with electricity. The maximum cooling demand in 2008 was about 8 MW, but if the DC system is expanded to also include the University of Örebro as well as the shops and offices in the city centre, the cooling demand could increase threefold.
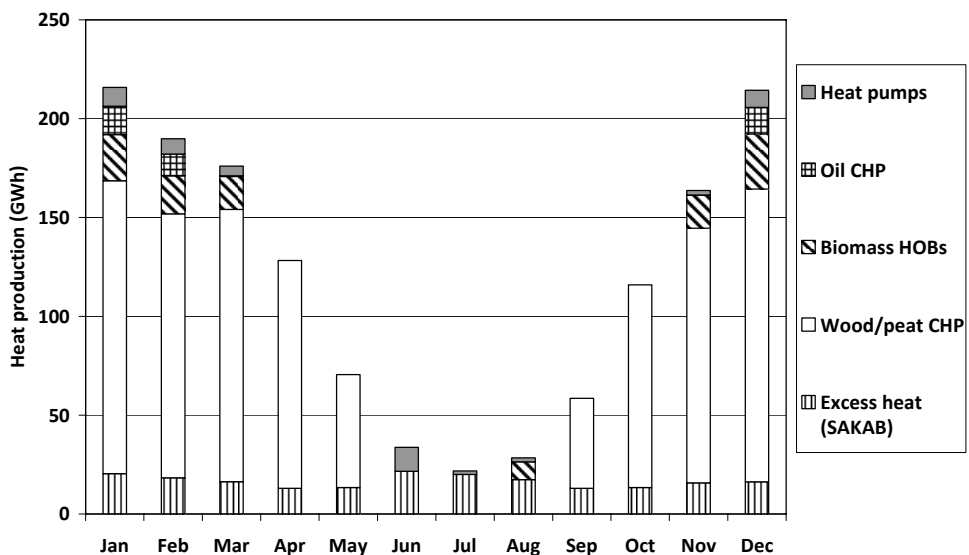
Figure 6.2. *Annual heat production (in GWh) in 2008 for the combined DH systems of Örebro, Hallsberg and Kumla.*

6.2. *Compilation of input data used in the district heating studies*

The studies performed for this thesis used different input data, such as fuel and electricity prices as well as policy instrument levels and taxes. Table 6.1 displays a compilation of the base line levels for prices and policy instrument used in the different case studies. The prices used in Paper I represent the price levels in 2007 for the DH system in Linköping, while in papers II and V the 2008 price levels are used. In papers VI and VII predicted price levels for

2013, developed by the TVAB organisation, have been applied. Paper III represents the price levels in 2007 for the Örebro DH system.

Table 6.1. Fuel prices (excluding taxes) and policy instrument levels applied to the DH systems (1 EUR=9.40 SEK).

Prices	Paper I	Paper III	Papers II+V	Papers VI+VII
Fuel prices (EUR/MWh)				
Light fuel oil	40	37	41	45
Heavy fuel oil	30	-	31	36
Coal	9	-	12	13
Natural gas	-	-	29	24
Waste	-16	7	-16	-13
Wood chips	20	20	17	29
Wood by-products	9	-	14	13
Policy instrument levels				
TGC[a] (EUR/MWh$_{electricity}$)	21	22	23	32
TEP[b] (EUR/tonne CO_2)	21	20	21	21

[a]Tradable green electricity certificates
[b]EU tradable CO_2 emission permits

In addition, sensitivity analyses were performed for the cases studied in papers II, V, and VII. In papers II and V, energy market scenarios were used to evaluate the robustness of the systems (see section 5.4). An illustration of the price range applied in the energy market scenarios for the different fuels can be seen in Figure 6.3. In Paper VII a sensitivity analysis was performed in which one factor at a time was varied (prices of biomass, natural gas and electricity).

Moreover, the electricity prices differ in the studies. In papers I and III, the electricity prices of 2007 were used in combination with the expected higher electricity prices, referred to as European electricity prices. The method for calculating the European electricity prices applied in papers I and III comes from a study conducted at Linköping University and financed by E.ON. The study examined the European electricity market's impact on Swedish electricity prices (Melkersson and Söderberg, 2004). Papers II and V use the electricity prices of 2008 along with the electricity prices developed from the energy market scenarios. For papers VI and VII, electricity prices predicted by the TVAB organisation for 2013 were used. An illustration of the electricity prices used in the different studies, representing the European electricity prices, the electricity prices for the energy market scenarios and the predicted electricity prices for 2013 developed by the TVAB organisation, can be seen in Figure 6.4.
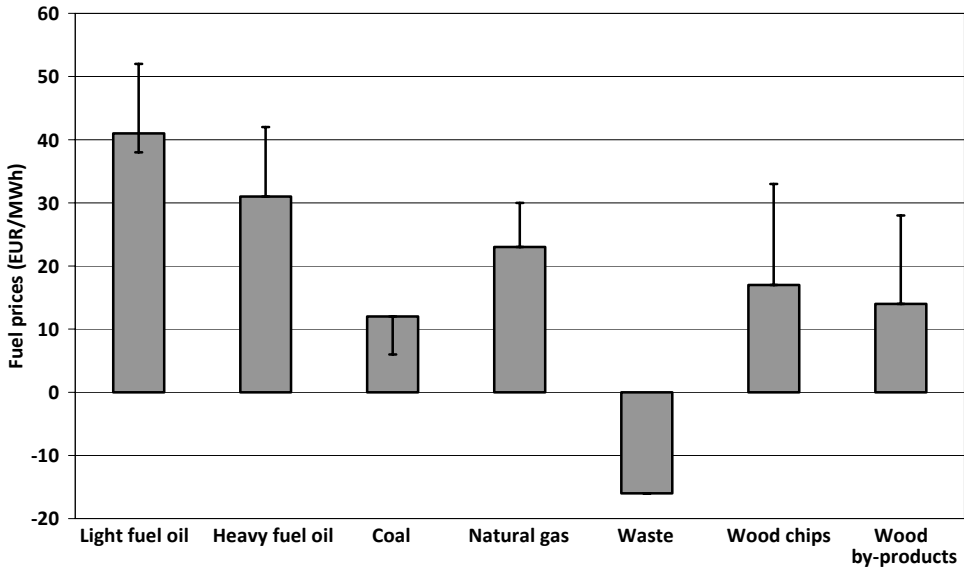
Figure 6.3. Illustration of the fuel price ranges in the energy market scenarios applied in papers II and V, where the grey bars represents the values in 2008 and the error bars represents the price range of the different fuels in the scenarios.
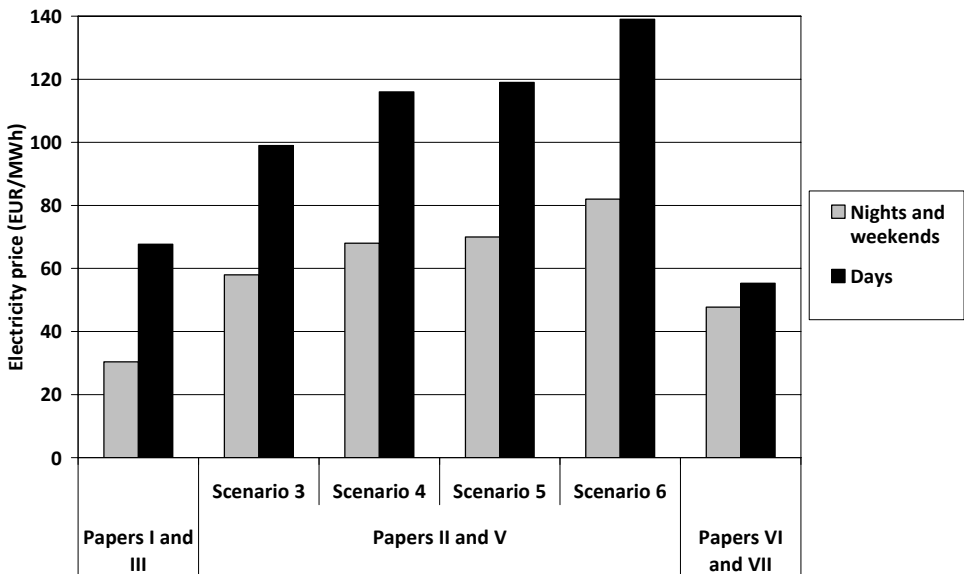
Figure 6.4. Electricity prices (excluding grid fee) used in the different studies. The price levels illustrate the potential future electricity prices for a fully integrated European electricity market.

To summarise, in papers I and III the prices of 2007-2008 were utilised (in combination with European electricity prices), while in papers II and V energy market scenarios in combination with price levels for 2008 were applied. In papers VI and VII predicted price levels for 2013, developed by the TVAB organisation, were used. For studies of the base line cases, i.e. when not including the sensitivity analyses, the price levels are similar (see Table 6.1). However, most of the price levels in papers VI and VII are somewhat higher than for the other studies since they represent price levels for 2013. In particular, the biomass price is higher than for the other studies, which can be explained by TVAB's prediction that the demand for biomass will increase. Regarding the forecasted fossil fuel prices, they correspond well to the projected fossil fuel reference prices for 2015 from IEA's World Energy Outlook 2009 (IEA, 2009).

7. Results and analysis

In this chapter, the results from the studies are summarised according to the research questions stated in the introduction. This chapter includes discussions about investment options for district heating systems, perspectives of energy demand-side measures, heat loads in district heating systems, pricing of district heating, energy policy instruments and climate change mitigation potential.

The results presented in this chapter are closely linked to the research questions stated in the introduction. The first research question about investments in DH system is discussed in the first section of this chapter. The second research question, which focuses on demand-side measures in DH systems, is dealt with in sections 7.2 and 7.3, while the pricing of DH is briefly discussed in section 7.4. Energy policy instruments, which are related to the fourth research question, are the main topic of section 7.5. Finally, the last part of this chapter focuses on the climate change mitigation potential. This topic is relevant to all four research questions stated, as well as to all the case studies included in this thesis. Furthermore, as has been mentioned before, the results from this thesis are based on the following assumptions: (a) Swedish electricity prices will increase and in the long run be equivalent to the marginal cost of electricity production in the European electricity market; (b) electricity generated and used in Sweden will affect the marginal source of electricity in the European electricity system; and (c) biomass is considered CO_2 neutral.

7.1. Investments in DH systems

In the appended papers II and III, different investment options for local DH systems were studied in terms of profitability, electricity production and global CO_2 reduction potential. The investments have been analysed in optimisation models with varying input data. It can be difficult to decide both the correct time to invest and the type of new production facilities in DH systems due to different circumstances, such as the complicated matter of predicting future fuel and electricity prices as well as policy instruments. The question of when to invest in new production facilities has not been addressed in the papers since this question can

depend on many factors, including company investment strategies, access to capital and risk tendency.

7.1.1. Biomass gasification

Paper II analysed different biomass gasification applications as investment alternatives for the local DH supplier in Linköping, TVAB. Biomass gasification applications can be interesting investment options since they enable higher electrical efficiency than conventional biomass combustion-based technologies; thus, the gasification technology will yield more electricity production for a given heat demand. Combustion also limits the range of biomass applications to heat and electricity, while biomass gasification could, in addition to heat and electricity production, also be used for production of renewable transportation fuels (biofuels) or other high-value chemicals (although not in the same plant). In Paper II two large-scale gasification applications, among others, were included in the study: BIGCC CHP and co-production of SNG and DH heat in a biorefinery. The different gasification applications were analysed in six scenarios, which differed in time perspectives, economic input data, investment options and technical aspects. For more information about the scenarios, see Paper II.

Results from the study show that including gasification applications in the DH system could be profitable for the local DH supplier. For all scenarios where gasification applications are available, one or both of the gasification applications (BIGCC and SNG) are chosen by the optimisation model, since they are more profitable to invest in than conventional biomass-fuelled CHP, which was the reference investment option. Which gasification application is most profitable is highly dependent on the level of policy instruments for electricity and biofuels. Moreover, the high added value of the gasification plant's products (electricity and SNG) makes heat from gasification investments competitive even for base load waste heat, which has a negative purchase cost. Also, the annual electricity production can increase considerably. When comparing the electricity production between the reference scenarios without gasification application and the scenarios where BIGCC is chosen (Scenarios 3 and 4), the electricity production can increase by an average of almost 60%.

Furthermore, not only are the scenarios where gasification applications are included more cost-effective than the reference scenarios without gasification applications, the potential reduction of global CO_2 emissions is also greater for the gasification scenarios. Compared to the reference scenario without gasification applications, the potential global CO_2 reduction is 600,000 tonnes CO_2 annually in the scenario where both the SNG and BIGCC are built and when the marginal electricity production is assumed to be coal condensing power. This is equal to a potential CO_2 reduction of 320 kg CO_2 per MWh of DH produced.

7.1.2. Absorption cooling

The demand for cooling is increasing; the introduction of ACs for producing chilled water could be an interesting investment option for DH systems. In the absorption cooling technique, heat and a small amount of electricity are required to produce chilled water. Since heat of about 70-150°C is the supply energy for an AC, it can ideally be interconnected to a DH system. ACs can either be placed centrally close to the DH production facilities or locally at the customer's facilities.

In Paper III the local energy system in Örebro is studied, which includes a DC system and a local DH system. The DC system, with a cooling demand of about 13 GWh per year, is presently supplied by modified heat pumps and free cooling. In the paper the economic aspects of introducing absorption cooling in the DC system of Örebro are studied, in

combination with the effects on global CO_2 emissions. Including ACs in the local energy system can lead to lower system cost than the DC system containing only CCs and free cooling[5]. With a predicted higher cooling demand of 34 GWh/year in combination with higher electricity prices (representing European electricity prices, see section 6.2), the profit for the local energy system will be even greater. The system cost for the DH and DC systems can in this case be reduced by 630,000 euro per year when introducing ACs into the DC system, which corresponds to a reduction of about 20 EUR/MWh DC compared to the scenario containing only CCs and free cooling. Also, by implementing heat-driven ACs in a CHP system instead of CCs, the demand for electricity will decrease and the potential for electricity production will increase. Hence, by introducing AC in the local energy system in Örebro the global emissions of CO_2 could potentially be lowered by 11,000 tonnes annually, corresponding to a reduction of over 300 kg CO_2 per MWh of DC.

In addition to the above-mentioned positive effects of introducing ACs, the heat load of the DH system can change in a favourable way, which can affect the operating time of the DH plants. This positive effect on the heat load when introducing ACs is further discussed in section 7.3.

7.2. *Perspectives of energy demand-side measures*

With rising energy costs, the implementation of energy demand-side measures is becoming an interesting reform alternative for industry as well as for the residential and service sectors. Efficient utilisation of energy is also vital for sustainable development. Industrial energy demand-side measures were studied in papers I and IV; energy demand-side measures for the residential sector were analysed in Paper VI. In all analyses the effects on the DH demand were studied, along with the global CO_2 reduction potential.

7.2.1. Industry

The energy efficiency and conversion potential for a number of industries was studied in papers I and IV by examining industrial energy audits. In Paper IV 34 industrial energy audits and seven industrial cooling audits were analysed. In the energy audits the conversion potential of processes to DH was established. By conversion of processes that utilise electricity and fossil fuels to instead utilise DH, the primary energy use can potentially be reduced in combination with other environmental benefits. By converting processes that today use electricity or fossil fuels to DH generated in CHP plants, the environmental benefits are twofold, since less electricity and fossil fuels are required for heating and cooling purposes while at the same time the extra electricity generated in CHP plants can replace the electricity produced in European condensing power plants.

For the companies studied in Paper IV, conversion of processes to DH could lead to an 11% annual reduction in the use of electricity, a 40% annual reduction in the use of fossil fuels and an overall annual energy system savings of 6%. Further, annual DH demand has the potential to increase from 102 GWh to 302 GWh, and the conversion to DH also has a potential to alter the DH load profile in a beneficial way. Additionally, conversions of industrial processes to DH could lead to a potential reduction in global CO_2 emissions by 112,000 tonnes per year. This is when the overall impact on the global CO_2 emissions are taken into account, i.e. the reduction in industrial electricity and fossil fuel use, the potential increase in electricity

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[5] Free cooling can be supplied November to March and the maximum cooling capacity is equal in all scenarios.

generation in CHP-plants, as well as the local emissions from increased DH production are considered.

In Paper I, not only the conversion of processes to DH but also energy efficiency measures focusing on reducing industrial electricity use were studied. The outcome from the study showed that industrial electricity use can be reduced by 30% for the eight companies analysed. Moreover, when implementing energy efficiency measures and converting processes to DH, there could also be economic advantages. Paper I demonstrates that companies can reduce energy costs when implementing energy efficiency measures and converting processes to DH. With increasing electricity prices (referred to as European electricity prices, see section 6.2), it is even more vital for industrial facilities to apply these measures. Also for the DH supplier, an altered DH demand can potentially reduce the DH system cost. Moreover, the global CO_2 emissions can potentially decrease by almost 23,000 tonnes per year when the marginal electricity production is assumed to be coal condensing power.

7.2.2. Residential sector

Paper VI analysed the effect for the DH supplier and DH customers when three ECMs were implemented: heat load control[6], attic insulation and electricity savings[7]. The ECMs were primarily chosen due to their effect on the heat load and for their different heat load profiles. For more information about the ECMs, see Paper VI. Each ECM was implemented in the energy system one at a time and the effects for users as well as for the DH supplier were analysed in terms of cost-effectiveness and global CO_2 impact. The effect for the DH supplier of changed DH use was analysed in the optimisation model MODEST. In the paper the implementation of ECMs applied only to multi-dwelling buildings, not other residences.

By implementing ECMs the total energy use of the residences can be reduced. With the investment costs and assumptions used in the paper, all ECMs analysed are profitable to implement for the residences. The most economic beneficial measure for the residences is changing to new household appliances, which indicates the profitability of changing heating source from electrical heating to DH (by reducing surplus heat from household appliances). Attic insulation is the least profitable measure of the three; even when only the oldest and least energy-efficient houses are considered, this measure is considerably less profitable than the electricity savings measure. However, the dispersions of the annual capital costs are substantial and hence the economic benefit for the residences depends on the situation.

On the other hand, when considering the local energy system as a whole, which includes both the residences and the DH supplier, the attic insulation measure is not a profitable investment. The electricity savings measure is clearly the most profitable investment for the local energy system. Regarding the global CO_2 emission reduction potential, again the electricity savings measure is the measure with largest potential, whereas the other measures show little CO_2 reduction or even a small increase in global CO_2 emissions, depending on what the assumed marginal electricity technology is.

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[6]A software program that is installed on the computer in the consumers' DH central which controls the heat supply. The idea is to utilise the building's heat inertia to reduce the peak load demand of DH, i.e. the house would act like heat storage.
[7]The electricity savings measure involved changing to new household appliances, such as more energy-efficient refrigerators and freezers and low-energy lamps.

7.3. Heat loads in district heating systems

Implementing energy demand-side measures in the industrial and residential sectors can change the heat demand for these sectors, both in total figures as well as in heat duration. If the heat demand is supplied by DH, the DH supplier will also be affected by these measures. In papers IV, V and VI the effects on the heat load when implementing energy demand-side measures were studied.

Since DH is presently mostly used for space heating and domestic hot water, the DH demand is to a large extent outdoor temperature-dependent. As a consequence, the heat demand between winter and summer can differ significantly, which in turn has resulted in unevenly utilised production resources. Consequently, if the minimum heat demand for the DH system is considerably lower than the maximum heat demand it can be difficult to invest in an optimal sized base load plant. The annual operating time for large-scale investments, such as base load plants, is critical for the profitability of the district energy system. Hence by converting industrial processes that are not outdoor temperature-dependent, but rather dependent on process hours, a more even heat load curve can be achieved and the annual operating time for base load plants can be prolonged.

7.3.1. Industry

In papers IV and V industrial energy audits have been examined and the potential changes in heat load characteristics for the companies were determined. Before the implementation of energy demand-side measures these companies' total DH demand was about 102 GWh, where the space heating demand accounted for about 90%. After analysing the industries' energy use and their potential to convert from electricity and fossil fuels to DH, the DH demand could potentially increase to 302 GWh. Besides the increase in total heat demand the heat load profile could change after the implementation. The utilisation time of the DH system, which is the total DH energy use (in MWh) divided by the maximum output (in MW), could increase by 13% from 4,530 to 5,140 hours per annum, indicating that the operations of the plants are carried out more effectively.

The monthly heat demand, divided among the different processes, is shown in Figure 7.1 for both cases (before and after the implementation of energy demand-side measures). The space heating process has the largest heating demand of all the processes listed. Even after conversions, the space heating demand still accounts for the largest share of the DH demand (in GWh), but it has decreased from 88% to 47% of the total heat demand. Since the space heating demand is related to the outdoor temperature, the heat load is less temperature-dependent after the implementation of energy demand-side measures. The heat demand is lowest in July and before conversions, this was only 40% of the heat demand in December. After conversions, the heat load for July has increased and now represents 58% of the heat demand for December, which levels out the heat load for the year. The main reason for the increased heat demand for July is the DH-driven absorption cooling, which after implementation constitutes 47% of July's total heat demand. For the other processes, hot tap water, heating and drying, the heat demand remains relatively constant during the year, since these are not outdoor temperature-dependent but instead are dependent on production and the employees' working hours.
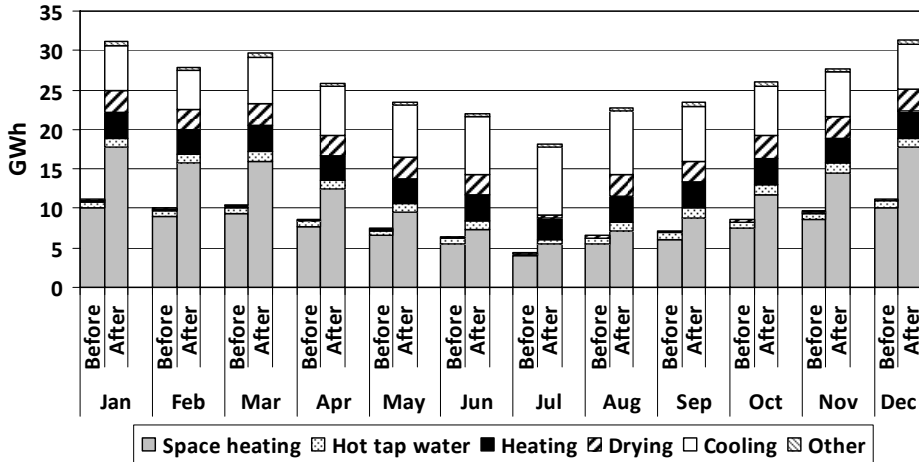
Figure 7.1. Potential monthly DH demand for different industrial processes before and after implementation of energy conversion measures.

The DH load profile, changed due to implementation of energy demand-side measures developed in Paper IV, was applied in Paper V to a fictive DH system and the effects on the DH system were analysed. Three base load plants were included in the study: NGCC CHP, waste-fuelled CHP (waste CHP) and biomass-fuelled CHP (bio CHP). Two heat demand perspectives were applied, before and after the implementation of energy demand-side measures. In five scenarios, in which the fuel and electricity prices as well as the policy instruments were varied, the effect of a changed heat load profile was examined for the fictive DH systems containing the different base load plants. The two heat load profiles, before and after implementation of energy demand-side measures obtained in Paper IV, were normalised for purposes of comparison, where the maximum heat demand was 100 MW for both heat loads. However, the actual heat load profiles remained unchanged for both perspectives.

Results from the study indicate that the changed heat load can lead to reduced operating time for peak load boilers and increased operating time for base load plants. The heat load profile after implementation increased the operating time in the present CHP base load plants and also made it possible to invest in larger CHP plants, which together enhanced electricity production by almost 20% compared to the heat load profile before implementation of energy demand-side measures. This effect occurred regardless of the type of CHP plant and scenario applied. Also, when considering changes in system costs an alteration of the heat load profile was found to be beneficial for all base load plants except in one scenario, where the high natural gas price in relation to the low electricity prices made the NGCC CHP plant less profitable after the implementation of energy demand-side measures.

Besides the influence on the system cost, global CO_2 emissions are affected when the heat load profile is changed. Assuming coal condensing power with low electricity efficiency as the marginal source of electricity, the potential global CO_2 emission reductions are between 12-20% compared to the reference case without implementation of energy demand-side measures. In this potential global CO_2 reduction, the decreased electricity and fossil fuel use in the companies is not included. An even larger global CO_2 reduction is possible when considering the total local energy system.

7.3.2. Residential sector

ECMs for the residential sector in Linköping were studied in Paper VI. An ECM affects the heating demand differently according to its characteristics. Included in the study are measures affecting the maximum and seasonal heat loads, as well as measures increasing the heat load. For example, attic insulation has the largest effect on the DH demand during the coldest period and hence affects the peak load boilers most. Heat load control has a different heat load profile and affects the DH demand typically during the spring and fall, when base load plants are used to produce DH. The electricity savings measures, on the other hand, reduce the surplus heat from the household appliances and thus increase the heat demand.

Figure 7.2 shows specific heat load profiles for the three ECMs. The figure shows what effect the ECM has on the heat load profile. For the DH supplier the implementation of ECM in residential buildings can change the operation of the DH plants and consequently the profits. Attic insulation has the largest potential for decreasing the local CO_2 emissions due to reduced fossil fuel use in the local DH plants, whereas the electricity savings measure, due to reduced surplus heat from the household appliances, instead increases the operation of the local DH plants and hence the local CO_2 emissions. Moreover, considering the overall effect on the global CO_2 emissions, which includes changes in local CO_2 emissions due to altered DH use as well as the changes in global CO_2 emissions due to altered electricity production and use, the implementation of attic insulation only contributes to marginal lower global CO_2 than the reference case. The ECM with the largest global CO_2 reduction potential is, as mentioned in section 7.2.2, the electricity savings measure. This measure show a larger effect on the global CO_2 reduction potential than the ECMs that only affect DH production and not electricity use. Consequently, from an economic and global CO_2 perspective and when considering the local energy system, where both the DH supplier and the residences are included, electricity savings should be prioritised over a reduction in DH use.
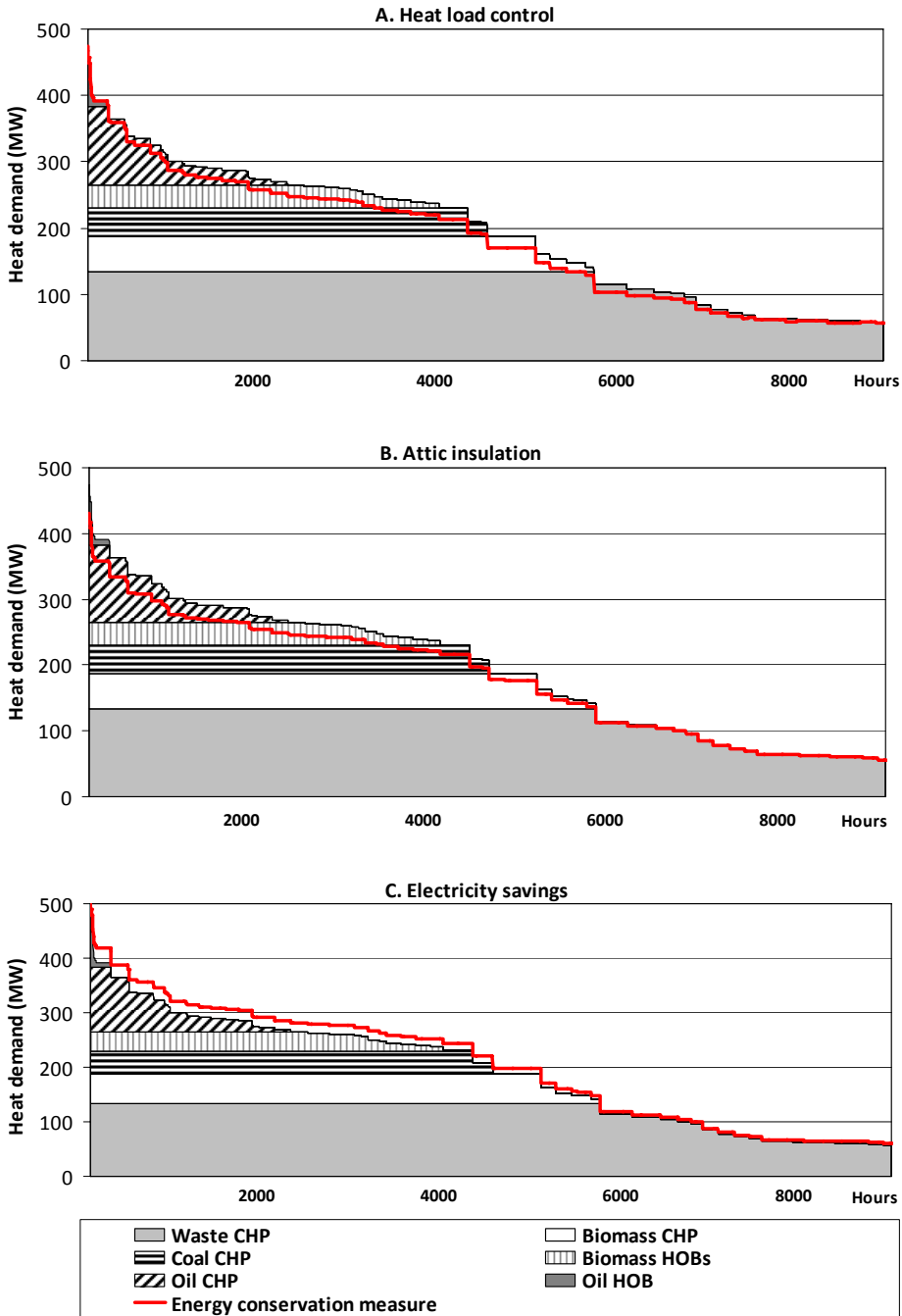
Figure 7.2. Annual DH demand including the DH plant operations in Linköping, where the red line represents the effect the ECM has on the DH demand. A. represents the measure Heat load control; B. Attic insulation and C. Electricity savings.

7.4. *Pricing of district heating*

In papers I and VI the pricing of DH was a subject of interest. In Paper I the effect on the industrial energy costs when converting industrial process to DH was analysed in combination with different electricity and DH prices. The study shows that if electricity prices rise to a European price level (referred to as European electricity prices, see section 6.2) and the companies keep the same energy use pattern, the industrial energy costs could increase by over 30%. However, when industries convert processes from electricity and fossil fuels to DH, industrial energy costs can remain the same or even be reduced if marginal DH costs are implemented. When Swedish electricity prices are levelled out to European electricity prices, the revenue for electricity generated in CHP plants will lead to lower marginal costs for DH production, especially during the summer period. This should thus be reflected in the price setting of DH; otherwise, industrial energy efficiency measures that increase the DH demand might not be applied. For the DH supplier the introduction of marginal costs as DH prices could increase the DH demand and consequently lead to more electricity production. Moreover, when implementing the industrial energy efficiency measures and also considering a utility investment in the local energy system, the local DH supplier has the potential to reduce the total DH system cost. As mentioned in the previous sections in this chapter, conversion of processes to DH has the potential to reduce global CO_2 emissions. Without correct pricing of DH this global CO_2 potential may not be fully utilised.

In Paper VI the relation between the peak demand fee and variable DH costs was highlighted as a key factor for the profitability of implementing ECMs. Since the peak demand fee and the variable DH prices are of the same magnitude (on a yearly basis) for the studied DH system, a reduction in the maximum heat load has a large impact on the annual DH costs, as can be seen for attic insulation. By adjusting the relationship between the variable DH costs and peak demand fee, the DH supplier can promote different measures. As illustrated in the results of this study the current relation between the variable DH costs and the peak demand fee makes it unprofitable for the DH supplier when DH customers implement measures such as attic insulation. This can seem remarkable since attic insulation reduces the operation of expensive peak load boilers the most and consequently the DH production costs. However, with a changed pricing system for DH and when considering that attic insulation has the possibility to postpone future investments in peak load DH plants and back-up DH plants, this measure can be profitable. Consequently, if the DH suppliers want to promote certain measures, the pricing of DH will play a major role in their implementation.

7.5. *The effects of energy policy instruments on the local energy system*

In papers II and V the effect of energy policy instruments on the local energy system was implicitly included with the application of scenarios, while in Paper VII energy policy instruments were explicitly studied.

In Paper II it is concluded that the profitability when introducing biomass gasification applications in a local DH system is highly dependent on the level of policy instruments for biofuels and renewable electricity. With the present price levels of policy instruments for biofuels (tax exemption) the gasification application producing SNG would be profitable already today. However, commercialisation of large-scale gasification applications still lies rather far in the future. To realise these capital-intensive investments in large-scale gasification applications, policy instruments are necessary.

The effect of national energy policy instruments on the local DH system in Linköping was explicitly studied in Paper VII. The study focussed on the effect national energy policies have on profitability for new investments in DH systems and on global CO_2 reductions. The new investments considered in the study are NGCC CHP, bio CHP and bio HOB. Two scenarios were applied, with national energy taxes and policy instruments and without them, respectively. EU tradable CO_2 emission permits were included in both scenarios. The DH system was analysed in an optimisation model (MODEST) where the investments were modelled one at the time for the two scenarios. The system cost and plant operations were compared for the case with the investment and the reference case without investments for the two scenarios.

With current national policies, such as TGC, the investment generating the lowest system cost for the DH system was found to be bio CHP, see Figure 7.3. The difference in system cost between the case including the bio CHP and the NGCC CHP is marginal, since the NGCC CHP investment only raises the system cost for the DH system by 3%. On the other hand, the bio HOB option is significantly less favourable compared to the other two technologies. Due to the insignificant difference in system cost for the bio CHP and NGCC CHP technologies, the results shift from the bio CHP technology being the most profitable investment to the NGCC CHP when national taxes and policy instruments are excluded. In the DH system containing the NGCC CHP plant, the system cost is 30% lower than the system cost for the DH system including the bio CHP, when excluding national taxes and policy instruments. The bio CHP is greatly affected by national energy policies, whereas the NGCC CHP technology proves to be a very robust technology that is rather insensitive to national energy policies.
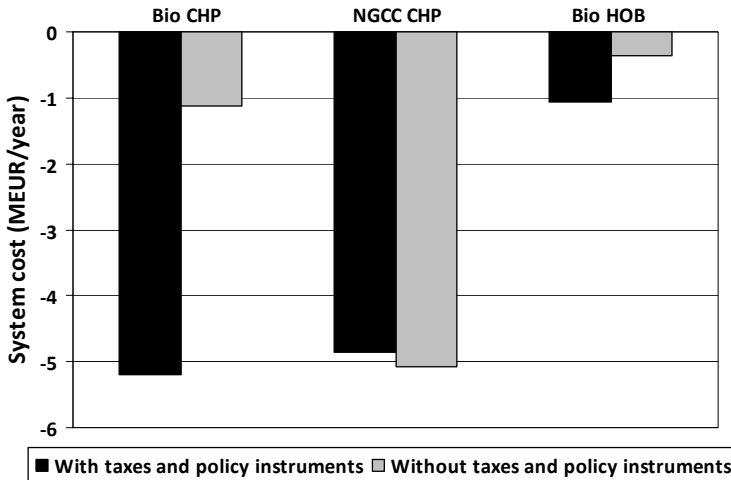
Figure 7.3. Difference in annual system cost (million EUR/year) compared to the reference case for the different technologies, when taxes and policy instruments are included or excluded (tradable CO_2 emission permits are included in both scenarios).

Also noticeable is the extra electricity production for the NGCC CHP technology compared to the bio CHP for the given heat demand. In the DH system containing the NGCC CHP plant, the electricity production is about twice as high compared to the DH system with the bio CHP and nearly three times as high as the electricity production in the reference case. Moreover,

the electricity production of the DH system has a large impact on global CO_2 emissions. Even though the NGCC CHP technology has substantial local CO_2 emissions, this technology has the highest electricity production, which makes this technology the most beneficial from a global CO_2 perspective given the assumed boundary conditions[8]. The DH system containing the NGCC CHP plant has the potential to reduce global CO_2 emissions by about 300,000 tonnes CO_2, which represents a CO_2 reduction of nearly 200 kg CO_2 per MWh of DH produced. This figure includes the local emissions of CO_2 and hence makes the local energy system a net reducer of CO_2 emissions. Overall, by implementing the NGCC CHP in the energy system a reduction in global CO_2 emissions of over 400% compared to the reference case is possible. This is achievable since the reference case has a net positive value of CO_2 emissions, while the DH system containing the NGCC CHP plant has a net negative value. The bio CHP technology has, due to lower electricity production, only about one-third of the NGCC CHP CO_2 emission reduction potential. The bio HOB technology also has less CO_2 emission reduction potential. However, the global CO_2 reduction potential for the electricity-producing technologies is highly dependent on the assumptions made about marginal electricity production.
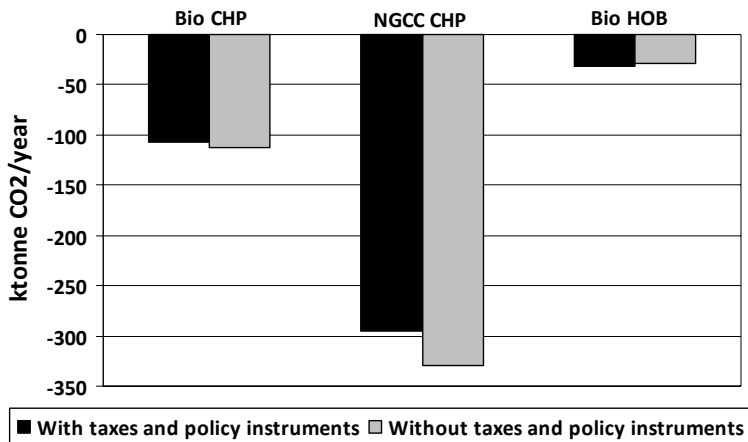

Figure 7.4. Difference in annual global CO_2 emissions (ktonne/year) compared to the reference case for the different technologies, when the taxes and policy instruments are included or excluded (tradable CO_2 emission permits are included in both scenarios).

7.6. Climate change mitigation potential

The effect on climate change mitigation potential was analysed for different measures associated with DH systems. Some of the global CO_2 reduction potentials were mentioned in the previous sections of this chapter, but this section summarises the climate change mitigation potential for these measures. The economic and global CO_2 emission effects for these measures are illustrated in Figure 7.5 and Figure 7.6. The outcome for supply-side measures is shown in Figure 7.5 while Figure 7.6 illustrates the effects of demand-side measures. For comparison reasons, the input data used in papers VI and VII were applied (see section 6.2 for input data) for all measures along with an SNG price of 57 EUR/MWh, which

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[8] The marginal source of electricity is assumed to be coal condensing power with a CO_2 emission factor of 1 tonne CO_2/MWh electricity.

is based on the fuel oil price used in papers VI and VII and the assumptions made in Wetterlund and Söderström (2010). Hence, additional studies were required for the supply-side measures. Regarding the global CO_2 emission reduction potential, this was evaluated with two different European marginal electricity production technologies, coal condensing power (CO_2 emission factor of 1000 kg/MWh electricity) and NGCC condensing power (CO_2 emission factor of 370 kg/MWh electricity) (Hansson et al., 2007; Sjödin, 2003; Uppenberg et al., 2001).

In the additional studies the DH system in Linköping was modelled, where different investment options were analysed one at a time regarding their effect on the DH system cost and on global CO_2 emissions. A reMIND model of the DH system was used for the additional studies. The model chooses the optimal design of the investment. Included in the studies are all costs associated with the investments, such as investment costs and fuel costs (for investment costs, see papers II and VII). For calculations of the change in DH system cost and global CO_2 emissions the DH system, where the investment option is included, is compared to the reference DH system without investments.

Figure 7.5 illustrates the potential annual change in DH system costs for the different DH investment options along with global CO_2 emission reduction potentials. Two sets of electricity prices were applied, where in Figure 7.5A the electricity prices from papers VI and VII were used (representing electricity prices at the lower end of the scale) and in Figure 7.5B the electricity prices from Scenario 5 in papers II and V were used (representing electricity prices at the higher end of the scale). The electricity prices in Scenario 5 were chosen because the oil prices and CO_2 charge used to calculate them correspond fairly well to the oil prices used in papers VI and VII. Since the model chooses the optimal size, the investment sizes and hence also the global CO_2 emission reduction potentials vary when the electricity prices change.

As can be seen from the figures, the outputs for the electricity generating plants (CHP) are highly dependent on the electricity prices. The two technologies with the highest electricity efficiencies (BIGCC CHP and NGCC CHP) are consequently the technologies that are most affected by electricity prices. With higher electricity prices the optimal investment in these technologies increases, which also enhances the potential for global CO_2 emission reductions. On the other hand, the outputs for the SNG technology are rather fixed regardless of the electricity price. Instead this technology is affected by the SNG price. Of the technologies studied, the biomass gasification applications (SNG and BIGCC CHP) and the NGCC CHP are the technologies with the largest global CO_2 reduction potential, while the biomass plant that only produces heat (bio HOB) is the investment with the smallest global CO_2 reduction and savings potential. However, the global CO_2 reduction potential for the technologies with high electricity efficiencies is highly dependent on the assumptions made about marginal electricity production. Regarding the effect on the DH system costs the SNG application is clearly the investment option with the largest savings potential for lower electricity prices, while with increasing electricity prices the two technologies with the highest electricity efficiencies are the most cost-effective investment options. Interesting to notice is that all investment options can contribute to cost-effective reductions in global CO_2 emissions.

A. Low electricity price

Global CO2 emissions (ktonne/year)

B. High electricity price

Global CO2 emissions (ktonne/year)
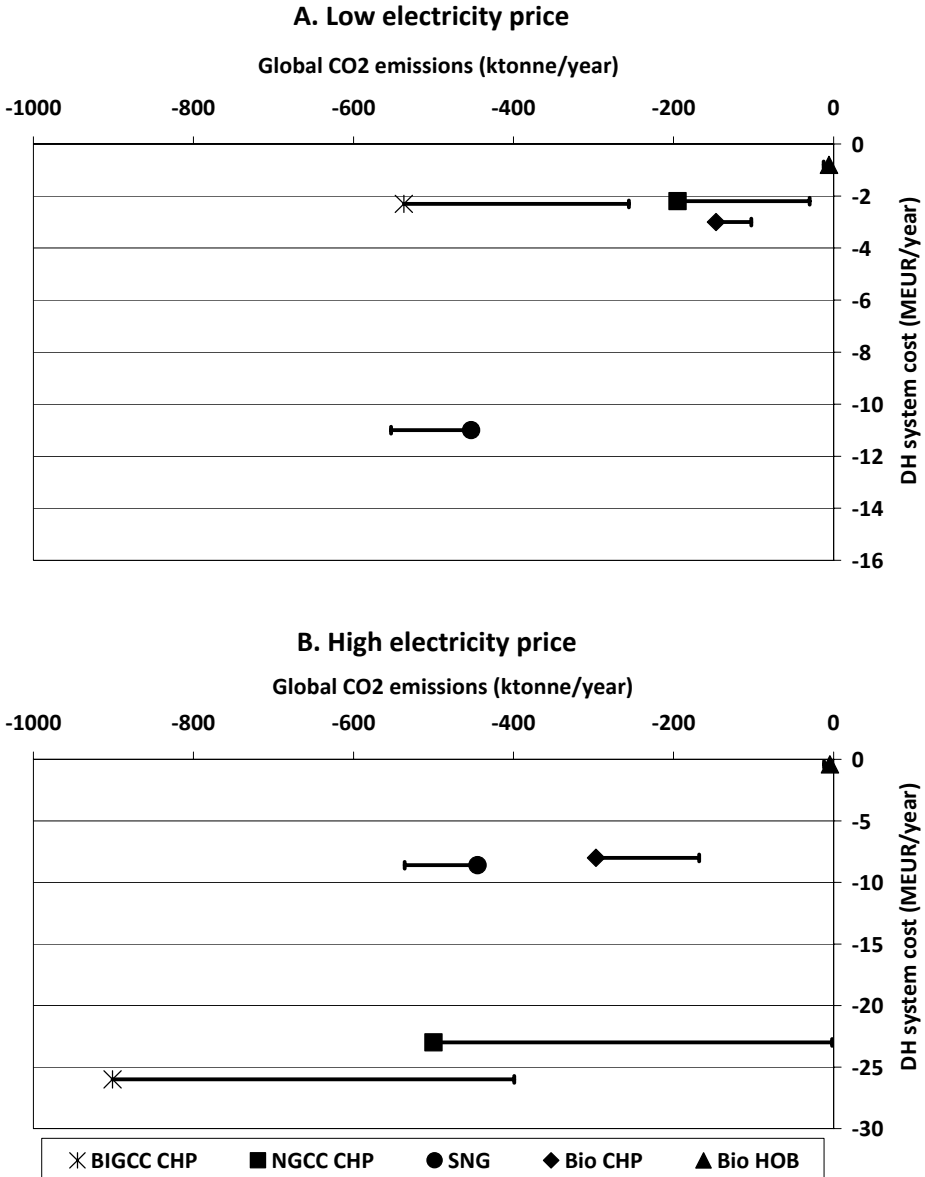
Figure 7.5. The potential annual change in DH system costs and global CO_2 emissions compared to the reference case, when implementing different investment options in Linköping's DH system for two electricity price levels. In A. lower electricity prices (used in papers VI and VII) and B. higher electricity prices (used for Scenario 5 in papers VI and VII) were applied. Two European marginal electricity production technologies were considered; the markers represent the global CO_2 emission reduction potential for coal condensing power and the error bars for NGCC condensing power.

The effect for the energy system costs when implementing different ECMs for the demand side in a DH system is displayed in Figure 7.6, along with the global CO_2 emission reduction potential. Considered in the energy system costs are both the changes in DH system cost and the end-users' energy costs. As can be seen in the figure, all the demand-side measures have the potential to decrease global CO_2 emissions. However, this depends on what the European marginal electricity production technology is. When coal condensing power is used to produce European marginal electricity, the heat load control measure can potentially increase the global CO_2 emissions. Of the demand-side measures studied, the electricity savings measure has considerably more global CO_2 emission reduction potential and the largest savings potential. The attic insulation measure can, on the other hand, increase the energy system costs.
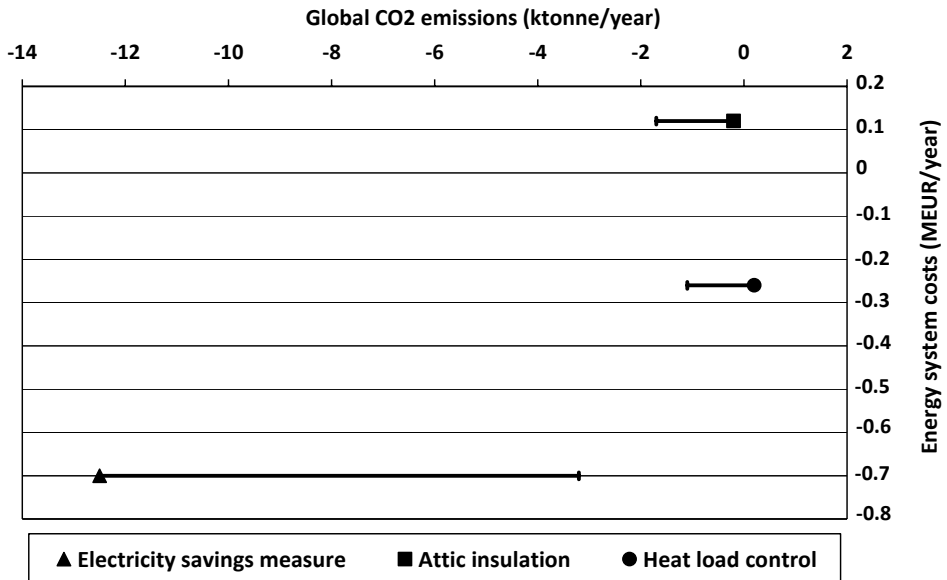
Figure 7.6. The potential annual change in the local energy system costs for Linköping, where both the changes in DH system costs and the change in residential energy costs are included, and global CO_2 emissions when implementing ECMs. Two European marginal electricity production technologies were considered; the markers represent the global CO_2 emission reduction potential for coal condensing power and the error bars for NGCC condensing power.

8. Discussion, conclusions and further work

This section includes discussions associated to the case studies performed in the thesis. Conclusions related to the research questions are also stated in this chapter, as well as some suggestions for further work.

8.1. Discussion

In many of the case studies performed in this thesis an optimisation model was used for energy system analysis. Energy models can be helpful tools for assessing the impact different measures and prices have on the energy system, but as with all models, the outcome is dependent on the input data. In many of the studies the energy system modelling is performed over a 10- or 20-year time period, and it is difficult to predict potential changes in future prices. In this thesis the input data, such as electricity and fuel price, have varied between the different case studies. In some cases scenarios or sensitivity analysis were applied to evaluate the energy system's robustness. The results are valid for the input data used, but changing the input data could alter the results, depending on the robustness of the energy system. Furthermore, most of the energy system modelling used the DH system in Linköping. When attempting to apply the results of this thesis to other DH systems, this aspect should be considered.

In all case studies the marginal electricity production method was applied. Estimating the marginal electricity production technology at every moment in the European electricity system is complicated enough; when considering a time perspective of 10-20 years this task becomes even more complex. Therefore, most studies performed in this thesis have considered various potential future marginal electricity production technologies.

Additionally, with the EU ETS and the cap on CO_2 emissions, GHG reductions in one part of the trading scheme can result in increased GHG emissions elsewhere within the scheme. The potential reduction in global CO_2 emissions illustrated in the case studies can hence induce increased CO_2 emissions in another sector included in the EU ETS. However, the CO_2 emission reductions shown in the case studies illustrate the global CO_2 reduction *potential*, which hopefully can contribute to a future lower cap on CO_2 emissions.

In the case studies where industrial energy audits were analysed the investment cost for the energy demand-side measures was not considered. Instead, the economic savings resulting from the energy demand-side measures are shown, i.e. the investment margin. Some of the measures require substantial investments, for example changing from electrical heating to DH, while other investments come with no costs or only minor expenditures, such as turning off equipment when no production is taking place or fine-tuning the ventilation system. Furthermore, the social aspects of implementing energy demand-side measures, i.e. barriers and driving forces, have not been considered in this thesis.

Moreover, in this thesis biomass is considered a renewable energy source and has hence been regarded as climate neutral. However, depending on the growth situation of a particular plant used for its biomass and the transportation it can be debated whether biomass should be considered climate neutral. Moreover, since there is a limit to biomass quantity, biomass cannot be used unrestrictedly. Consequently, alternative use of biomass should be considered for not overestimating the CO_2 mitigation potential. This aspect has not been considered in this thesis but should be considered for more comprehensive CO_2 emission evaluations.

In Paper VII the results indicate that NGCC CHP plants can contribute to reduced global CO_2 emissions even though the local CO_2 emissions increase. However, for comprehensive analysis of the utilisation of natural gas other aspects must be considered besides CO_2 emissions. Natural gas is a fossil fuel with limited quantities. Also, the security of the supply must be taken into account. Natural gas is currently only available in the southern and southwestern parts of Sweden, but expansion plans include augmenting the present transmission network to also include the county of Östergötland and the municipality of Linköping (Amiri et al., 2009).

8.2. Conclusions

To minimise environmental impacts it is necessary to construct efficient energy systems, where energy is used in a resourceful way. The aim of this thesis is therefore to identify how a local energy company can contribute to energy-efficient systems and cost-effective reductions of global CO_2 emissions along with its customers. The hypothesis stated in the introduction is that measures can be identified, both for the local energy company and its customers, that will lead to more energy-efficient systems in combination with cost-effective global climate change mitigation when using a European energy systems approach. This hypothesis was evaluated in the following four research questions, which are further discussed here:

1. Which investments in a local DH system can lead to decreased global CO_2 emissions in combination with reduced costs for the DH system?

2. What effect will energy demand-side measures have on the local energy system in terms of energy usage, end-user energy costs and DH system costs, as well as on climate change mitigation potential?

3. How will the pricing of DH affect the DH system and its customers regarding end-user energy costs, DH system costs and global CO_2 emissions?

4. How do energy policy instruments influence the choice of investments in the DH sector and the reduction potential of global CO_2 emissions?

Regarding the first research question, biomass gasification applications can be favourable investment options for DH systems, as concluded in Paper II, given further technology development. The high added value of the products of gasification applications (electricity and SNG) makes heat from gasification applications competitive even with heat from waste incineration, where the fuel has a negative purchase cost. Biomass gasification, which can enable higher electrical efficiencies than conventional biomass-combustion-based technologies, can hence be a step on the way to reaching the EU targets of higher energy efficiencies and increased use of renewable energy sources. For the next generation of biofuels, such as SNG, biomass gasification can be a potential production application. However, due to the large amounts of heat generated from the SNG process, integration with a heat sink, such as a DH system, is essential to achieve an energy-efficient process. It is also concluded in the study that policy instruments promoting biofuels are necessary for the implementation of biomass gasification of SNG. Moreover, besides being economically beneficial, biomass gasification applications can contribute to larger reductions of global CO_2 emissions compared to a DH system without gasification applications.

Another application feasible for DH systems is absorption cooling, explicitly studied in Paper III. Absorption cooling is extremely compatible with DH systems because cooling demand peaks during the summer, when DH systems have a surplus of heat. In both economic and environmental terms, in the form of reduced global CO_2, ACs are preferable to CCs. The potential global CO_2 emission reduction for DH systems containing ACs can be as high as 300 kg CO_2 per MWh of DC produced, compared to systems without ACs. ACs can also be utilised on the demand side instead of CCs. Demand-side measures are connected to the second research question. By examining energy audits the industrial energy use was mapped out and the potential for reducing the electricity and fossil fuel use in combination with converting processes to DH was analysed. As concluded in papers I and IV, the potential for decreasing electricity and fossil fuel use is substantial when converting processes to DH and DC. By converting industrial processes to be DH-driven instead of electricity- or fossil fuel-driven the local energy system can become more energy-efficient. The applications where DH can replace electricity are primarily when converting electrical heating and compression cooling to DH and DC. Paper I demonstrated that the industrial electricity use can be reduced by 30% for the eight companies studied, when considering both electricity efficiency and conversion measures. In Paper IV 34 industrial energy audits and 7 cooling audits were studied and the outcome showed that when only considering conversion measures to DH, the industrial electricity use can be reduced by 11% and the fossil fuel use reduced by 40% with an overall energy savings of 6%.

Besides reductions in industrial electricity and fossil fuel use, conversion of processes that are not outdoor temperature-dependent can generate a more evenly distributed heat load for the DH system. A more evenly distributed heat load can decrease the operation of peak load plants and increase the operation of base load plants, such as CHP plants, as well as increase the minimum heat demand, which can result in investments in larger base load plants. Paper V demonstrates how a changed heat load, due to conversion of industrial processes to DH, can increase the electricity production in a DH system by up to 20%. This increase is possible since the changed heat demand also affects the minimum heat demand, making it possible to invest in larger base load CHP plants. Overall, the changed heat load results in a more uniformly utilised heat demand. Consequently, conversion of industrial processes from fossil fuels and electricity to DH can both reduce the industrial electricity and fossil fuel use and contribute to extra electricity production in CHP plants. This extra electricity production and the freed electricity when converting industrial processes to DH can, when taking into account

a deregulated European electricity market, result in replacement of electricity that would otherwise be produced in European condensing plants. For example, in Paper IV it is established that the global CO_2 emissions can potentially decrease by 260 kg CO_2 per MWh increased DH when converting industrial processes from electricity and fossil fuels to DH. When also considering the extra electricity production in CHP plants, the global CO_2 emission reduction potential can double.

In addition to industrial energy demand-side measures, ECMs for the residential sector were analysed. Since the DH supplier has the possibility to promote certain measures by offering services such as energy audits, the effects on the DH supplier and the residences were studied when implementing ECMs. For the ECMs included in the study (heat load control, attic insulation and electricity savings measure) the electricity savings measure is the most economically beneficial measure for the residences, the DH system and consequently also the local energy system. Heat load control also shows profitable results for both the DH users and supplier, while attic insulation is unprofitable for the DH supplier and hence also for the local energy system. For the residences, attic insulation can be economically beneficial, but this depends on the building category. Consequently, for the residences there is a potential for reduced energy costs when implementing ECMs but this has to be evaluated on a case by case basis. From a global CO_2 perspective the electricity savings measure has the largest effect regardless of the marginal electricity production considered. Thus, reduced electricity use should be prioritised over a reduction in DH use, both from an economic viewpoint as well as from a global CO_2 emission aspect.

Furthermore, in the study of the ECMs' influence on the local energy system, marginal DH costs were calculated as variable DH prices along with a peak demand fee. The pricing of DH is connected to the third research question. Conclusions from the ECM study (Paper VI) are that the peak demand fee has a large impact on the cost for the DH supplier and that the DH supplier can promote different measures by adjusting the relation between the variable and fixed DH costs. The pricing of DH has also been studied in Paper I. To avoid increased industrial energy costs when electricity prices rise to a European level, the industries can convert processes from electricity to DH, given the assumption that the DH tariffs are based on marginal DH costs. Hence, to construct a favourable DH system the DH supplier has to review the pricing system for DH. Also, with an incorrect pricing system for DH, measures that would increase DH demand, such as conversion of electrical heating and cooling systems to DH and DC, might not be implemented. When marginal costs are used as DH tariffs the heat demand can increase, which can affect the DH system cost in a favourable way. Conversion of electricity-using processes to DH also has the potential to reduce global CO_2 emissions – without correct pricing of DH this global CO_2 potential may not be fully utilised.

The last research question addresses the effect of national energy policies on the climate change mitigation potential. Conclusions from Paper VII are that TGCs, which aim to promote renewable electricity, instead can decrease the global CO_2 emissions reduction potential. Since CO_2 emissions have a global character it is important to consider the whole perspective and not solely focus on national CO_2 emissions. For a DH system containing the NGCC CHP plant electricity production can increase by over 160% compared to the reference scenario and by 100% when comparing with the DH system containing the bio CHP plant. This extra electricity production can replace marginal European electricity production, resulting in an annual global CO_2 emissions reduction potential of nearly 200 kg CO_2 per MWh of DH. If the alternative use of biomass is also considered, the climate change mitigation potential for the bio CHP technology decreases even further. Hence, an efficient

fossil fuel technology like the NGCC CHP technology with high power-to-heat ratio can potentially reduce the global CO_2 emissions more than a biomass-fuelled electricity generating technology. However, this is highly dependent on the marginal electricity production technology in use in Europe.

Interesting to notice is that the results from this thesis indicate that for most measures studied there is no conflict between reduced CO_2 emissions and the economic aspect. For all measures studied (except attic insulation) the CO_2 mitigation cost is negative, implying that the measures are cost-effective while simultaneously having potential to decrease the global CO_2 emissions.

The major conclusions from the thesis can be summarised as follows:

- Of the technologies studied, the biomass gasification applications (SNG and BIGCC CHP) and NGCC CHP are the technologies with the greatest global CO_2 reduction potential. However, the global CO_2 reduction potential for the CHP plants is highly dependent on the marginal European electricity production technology.

- Regarding DH system costs the SNG application is clearly the investment option with the largest savings potential for lower electricity prices, whereas with increasing electricity prices the BIGCC CHP and NGCC CHP are the most cost-effective investment options.

- DH-driven absorption cooling is an application suitable for DH systems, because cooling demand peaks during summer months, when DH systems often have surplus heat from CHP plants. Absorption cooling can contribute to the DH heat load profiles becoming less outdoor temperature-dependent, which can increase electricity production in CHP plants. In both economic and environmental terms, in the form of reduced global CO_2, ACs are preferable to CCs.

- Conversion of industrial processes that utilise electricity and fossil fuels to DH can have the following benefits: (1) DH heat loads become more evenly distributed over the year; (2) electricity production in CHP plants increases; (3) electricity and fossil fuel use decreases; (4) an overall energy savings; and (5) reduced global CO_2 emissions.

- From economic and global CO_2 emission perspectives, residential ECMs reducing electricity use should be prioritised over a reduction in DH use.

- The TGC system can, when applied to DH systems, contribute to investments that will not fully utilise the DH systems' potential for global CO_2 emissions reductions.

To conclude, in this thesis it is demonstrated that by applying supply- and demand-side measures in a local energy system, energy-efficient systems can be realised and significant contributions to the climate change mitigation can be achieved in a manner that is cost-effective.

8.3. Further work

There are many interesting studies that could be performed in the area of local and regional energy systems and the synergetic effects between participants. Some of the potential developments of this thesis are stated here.

In this thesis mainly the DH system in Linköping was studied. This DH system has its specific plants and load profile; it would be interesting to study other DH systems for validation of the outcomes from this thesis. Some further development could also be done by including additional investment options. Also, additional studies of the effect of TPA to the DH systems regarding the plant operation, system cost and climate change mitigation potential would be interesting to perform.

Although a number of industrial energy audits were analysed in this thesis, additional industrial energy audits could establish the energy use pattern for different sectors of trade. From these energy use patterns generalised heat load profiles could be obtained for different industrial sectors of trade as well as for different processes. The local DH supplier could then, with the help of the generalised heat load profiles, analyse the total effect on the local DH demand when converting the regional industries' processes to DH. Also, further studies of the price structure for DH should be performed in order to construct ideal DH price systems.

For the residential sector three ECMs were included but additional measures and sensitivity analysis of investment costs for the ECM could be included in future studies.

Other studies interesting to perform include more thorough analyses of energy policy instruments in order to design policy measures that would stimulate energy-efficient systems. Studies could also be performed in which policy instruments are replaced by external cost and the effect on the energy system is evaluated.

Also, further studies could take into consideration a limitation in biomass quantity and an alternative use of biomass, in order to more comprehensively evaluate the CO_2 emissions mitigation potential for energy systems.

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