EFFICIENT HEAT SUPPLY AND USE FROM AN ENERGY-SYSTEM AND CLIMATE PERSPECTIVE

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This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyzes processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

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

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ABSTRACT
The aim of this thesis is to illustrate whether the heat demand in district heating systems can be seen as a resource that enables efficient energy utilization, how this can be achieved and to discuss consequences of this assumption. Based on the answers to posed research questions and on the studies included in this thesis, it is concluded that the hypothesis “A common system approach for energy supply and heat demand will show climate and economic efficient solutions” is true.

In cold-climate countries, energy for heating of buildings is essential and heating options that interplay with the power system through electricity use or generation have potential for efficiency improvements. In Sweden, district heating is used extensively, especially in large buildings but to a growing extent also for small houses. Some industrial heat loads and absorption cooling can complement space heating demand so that the production resources may be more evenly utilised during the seasons of the year.

Rising electricity prices in recent years cause problems for the extensive use of electric heating in Sweden and further switching to district heating should be a possible option. To be economically favourable, district-heating systems require a certain heat load density. New low-energy houses and energy-efficiency measures in existing buildings decrease the heat demand in buildings and, thus, in district heating systems.

Optimisation models have been used in several studies of large, complex energy systems. Such models allow scenarios with changing policy instruments and changed consumer behaviour to be analysed. Energy efficiency measures as well as good conditions for efficient electricity generation, which can replace old, inefficient plants, are needed to reduce carbon dioxide emissions from the energy sector.

Results when having a European energy perspective to studies of changes in Sweden differ from when having for example a Swedish energy system perspective The effects on global carbon dioxide emissions, when studying combined heat and power electricity generation in Sweden, are greater than it is on local emissions.
SAMMANFATTNING
Syftet med denna avhandling är att visa om värmebehovet i fjärrvärmesystem kan betraktas som en resurs som möjliggör ett effektivt energiutnyttjande, hur detta i så fall kan uppnås och att diskutera följderna av att göra ett sådant antagande. Baserat på svaren på ställda forskningsfrågor och studier som genomförts har hypotesen som lyder: *En gemensam systemsyn för både tillförsel och användning av energi för uppvärmningsändamål leder till ekonomiskt såväl som ur klimatsynpunkt effektiva lösningar*, visat sig stämma.

I länder med kallt klimat är energi för uppvärmning av byggnader viktigt och uppvärmningsalternativ som samverkar med elsystemet genom elanvändning eller elproduktion har potential för effektivitetsförbättringar. I Sverige är fjärrvärmeanvändningen utbredd, speciellt i större byggnader men användningen ökar också i småhus. Vissa industriella värmelaster och absorptionskyla kan fungera som komplement till andra värmebehov i fjärrvärmesystem så att produktionsresurser kan användas mer jämnt fördelat över året.


Optimeringsmodeller har använts i flera studier för stora, komplexa energisystem. I dessa kan scenarier med olika styrmedel och förändrad energianvändning analyseras. Nya användningsområden för spillvärme, som att använda värme till absorptionskyla och att växla från olja och el till fjärrvärme i industriella processer kan också studeras. Energieffektiviseringsåtgärder såväl som bra förutsättningar för effektiv elproduktion, som kan ersätta gamla ineffektiva anläggningar behövs för att minska koldioxidutsläppen från energisektorn.

Resultaten då ett europeiskt energisystemperspektiv använts, för att studera förändringar i Sverige, skiljer sig från när endast ett svensktsystemperspektiv används. Påverkan på globala koldioxidutsläpp, då elproduktion från kraftvärme i Sverige studeras, är större än vad påverkan på lokala utsläpp är.
From all of these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.
LIST OF APPENDED PAPERS

Paper I
**Stockholm CHP potential- An opportunity for CO2 reductions?**

Paper II
Patrik Thollander, Maria Danestig and Patrik Rohdin, (2007).
**Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs**

Paper III
Kristina Difs, Maria Danestig, and Louise Trygg
**Industrial district heating applications**
Submitted for journal publication.

Paper IV
Maria Danestig and Dag Henning, (2004).
**Increased system benefit from cogeneration due to cooperation between district heating utility and industry**
Proceedings of the 9th international symposium on district heating and cooling, Espoo, Finland, 30-31 August, ed. T. Savola, Helsinki university of technology, Department of mechanical engineering, Energy engineering and environmental protection publications TKK-ENY-20, pp. 97-104.

Paper V
**Modelling the impact of policy instruments on district heating operations experiences from Sweden.**
In lectures, 10th International Symposium on District Heating and Cooling, Hanover, Germany, 3-5 September. AGFW-VDEW, Frankfurt a M, Germany.

Paper VI
Dag Henning and Maria Danestig, (2008).
**Local development possibilities for sustainable energy supply and use in Sweden.**

Paper VII
Maria Danestig and Dag Henning (2008).
**Efficient heat resource utilisation in energy systems**
Paper VIII
Maria Danestig and Karin Westerberg
A multidisciplinary and interactive method for exploring energy systems in municipalities.
Submitted for journal publication.
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One of the most exciting times during the past years was when having the introduction courses in the Program Energy systems since it led to contacts with researchers from different disciplines and from several universities. I would like to thank Karin Westerberg for the fun and interesting sharing of knowledge and good co-operation. Thank you also to all the participants in the consortium for local and regional energy systems, which gave the opportunity to lift eyes from the own work and see some other things for a while.

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The work has been carried out under the auspices of the Energy Systems Programme, which is financed by the Swedish Energy Agency. I would also like to thank the Swedish Energy Agency for being an understanding and vitalising employer during the last six months.
THESIS OUTLINE
The thesis consists of an introduction to, and a summary of, the eight appended
research papers. The thesis is outlined as follows:

In Chapter 1 a brief background and introduction to the studies is done. It also
contains the hypothesis and research questions on which the studies and the
results, presented at the end of the thesis, are based and discussed.

Chapter 2 gives an introduction to energy systems, mainly as they are described
by national, European and international organizations. It contains statistical,
regulatory and other information on energy in order to give a perspective of the
properties and the importance of energy supply and demand in Europe with a focus
on Sweden. Special attention is paid to electricity and heat, what the resources are,
how electricity and heat are produced and what they are used for.

In Chapter 3 the negative effect that carbon dioxide emissions have as regards
global warming is described along with the connection to energy supply and use.
An indication that CHP and district heating can contribute to decrease the
emissions in the short term is also given.

Chapter 4 presents some important facts on district heating together with the
connection between district heating and CHP.

Chapter 5 discusses energy policies where it is most common to address economic
energy policy instruments. This description will only include some of the policies
and how the Swedish energy system has been developed and is affected.

In Chapter 6 an overview of some methods and assumptions together with some
basic technical issues is given to provide some background to the studies carried
out in the thesis. Other related studies are referred to in the descriptions as
complements to increase understanding.

The studies that were carried out are presented in Chapter 7 in the form of short
descriptions of the resulting papers.

In Chapter 8 the results are presented under the following themes: system
perspective in the light of global warming, supply and demand of heat, heat loads
in district heating systems, local planning and energy, impacts of economic
policies, and impacts of local activities.

A discussion is presented in Chapter 9 with the aim to throw light upon some
questions at the same time as the view of the results is broadened.

The conclusions are presented in Chapter 10. The research questions are
answered to and an answer to whether the hypothesis is true or false is also given.

Suggestions for further work related to this thesis are given in Chapter 11.
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Chapter 1

1 INTRODUCTION

This chapter provides a brief background and introduction to the studies. It also contains the hypothesis and research questions on which the studies and the results, presented at the end of the thesis, are based and discussed.

Since most researchers around the world now state that an intensified greenhouse effect is a reality and that human activities contribute to global warming, action should be taken to reduce the effects. Fossil fuels (coal, oil and gas, see Figure 1) supply 65-70 percent of the world’s energy and also account for the largest part of global anthropogenic carbon dioxide (CO₂) emissions. Since CO₂ emissions in one place affect global warming, local energy systems should be studied in a larger system perspective to embrace the total effect on CO₂ emissions of local actions. In the European Union (EU), over 50 percent of the electricity comes from fossil fuels, mainly coal, which accounts for about 30 percent of overall electricity generation in the EU. In 2005, CO₂ emissions from coal-based electricity generation accounted for 70 percent of total CO₂ emissions from electricity generation in the EU, and 24 percent of CO₂ emissions from all sectors taken together (COM 2006). Most of the thermal electricity generation in EU takes place in condensing power plants.

In cold-climate countries, energy for heating of buildings accounts for a large part of the total energy supply and use. Reducing CO₂ emissions from this sector is therefore necessary in the efforts to dampen the effects of global warming. District heating has played an important role in the Swedish energy system when changing the supply for heating from mainly oil at the beginning of the 1970s to bio-fuels and waste combustion over the last 20 years.

About 30 percent of the heat in district heating systems in Sweden is supplied from combined heat and power (CHP) plants, which is low compared with neighbour countries with a large share of district heating. In Finland and Denmark, CHP supplies 70-80 percent of district heating. Since district heating exists in almost every
In residential and service sectors, some 20 percent of Swedish buildings are heated by electricity (including input electricity for heat pumps) and about 45 percent by district heating (SEA, 2008). Rising electricity prices in recent years are causing trouble for electrically heated buildings and industries with electricity based processes. Almost 40 percent of the energy used in Swedish industries comes from electricity and only 3 percent from district heating. When comparing the alternatives for electric heating, further switching to district heating should be one possible option in several applications.

The heat load density of a built area is crucial when evaluating the economic possibilities for district heating. The heat load density depends on how highly an area is exploited and the type of activity that takes place in that area. The heat load density can be decreased by energy efficiency measures and be low in, for instance, places with low-energy buildings.
Chapter 1

When changing the heat demand in district heating systems, in particular when combined heat and power, waste incineration, or industrial waste heat is used, the consequences are complex. The aim of decreasing heating demand is often to decrease the use of natural resources. To achieve this, the end user, or other decision maker, must have the knowledge and incentives for choosing an appropriate alternative. This thesis could contribute to the required knowledge.

1.1 Aim, scope and research questions

In this thesis the focus is on heating, more specifically heat that could be supplied from district heating. A district heating system with CHP production is closely connected to the electricity system. Electricity is also often used for heating, which connects not only the technical energy system but also the energy markets and economies. The aim of this thesis is to illustrate whether the heat demand in district heating systems can be seen as a resource that enables efficient energy utilisation, how this can be achieved and to discuss consequences of this assumption.

Hypothesis:

A common system approach for energy supply and heat demand will show climate and economic efficient solutions

This is evaluated through the following research questions:

- How important are concerns about local carbon dioxide emissions in relation to global carbon dioxide emissions?
- What are the benefits of combined heat and electricity generation?
- How does a European energy perspective and assumptions of marginal electricity generation affect energy system studies?
- How can energy system studies comprising both industry and households be useful?
- How can a focus on knowledge and implementation of energy measures be reached?

1.2 Co-author statements

Paper I
The model calculations were made and the paper was written by the author, with complementary support on facts and model design issues from Gebremedhin. The work was supervised by Björn Karlsson.

Paper II
The paper builds on Thollanders earlier work. The author contributed to parts on local energy and industrial programmes as well as in analysing results. The paper was
completed in collaboration with Thollander and Rohdin and the work was supervised by Mats Söderström.

Paper III
The idea of the content of the paper was formulated by the three authors together. The author was responsible for the paper until last review. After this, Difs was responsible for most part of revisions and all authors contributed to the completion of the paper.

Papers IV, VII and VIII
The author was responsible for the paper, which was written by the two authors in collaboration.

Paper V
Henning edited the paper and authors participated with different parts. The author contributed on emission allowances and district heating as heat sink.

Paper VI
Henning edited the paper, which was written by the two authors in collaboration.

1.3 Other publications not included in the thesis


2 ENERGY SYSTEMS IN EUROPE AND SWEDEN

This chapter gives a brief introduction to energy systems, mainly as they are described by national, European and international organizations. It contains statistical, regulatory and other information on energy in order to give a perspective of the properties and the importance of energy supply and demand in Europe with a focus on Sweden. Special attention is paid to electricity and heat, what the resources are, how electricity and heat are produced and what they are used for.

In the European Union (EU), directives have been introduced aimed at establishing an internal market for electricity where customers are offered freedom of choice at fair, competitive prices. Although the internal energy market is well established, attention has been paid to the fact that malfunctioning still persists, preventing both consumers and the economy from receiving the full benefit of the advantages of a fully functioning market. This has been addressed in the communication from the EU Commission to the European Council and Parliament in *An Energy Policy for Europe*, of which the goal is to combat climate change and boost the EU’s energy security and competitiveness (COM 2007:1). The policy states that in order to increase competitiveness in the European energy market, there must be a clearer separation between the management of gas and electricity networks, production and sales. This is to prevent a company which controls both management of networks as well as production or sales from discriminating and abusing consumers. To overcome the difficulties of achieving cross-border trading, disparities between different national technical standards and shortages of network capacity must be eliminated. According to the EU commission this requires harmonisation of competences and independence of energy regulators and that they are obliged to take on the objectives needed to realise the internal market.

Since energy accounts for 80 percent of all greenhouse gas emissions in the EU, several important goals have been set to limit emissions, see Chapter 3. Over 50
percent of the primary energy use in EU, Figure 2, is imported hard coal, crude oil and natural gas (natural gas mainly from Russia). A considerable part is also imported from Norway, Saudi Arabia and Algeria (Eurostat, 2007). The security of energy supply issue concerns for instance the problem that some EU Member States are dependent on one single gas supplier. The new EU energy policy emphasises the importance of measures which ensure solidarity between EU Member States and diversification of supply sources and transportation routes (COM 2007:1). Measures supporting strategic oil stocks must be reinforced and the possibilities for improving the security of gas supply must be explored. Greater security of electricity supply, which remains crucial, must also be guaranteed. This cannot all be done by the EU itself and requires cooperation and international energy agreements with other countries outside the union. This is also most important as regards climate change issues.

The EU must develop both existing energy-efficient technologies and new technologies, in particular as regards renewable forms of energy. Even if the EU considerably diversifies its energy mix, it will still be highly dependent on oil, coal and gas. In *An Energy Policy for Europe*, low carbon-output fossil fuel technologies, especially carbon capture and storage systems, are highlighted as important.

*Figure 2. Gross primary energy use in EU27, 2006 (Eurostat, 2007). (Conversion 1 TWh=86000toe (SEPA, 2009)).*
The natural preconditions for energy supply and use vary among regions and countries. For heating demand the varying outdoor temperature conditions have major effects. Concerning supply, resources such as hydropower and geothermal energy also have major effects on the differences.

### 2.1 Electricity

The primary energy use for electricity generation in the EU is to more than 50 percent based on fossil fuels (Figure 3 and Figure 4).

![Figure 3. Electricity generation 2006, TWh. Fuels in thermal generation: hard coal, lignite and peat, petroleum products, natural gas, derived gases, biomass and industrial wastes, (Eurostat, 2007).](image)

The Swedish electricity system on the other hand is based on approximately 50 percent hydropower and 50 percent nuclear electricity generation. This shows that the Swedish
generation system has major differences compared to electricity generation in the rest of the EU, but the Swedish contribution is only about 5 percent of the total EU generation.

The deregulation of the electricity market in the EU facilitates trading, which should be based on market prices. The power plant in operation with the most expensive electricity generation at a given moment in the common energy system is the marginal generation plant, which ideally increases and reduces electricity generation as the electricity demand varies. The cost for running this plant should be the current market price for electricity. If someone more is willing to pay this price, the marginal generation plant increases generation. In practice, this does not work exactly according to the theoretical model of a perfect market; but when modelling future changes, assumptions must be made and one way of doing this is to study the intended functioning of the system. When considering Sweden as a part of the common EU electricity market, the valuation of Swedish electricity supply and use must be made assuming that Sweden is integrated in the European system.

The Swedish electricity system is more often seen as a part of the Nordic electricity market, including Denmark, Finland and Norway. Most wholesale trading of electricity takes place on the Nord Pool exchange, which harmonises the Nordic electricity prices, even though different prices appear in different system regions primarily due to bottlenecks in the electricity transmission system (Nord Pool, 2009). In addition to the common wholesale exchange, the Nordic power system includes

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Figure 4. Total gross electricity generation in EU 27, year 2006, 3358 TWh (Eurostat, 2007).
common grid planning, i.e. criteria for transmission system planning, rules for system operation, and minimum technical requirements for connecting power plants to the grid. It also comprises auctions of cross-border capacity between the Nordic countries, co-ordinated planning of required outages in the transmission grid, and continuous exchange of real-time operational data to ensure that the Nordic power system is operated as a single regional system (IEA Sweden, 2008).

Due to the favourable electricity generation preconditions the electricity prices in Sweden have historically been relatively low and electricity has been used extensively in several applications such as electric heating and mechanical processes in the paper and pulp industry, which are not common in other countries. Annual electricity use is almost 16 MWh per citizen, one of the highest in the world (IEA Sweden, 2008).

Wholesale prices in the Nordic region have been driven higher in recent years by more expensive fossil fuels, and, since 2005, by the European emission trading system (ETS, see chapter 5). Although the bulk of electricity in the Nordic market is generated by hydropower and nuclear power, the price of CO₂ allowances needed for fossil-fired generation is reflected in the wholesale prices, because coal-fired power is normally the price-setting marginal production mode. This mechanism has generated so-called windfall profits for the owners of plants not emitting CO₂ (IEA Sweden, 2008).

Electricity use in Sweden varies from year to year, mainly as a result of changes in outdoor temperature and in the business cycle of heavy industry. The cold climate and high proportion of electrically heated residences also make Swedish electricity demand peak in winter.

Sweden is well connected to the other countries in the Nordic market area and it also has interconnectors to Poland and Germany. The maximum net trade capacities in the north European electricity system are shown in Figure 5. The total trade capacity from and to Sweden exceeds 8000 MW.
2.2 Heating

The difference in heating demand among European countries is substantial and heating is one of the basic needs for people living in cold-climate countries. Indoor climate control also often includes cooling in the hot seasons which has a large impact on energy demand in warm-climate countries. The annual mean outdoor temperature in Palermo, in southern Italy, is very close to the desired indoor temperature ($20^\circ$C). In Kiruna, in northern Sweden, the heating demand is present almost every day of the year (Euroheat & Power, 2006a). History and natural resources have also affected the nature of heat supply in different countries. The top five European heating demand per capita countries, for industrial and residential sectors, are Finland, Luxembourg, Sweden, Iceland and Norway. In these countries, except Luxembourg, electricity accounts for a large part of the heating and natural gas has a small share in comparison with most other countries in Figure 6.
The hydropower resources in Sweden and Norway are one explanation for the large share of electricity and in Sweden and Finland large amounts of nuclear power are another reason. Electric heating in buildings is mainly resistant panel radiators or water distributed heating from electric boilers. Electric heating is one of the most common heating alternatives in Swedish single and two-family houses, even though electric heating has steadily decreased its share in recent years. The switch to electric heating evolved after the oil crisis of the 1970s and was earlier a cheap heating method due to the historically low electricity prices in Sweden.

Individual solutions such as boilers for fuel oil, LPG, coal, and firewood are normally used in European rural areas. Other individual solutions are electricity use in boilers, panel radiators-, or heat pumps and hot water storage tanks. The solutions can also be used in urban areas, but the use of firewood is normally only allocated to rural areas close to supplies. Natural gas, for local heat generation in boilers or stoves, is mainly distributed in urban and suburban areas. If the population density is high enough, natural gas is also distributed to small towns and villages in semi-rural areas. But in Sweden, natural gas is only available in the South-West part of the country.

Figure 6. Industrial and residential sectors heat demand and final energy supply, MWh per capita (Euroheat&Power, 2006a).
District heating networks, in Sweden, are most common in high density urban areas with multi-family, public, and commercial buildings, see Figure 7. District heating is also competitive in less dense suburban areas if the district heat source is cheap and the alternative heat supply is expensive (Euroheat & Power, 2006b). District heating has increased strongly in Sweden since 1990. Measured by floor area, 77 percent of apartments and 59 percent of commercial premises are heated with district heating.

Biomass is an important heat source in Sweden and its contribution to total primary energy supply grew from 12 percent in 1990 to 18 percent in 2006. Nearly half of the total biomass consumption for energy purpose is used by industry, around 40 percent in district heating and CHP plants, roughly 10 percent in the residential sector, and 2 percent for road transport (IEA Sweden, 2008).

In the industrial sector, high temperature heat demand is predominant with a 43 percent share, while medium temperature demand accounts for 27 percent, and low temperature demand for 30 percent (Euroheat & Power, 2006a). High temperature means temperature levels over 400°C. This high quality energy is needed for the manufacture of metals, ceramics, glass, etc. These temperatures can be achieved by using hot flue gases, electric induction, etc. Medium temperature covers an interval between 100°C and 400°C. This heat is normally supplied using steam as heat carrier. The purpose is often to evaporate or to dry. Low temperature is defined as below 100°C. This heat is used in low temperature industrial processes such as washing, rinsing, and food preparation. Some heat is also used for space heating of industrial buildings and on-site hot water preparation (Euroheat & Power, 2006a).
3 CARBON DIOXIDE EMISSIONS – THE GLOBAL CONNECTION

The negative effect that carbon dioxide emissions have as regards global warming is described along with connection to energy supply and use. An indication that CHP and district heating can contribute to decrease the emissions is also given.

In its fourth assessment report, "Climate Change 2007", the intergovernmental panel on climate change (IPCC) states that warming of the climate system is now unequivocal. This is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC, 2007). Global greenhouse gas (GHG) emissions from human activities have grown since pre-industrial times, with an increase of 70 percent between 1970 and 2004. Carbon dioxide (CO₂) is the most important anthropogenic GHG. Annual CO₂ emissions grew by about 80 percent between 1970 and 2004 when the CO₂ from fossil fuels accounted for almost 60 percent of the GHG emissions. The long-term trend of declining CO₂ emissions per unit of energy supplied reversed after 2000. Atmospheric concentrations of CO₂ and methane (CH₄) in 2005 far exceeded the natural range over the last 650,000 years (IPCC, 2007).

One of the main issues in the EU is to handle the question of climate change and in the Energy Policy for Europe measures to limit the global average temperature increase to 2°C Celsius compared with pre-industrial levels, was put in place. To meet the demands to reduce carbon dioxide emissions, the goal is to reduce EU CO₂ emissions by at least 20 percent compared to 1990 levels by 2020. Goals have also been set to reduce energy use by 20 percent, increasing the fraction of renewable forms of energy in the EU energy mix to 20 percent and to raise the share of bio-fuels to at least 10 percent of fuel consumption for transport (COM 2007:1 and 2). Among the largest challenges is to cope with energy use for transportation which accounts for over 30 percent of the European primary energy use, see crude oil and petroleum products in Figure 2.
Chapter 3

In a short time perspective, 10 to 20 years, district heating and combined heat and power production can contribute significantly to reducing CO₂ emissions in the European energy system. Driving forces for this are the emissions trading system (see chapter 5) and the current electricity production system which has high marginal emissions of CO₂ (Werner, 2001).

![Figure 8. Share of renewable energy to final energy use, 2005, including use in energy business and distribution losses (Eurostat, 2007).](image)

The contribution from renewable electricity varies between countries, as can be seen in Figure 8. Since some countries, like Sweden and Austria, have a major part of renewable electricity generation from hydropower, the renewable part of the electricity generation is high, but in Sweden the CHP electricity production does not contribute to the renewable electricity production as much as could be expected when considering the cold climate and extensive district heating systems.
Chapter 4

4 DISTRICT HEATING – AN OPPORTUNITY FOR CHP

Some important facts on district heating are presented together with the connection between district heating and CHP.

Deliveries from the first Swedish district heating system began in 1948, almost 30 years after the first European district heating system, in Hamburg, began operating. District heating deployment increased in the 1950s and at this time it was seen that the major hydropower resources would be fully exploited in the not too distant future. The municipalities saw the possibilities of CHP and further district heating networks were built in the 1960s and 1970s. Due to the starting up of the Swedish nuclear programme, the district heating systems evolved without CHP (Hård & Ohlsson, 1994), driven by the possibility to use cheap heavy oil as fuel. Later on, other motives such as possibilities to cope with local environmental problems, and in recent years the possibility to use bio fuels (See Figure 9) and decrease CO₂ emissions, have been beneficial for the development of district heating systems.

The total Swedish heat market for heating of buildings and hot tap water is about 100 TWh. Today, about 50 percent of the market is supplied by district heating and district heating has the possibility to reach about 75 percent of the heat market (SDHA, 2004). The heat load density in different locations is crucial to economy when calculating for introducing and expanding district heating pipe line grids. This is evident when studying district heating to detached houses, where about 9 percent uses district heating at a total heating demand of 4 TWh/year (SEA, 2009). Other important factors for district heating are geological and topographical conditions. The costs for district heating, however, are dominated by fuel costs, which represent 50-60 percent of the total costs. Fuel costs vary due to, for example, access to surplus heat or waste resources. Capital costs, interest rates and depreciation costs are 20-30 percent of total costs. The rate of return on total capital requirement is 6-8 percent for several district heating companies but considerably higher for some companies, and administration costs account for about 20 percent (Wirén, 2005).
Since fuel costs dominate costs for district heat production it is important that cheap fuel is available, such as (Euroheat&Power 2006b):

• Useful waste heat from thermal power stations (CHP)
• Useful heat obtained from waste incineration
• Useful surplus heat from industrial processes or fuel refineries
• Natural geothermal heat sources
• Fuels difficult to handle and manage in small boilers, including most combustible renewables such as wood waste, peat, straw, or olive residues.

If these resources co-exist in the same district heating system they will compete with each other for supplying the heat demand. In Figure 10 the base load production plant is a waste incineration plant which has lower costs than the combined wood and coal fuelled CHP plant, with fewer hours of operation during a year. Waste incineration decreases the possible CHP electricity generation. The wood-fired heat-only boiler runs throughout the winter. The most expensive alternatives, oil-fired boilers which are only run for a few hours during the coldest season, are at the top.
When studying the 27 Member States of the EU, one EU accession country and three EFTA countries, only a fraction of some suitable sources for district heating was used. From the available sources of about 5300 TWh from residual heat from all thermal power generation only 440 TWh was used for district heating and 500 TWh in industry. From available surplus heat from industries, 8 out of 300 TWh was used and from available 140 TWh of waste (550 TWh if waste that at present is not recycled is also considered) 40 TWh was used (Euroheat&Power 2006b).

In the early 1990s the Swedish electricity market was investigated to find ways to introduce competition. A new law (1994:618) came into force, which among other things aimed to introduce changes so that electricity production and sales would now be managed according to the established rules for competitive business activities. The new law also came to encompass district heating and had major effects on the restructuring of both district heating and electricity companies in the energy market. Until 1994 all municipally owned district heating systems were subject to the Swedish municipality law, which stated that price setting should be according to prime cost principles (SOU 2003:115). Prime cost means that an organisation can only set prices to obtain full cost compensation but no profit from the business. The change towards market prices in the district heating sector highlighted the question of regarding district heating as a natural monopoly (SOU 2004:136). This is because of the almost impossible action of investing in parallel district heating systems, which gives the

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**Figure 10.** Duration curve for district heating system.
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owner of the system a monopoly position. Among district heating owners, the view is that this way of describing the heat market has no relevance since heating customers have several competitive alternatives to district heating (SDHA, 2004) such as heat pumps and domestic pellet-fuelled heat boilers.

The Swedish district heating companies are in principle divided into two types: partly or wholly owned by municipalities or owned by larger energy companies. There are a few large energy companies that own district heating networks in several municipalities and locations. These companies often have other services within the energy sector, such as electricity generation, distribution and selling. There are also companies that only focus on district heating and CHP and own district heating networks in some municipalities. Historically, most district heating networks were developed by the municipalities but a trend in the 1990s was that large energy companies acquired several municipality owned. The municipally owned companies are often controlled (wholly or partly) by local politicians and expansion plans etc are affected by political intentions such as secure energy supply to as many inhabitants as possible. The principles for rate of return on invested capital may also differ from the privately owned companies since the cost of reaching many inhabitants may increase investment costs at the same time as energy prices must be low in order to compete with alternative energy supply methods.

Prices of district heat have generally been increasing faster than inflation in recent years, and they also differ widely across the country. In 2006, the cost of district heat, on average, was 17 percent higher than in 2000. This is partly explained by increases in the prices of competing sources of heat. (IEA Sweden, 2008). According to the industry, prices differ across municipalities because of differences in fuel supply, customer base, plant type, etc.(IEA Sweden, 2008).

The European Commission has officially focused on CHP since its 1997 communication on a community strategy to promote CHP. The target of doubling the 1994 EU15 CHP share of 9 percent of all power generation to 18 percent by 2010 was seen as realistically achievable. The Swedish CHP share of national electricity generation in 2006, was 9 percent, including industrial back pressure, and in district heating systems 5 percent. The potential for electricity generation in present district heating systems depends on the fuels and technologies being used. Calculations of the potential for CHP when total Swedish district heating supply is about 60 TWh shows a CHP share of electricity generation at 18-19 percent with a common present fuel mix. If an expanded natural gas distribution system is assumed, the potential CHP electricity share increases to 28 percent (SDHA, 2004 and SEA, 2008). As can be seen in Figure 11, CHP generation has increased in recent years.
Figure 11. Electricity production in Sweden 1970–2007, TWh (SEA, 2008).
5 ENERGY POLICY INSTRUMENTS

When discussing energy policies it is most common to address economic energy policy instruments. But policies can also have a broader definition if administrative measures, information and possibilities to change institutional frameworks for markets, institutions or organisations, are included. Policies can also include education, research, development and demonstration efforts. This description will only include some of the economic policies in Sweden.

Economic policy instruments affect prices and costs and can, for example, be taxes, fees, costs for emission allowances, subventions, and grants. Sweden has a long tradition of using taxes as energy policy instruments. Energy taxation aims to improve the efficiency of energy use, promote renewable energy supply and use, and encourage companies to reduce their environmental impact. Energy taxes include taxes on fuels and taxes for electricity end users. When an effect of the taxes is lower energy use, this also means decreased income for the state, which can be difficult to handle if the taxes represent a large portion of national finances. Energy taxes accounted for about 8 percent of the total Swedish state income in 2007 (SEA, 2008). Energy policies are gradually being harmonised in the European Union and this has led to several changes recently. Early in 2007, the European Union proposed a new energy policy to be supported by market-based tools, which will most probably affect policy formulations in the immediate future (see chapter 3).

One newly introduced economic policy instrument is the EU’s emission trading system (ETS) for CO₂ emissions. This is based on the market functions of supply and demand which give no income or cost for the whole economy but require institutional frameworks. The ETS limits the total amount of CO₂ emissions from installations in six energy-intensive industries: power and heat, iron and steel, cement, glass and ceramic construction materials, pulp and paper, and oil refining. The overall planned scarcity of emission allowances on the market, which is what gives them a value, is a result of the allocation process. The member states submit proposals for their National
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Allocation Plan to the European Commission, and these proposals must be in line with the criteria defined in the Emissions Trading Directive (2003/87/EC). The sum of the member states’ allocations represents the cap on overall emissions from the EU-ETS sector’s emissions. The EU-ETS has an indirect, but significant, effect on energy efficiency in heavy industry and the heat and power sector.

Another newly introduced market-based policy instrument in Sweden is the certificate system for renewable electricity. The framework is based on suppliers of electricity being required to buy electricity certificates equivalent to a predetermined percentage of the total electricity they supply. The size of this quota obligation changes from year to year, increasing the demand for certificates and, thus, renewable electricity. Suppliers may obtain the certificates needed through generation from their own eligible plants, or they can purchase certificates from other companies which generate electricity using eligible technologies in excess of their obligation.

Energy efficiency has long been one of the priorities of Sweden’s energy policy. Steering methods fall into four groups:

- Legislation, regulations and guidelines
- Financial mechanisms such as taxes and subsidies
- Voluntary energy efficiency agreements
- Education and communication


Swedish industry was earlier exempted from paying electricity taxes, but EU legislation made it necessary to introduce this in July 2004. The tax was set to the minimum level accepted by the EU and at the same time Swedish energy intensive industries were offered a tax subsidy if they joined an energy efficiency programme (the PFE programme). Companies participating in the PFE programme can receive a full rebate of the energy tax on electricity that they would otherwise have had to pay. In return, they undertake to introduce, within the first two years, an energy management system and perform an energy audit to determine their potential for improving the efficiency of their energy use. Companies must also undertake to implement, within five years, all the energy efficiency improvement measures that have been identified and which have a payback time of less than three years (SEA, 2007).

The Directive on the Energy Performance of Buildings (2002/91/EC) sets requirements for a more energy-efficient building code. Requirements for energy labelling of household appliances, in turn, are based on several directives adopted over the past 15 years. They also include compulsory minimum efficiency requirements. Over the longer term, the Directive Establishing a Framework for Setting Ecodesign
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Requirements for Energy-Using Products (2005/32/EC) will improve the energy efficiency of all new products outside the transport sector.

5.1 Swedish policy instruments for heating and CHP

Electricity production in Sweden is exempted from energy and carbon dioxide taxes, although it is subject to NO\textsubscript{X} and sulphur taxes in certain cases. The exemption is to avoid double taxation for end users, so only the end use of electricity is taxed at rates that vary depending on where it is used and for what purpose.

For heat the taxation is allocated to production and includes energy tax, carbon dioxide tax, and, in certain cases, sulphur and NO\textsubscript{X} taxes. The use of heat, however, is not taxed. In principle, biomass and peat are tax-free for all users, although the use of peat attracts sulphur tax. The taxation regime for CHP was changed in 2004, so that the tax on the fuels used for heat production in such plants is now taxed at the same lower rate as on these fuels when used in industry. With effect from 1st July 2006, combustion of certain domestic refuse was made liable to energy tax (SEA, 2007).

Swedish policies contain several grants affecting heating systems in buildings. Owners of buildings having direct electric heating can receive a grant for the cost of switching of such heating systems by district heating or by rock, earth or lake-water heat pumps, or by bio-fuelled boilers. Builders of new detached houses can apply for a grant for the installation of a bio-fuel-fired facility, such as a pellets-fired boiler, as the primary heating source. Owners of premises used for public activities can apply for grants to switch heating systems from electricity or fossil fuels to bio-fuels, district heating or earth, rock or lake-water heat pumps. A grant for installation of solar heating systems for space heating and domestic hot water production has been available for projects started since June 2000 (SEA, 2007).

A special Climate Investment Programme (KLIMP) allows local authorities and other parties to apply for grants for measures intended to reduce the emission of greenhouse gases in Sweden or assist the restructuring of the energy system, or which include interesting new technology that can contribute to these objectives. Such activities have, for example, included expansion of district heating systems, switching to biomass, and provision of local information on climate-related matters.
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6 FRAMEWORK AND APPROACHES

An overview of some methods and assumptions together with some basic technical issues is given in this chapter to provide some background to the studies carried out in the thesis. Other related studies are referred to in the descriptions as complements that may increase understanding.

Studies of energy systems may mean very different things to different researchers and also depend on what the research questions are. Whether a study focuses on a technical detail, a technical system or includes, for instance, organizations, different background information and explanations may be relevant. One definition of an energy system is: Energy systems consists of processes and artefacts for the conversion, transport and utilisation of energy, combined together in order to fulfil a specific need.

6.1 Energy system approach

A solution that seems sustainable for one part of an energy system may not be sustainable for the whole energy system. Primary energy use for different energy applications is one way of encompassing more than the local effects of energy use. It is, important to integrate the studied object, for instance a building, in a system perspective. How to delimit and define the energy system depends on the purpose of the study. The purpose of evaluating, for instance, economic conditions for a private person, a company or society requires different approaches to the studied energy system. The purpose of evaluating environmental effects is another example where different system perspectives must be considered. Emissions affecting local environment can be studied in a radically different system compared to in what system global greenhouse gas emissions must be studied.

Ingelstam (2002) asks the question; what is a system? A common answer is that a system consists of components and the relationships between them. There is a reason
why a specific set of components and relations has been defined to be the system; together they build up some form of unity. It must be possible to separate the system from its environment: there is a system boundary. But only in a few cases is the system closed, without any connection to the surrounding world. The rest of the world which does not belong to the system but which in some sense affects the system is called the system’s environment. The connection between the system and its environment can vary but clarifying this may be just as important for the system analysis as the study of the system itself. In several practical applications the criteria for deciding which components belong to the system is that it is something that an actor in the system controls, while anything outside the system is beyond the control of the actor (Ingelstam, 2002).

Churchman introduced the question of what the purpose of the system is when trying to define the system (Churchman, 1968). With the best system functioning for society as the goal of a study, the studied system must encompass almost everything, which is naturally very complex and therefore requires delimitations.

Energy supply system studies can be conducted with the purpose of supplying a fixed energy demand and finding the best way of doing so. The goal can, for example, be to minimize emissions or cost, or to replace and develop techniques. The supply is in many studies coupled to security of supply questions. But one way of dealing with security of supply can be to limit the dependency on secure supply by for example decreased demand through energy efficiency measures. The definition of the studied energy system must then be redesigned and changed from the two separately studied energy systems supply and demand to the left in Figure 12, to one common studied energy system comprising both supply and demand to the right in Figure 12.

Figure 12. System approaches for supply and demand of heat.
Research concerning energy demand has to a greater extent than supply system studies incorporated human behaviour and social science. This is, for instance, the case in some studies of barriers to energy efficiency. Even though energy efficiency measures often are about technical improvements and development, this is not the only way of affecting energy demand. A large potential for energy demand changes may be associated to behaviour and habits, which increases the complexity by requiring research skills from several different disciplines in energy system studies.

6.1.1 European electricity market
Swedish electricity is produced by hydropower plants and nuclear condensing power plants each producing about half the country’s electricity (see section 2.1). In hydropower, the losses can be ignored but in condensing power plants the losses are substantial. This also means that the primary energy use is high for European electricity production, especially from coal condensing plants.
Combined heat and power plants connect the district heating supply system with the electricity supply system. This is illustrated in the simplified energy system model of the European energy system in Figure 13. The model shows how the electricity system is intended to work and includes the ambitions for a deregulated, functioning European electricity market. System failings in this market are described by Sjödin (2003) and system failings as regards Swedish industry have been studied by Trygg (2006).

The two electricity generation alternatives, condensing power and CHP, deliver electricity to the European electricity market. In Figure 13, the major difference between these two alternatives is that CHP has an efficiency of almost 100 percent but condensing power an efficiency of about 30 percent. A precondition for CHP is that the excess heat from electricity generation can be utilised for example in a district heating system. This is normally possible in cold-climate countries such as Sweden where district heating is very common. In warm-climate countries and in the summer, the demand for district heating is low and new heating applications, which help increase CHPs’ efficient production and use of heat, are welcome. In Figure 13 this is
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illustrated by an absorption chiller, which is driven by heat from the district heating system and delivers cooling. The excess heat from a CHP plant can also be supplied to industrial plants. The oil square in the middle of Figure 13 represents switching between heating alternatives.

The efficiency of new condensing power plants is generally higher than 30 percent, and the figures in Figure 13 correspond to an old condensing plant with the highest production cost in the system, the marginal generation plant. Over time, new electricity generation is assumed to replace this marginal generation. More electricity use increases the marginal electricity generation and less electricity use decreases it. This is assumed to be true until the old coal condensing marginal plants are replaced in the European electricity system (SEA, 2002). New coal condensing plants can have an efficiency of 47 percent, which, according to calculations, will be 37 percent if carbon capture and storage is included (Elforsk, 2007).

The development of the electricity market, according to intentions described in chapter 2, is assumed to lead to higher Swedish electricity prices, similar to those in continental Europe (Sjödin, 2003, Dag, 2000). This will also lead to increased profitability in existing electricity generation in Sweden and along with the cold climate and extensive use of district heating it should also support the growth of CHP generation.

6.1.2 Energy system studies of heating

If heat is considered the main product in CHP generation it is the heat demand rather than the electricity demand that has to be met. The dimensioning of a CHP plant depends on how large the heat load in the district heating is. Without CHP generation, the district heating demand needs to be met through heat-only boilers, heat pumps or waste heat, if available.

Sjödin argues that the cost of heat produced in CHP plants should be credited with the market value of generated electricity. With higher electricity prices, district heating derived from CHP plants should become cheaper (Sjödin, 2003). Price development statistics for the district heating market (see chapter 2) have so far not shown this. Since the deregulation of the electricity market the energy utility company structure has changed from mainly municipally owned into large, national and international companies. District heating prices are in general lower in those companies that are still municipally owned than in other companies. The price setting philosophy has developed from being mainly prime cost based into market price based, where the alternatives such as individual boilers, electric heating and heat pumps compete with district heating.

One distinction between energy system studies might be whether they are performed from a top-down or a bottom-up perspective. When planning for district heating production, the approach has often been top-down. This means that the study starts
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with an aggregated description which is subdivided into a more detailed level as the study proceeds. The heat load in district heating systems was analyzed by Werner (1984) in order to create a model which describes the heat load and how it consists of several components. Dotzauer (2005) used mathematical programming for modelling and optimization of district heating production and creates a simplified model for describing existing district heating loads (Dotzauer, 2005). Knutsson has analyzed the aggregated supply of district heating in Sweden and concluded that the largest carbon dioxide reduction potential is when introducing natural gas CHP (Knutsson, 2003).

When a system is described in great detail, it may be difficult to decide whether the study is top-down or bottom-up. MARKAL is an optimization model which can be used to analyze, for example, how the energy system reacts to different policy options. The energy system optimisation model MODEST (further described in section 6.5) has also been used in local, regional and national studies of energy systems (Henning, 1999, Gebremedhin, 2003) but, unlike MARKAL, has only been developed for limited commercial use. In these models it is possible to describe technical details as well as setting limitations coupled to, for example, market conditions.

Bottom-up studies start with a detailed understanding of the fundamental elements and components in the system. As the study continues the energy use is traced upstream from the components. Joelsson (2008) compares different heating alternatives and increased energy efficiency in two different houses according to primary energy use in a life cycle perspective. The results show that the choice of heating system in the house has a greater effect on the primary energy use than measures on both the house envelope and the energy supply chains. District heating based on cogeneration and bedrock heat pumps were found to be the most energy efficient systems.

Using a top-down perspective Johansson et al. (2006) conclude in a regional study that heat pumps should replace electric heating only in regions with low heat density where district heating is not competitive. With commercially competitive heating technologies they show, in another study (Johansson et al. 2007), that it is possible to achieve a 47 percent reduction in primary energy use for heating where 34 of the 47 percent are due to reduced final heating demand. The current trends in the heating market, however, increase primary energy use by about 10 percent due to switching of heating systems in spite of a heat demand decrease (9 percent) as a result of energy efficiency measures (Johansson et.al. 2007). This can be explained, for example, by the fact that electricity (and primary energy) use increases when bio-fuelled heating systems are switched to heat pumps.
System boundaries can be different for actors with different interests in the system, for instance when considering economy. The technical energy system for buildings can be described as in Figure 14. If energy conversion inside a building is considered to be fixed, the house owner’s economy is at system boundary 1, where information about the economy for investing in surplus insulation or in new energy-efficient windows can be observed and evaluated. When considering switching of energy supply system for a building proprietor, system boundary 2 should be evaluated. For an energy utility, system boundary 3 is relevant but when considering economy and environmental effects for society as whole, other system boundaries may be necessary. In the mining and refining industry, boundary 4 should be of interest and from a natural resource and sustainability perspective boundary 5 is important.

6.2 Carbon dioxide emissions from heating

When adopting the European electricity market concept (see chapter 7.2) in studies of heating, carbon dioxide emissions from changes in electricity use or generation will be based on emissions from the marginal electricity generation. A dilemma with carbon dioxide emissions is that they are caused by local actions but have global effects.
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The possibility to transfer electricity over long distances has many advantages, such as utilizing natural resources, e.g. hydropower, and optimizing the production mix. When enlarging the electricity market, the possibilities for interaction between the different electricity production resources increase but at the same time the allocation of sources for carbon dioxide emissions is more complex. Hughes et al. demonstrate this problem when describing the effects when removing the equivalent residential emissions in accounting from the category “Public Electricity and Heat Production” and including them in the category “Residential” in Nova Scotia, a Canadian province. The region relies heavily on fossil fuels for electrical generation. Allocating all emissions to the production plant withdraws the possibilities to change demand for and use of electricity, which is actually causing the emissions. The shift in emissions accounting changes an apparent 4.1 percent decrease in Nova Scotia’s residential emissions between 1991 and 2001 to an 8.2 percent increase (Hughes et al., 2004).

How the valuation of carbon dioxide emissions from electricity generation in Sweden is done varies a lot between different studies. Local CO₂ emissions from different heating alternatives and global emissions are shown in Figure 15. Assuming that all the plants are located in Sweden (local energy system) the white bars show emissions from these plants for different heating alternatives. The black bars show the total emissions for different heating alternatives when marginal European electricity generation is assumed and both local and other emissions from the European system are included. Since electricity in Sweden is mainly produced by hydro and nuclear

![Figure 15. Carbon dioxide emissions from heating in Sweden. Local carbon dioxide emissions and total European emissions (Werner, S and Karlsson, B)](chart)

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generation with almost no carbon dioxide emissions, the electrical heating emission from the local energy system perspective is zero. In a European energy system perspective the carbon dioxide emissions for electric heating exceed 1000 kg of CO₂ emission per MWh of electricity produced in a low-efficiency marginal generation plant. Biomass is considered not to make any net CO₂ emission. (But waste contains plastics etc of fossil origin, which contribute to the higher atmospheric CO₂ concentration.). Also in Figure 15, the local CO₂ emissions from heating with district heating from natural gas combine CHP, exceeds 400 kg/MWh. These emissions, however, are turned into a decrease of more than 500 kg/MWh with the European energy system perspective. The reason for this is that district heating from CHP is assumed to enable electricity generation from CHP, which replaces marginal electricity generation.

6.3 Energy management

Energy management is used to minimize the resources used to satisfy a certain demand for a service which uses energy. It can be done in all steps of the supply chain in Figure 14 but it can also be focused on decreasing the demand for energy. Energy management on the demand side can be divided into energy savings, conservation (efficiency measures), load management and switching from one energy carrier to another. One energy savings measure might, for example, be to lower the indoor temperature in the cold seasons and wear warmer clothes instead. The reduced energy use means a lower quality of energy services, e.g. lower heating levels, through turning down thermostats, or in other cases speed limits for cars, and capacity/consumption limits on appliances (Herring 2006). An example of energy efficiency is to invest in a new energy efficient refrigerator or to shut off electrical appliances not in use, which means that the same benefit is achieved but with lower use of energy. Load management involves shifting the time when energy is used. For example, in district heating systems there is a demand peak in the mornings caused by common habits (showering, cooking etc) among many heat users. If the peak load can be removed by spreading or moving activities in time the use of peak load production resources can be reduced. Switching from electric heating to heating by bio-fuelled boiler is one example of energy carrier switching.

6.3.1 Energy efficiency and heating

The energy demand for heating in a building depends on the outdoor temperature and the power equation for heat can be described by:

\[
P \cdot \eta + P_1 = \{U \cdot A \cdot (T_i - T_u)\}_{\text{transmission}} + \{q_a \cdot c_{pa} \cdot (T_i - T_u)\}_{\text{ventilation}} + \{q_w \cdot c_{pw} \cdot \Delta T_w\}_{\text{sewage}}
\]

P: Supplied power (W)
\(\eta\): Efficiency
\(P_1\): Internal power; solar irradiation, heat from electrical appliances, people etc. (W)
U: Thermal transmittance for building elements (W/m²K)
With this equation as the starting point, the possibilities for energy efficiency in buildings depend on how transmission, ventilation and hot tap water losses can be reduced. The possibilities for energy efficiency are often divided into technical measures and behaviour-dependent measures. Typical technical measures for a building are insulation of walls and attic, replacement of inefficient windows, installation of a ventilation heat recovery exchanger, etc. These measures will affect the so-called technical heat load in district heating systems. Changes in behaviour might include taking shorter showers and turning off electrical appliances when they are not being used. These behaviour-dependent measures may not be directly related to outdoor temperature changes and in district heating systems these heat load changes affect the so-called social dependent heat load.

Since most of the heat in district heating systems (Q) is delivered for space heating in buildings (Q_{buildings}) the heat load curve for district heating systems follows seasonal temperature changes, Figure 16. In addition to hot tap water (Q_{hot tap water}) there are also distribution losses (Q_{distribution}) which vary over a wide range (2-30 percent) in different district heating systems but which in most systems are about 10 percent (Frederiksen and Werner, 2001).
Components of heat load in district heating systems:

\[ Q = Q_{\text{buildings}} + Q_{\text{hot tap water}} + Q_{\text{distribution}} \]

The distribution losses, \( Q_{\text{distribution}} \), depend on the dimension and insulation standard of the heat pipes, forward and return temperature in the pipeline system and the geographical concentration of heat demand. When studying the environmental impact from a district heating pipe over its lifetime, the greatest impact is undoubtedly related to heat losses during the operating time (Fröling, 2002).

The typical dimensioning temperature level in district heating systems in Sweden is 120°C at 16 bar pressure. The benefit of heat load increases if there is a great difference in temperature (cooling) between forward and returning water. This can be achieved by large heat demands but also depends on the design and regulation of the heating supply. The cooling of district heating flows seems to be better for large consumers then for small, probably because of less well functioning regulation in small consumers’ equipment and higher heat losses in forward heat distribution pipes for small consumers (Frederiksen and Werner, 1993). The use of district heating in industrial processes must be tailored to the temperature and pressure limitations that delimit district heating applications. In a system with CHP, however, steam may be supplied to some industrial processes.
Changing industrial energy use towards increased use of district heating will consequently affect the local energy suppliers. Trygg has shown how system costs are reduced by 50 percent when a local energy supplier invests in CHP and co-operates with an industry that has altered its energy use towards increased use of district heating (Trygg, 2006).

An energy efficiency audit in an industry explores not only the energy efficiency potential but also the possibilities for switching heat supply. Energy efficiency audits in industries can be carried out by examining supporting and production processes. The supporting processes may include lighting, ventilation, compressed air, space heating, hot tap water and pumps which are processes that are necessary for production to take place but are not directly linked to and integrated in the production processes. Examples of production processes are processing of materials by mechanical and chemical means and heating/melting.

Industrial processes can have other energy demand load curves than the normal so-outdoor dependent district heating heat load curve. If the utilisation time for district heating production resources can be prolonged, as shown in Figure 17, this will increase efficient use of installed capacity and also increase possible electricity generation when district heating is supplied by CHP.

![Figure 17. Principle sketches of common and for production resources “ideal” district heating duration curve (See also Figure 10).](image-url)

In principle, measures which only cut the peak heat loads in the winter season should be beneficial for the operation of a district heating system, since it is the most expensive fuels and boilers (normally oil) that are used during these peak demand hours of the year, see Figure 18.
In order to increase the productivity of the district heating system increased demand during normally low heating demands hours should be beneficial, see Figure 19.

Base load production plants in district heating systems benefit from increased utilisation time. It is therefore desirable to find heat-driven processes that can increase the heat demand when it is low. When industries, like most customers, use district heating only for space heating and hot tap water, there is a significant difference between the heat loads in the winter months and in the summer months. This affects a
base load plant since the summer heat load is often less than the plant’s minimum operating heat load, resulting in the commitment of other plants with higher operational costs and environmental impact. When industries convert other processes to district heating, like heating, melting and drying, the difference in heat load between winter and summer months is less significant. Especially if the cooling demand is converted to heat-driven absorption chillers, the heat load for the summer months increases.

One result of converting industrial processes to district heating may be a more evenly distributed demand curve over the seasons, which would benefit the production from base heat load plants such as CHP. Sectors and processes which are beneficial for the district heating system can be identified and should be the first to convert to district heating.

These measures may be promoted by price setting of district heating follows the actual operation costs during each hour of production. In some studies, problems with price setting of district heating not following the production cost, also called the short range marginal costs (SRMC), have been evaluated.

Price setting based on SRMC is supposed to maximize benefit for both energy user and energy supplier and this is in a case, by Rolfsman, compared with the existing price setting (Rolfsman, 2003). The existing price setting shows that it is profitable to invest in a heat pump and use this together with district heating in a bivalent system for a building. With the SRMC price setting a heat pump is not profitable at all. Extra insulation in the building is not profitable for any price setting method but the incentive is somewhat stronger with existing price setting. Gustavsson and Karlsson (1990), among others, argue that energy conservation measures in district-heated buildings are not profitable in the city of Malmö. Heat savings in district-heated buildings lead to less opportunity for electricity generation in CHP plant and decreased profitability for district heating company.

Energy efficiency measures in multifamily and service buildings often lead to lower district heating demand and thereby decreased revenues for the district heating business. When CHP is present such measures will also lead to less electricity generation.

In CHP district heating systems the question is whether the good intention of performing energy efficiency measures is positive or negative. Rolfsman examines how changes in the surrounding energy system affect a building and how the surrounding energy system can be affected by changes in a building. A building supplied with CHP based district heating is examined along with the district heating system. Three energy efficiency measures were examined: extra insulation, new windows and introduction of a heat pump. The last is partly a kind of energy-carrier switching. From a local energy system perspective (see section 6.2) the measures extra insulation and new windows reduce CO₂ emissions but from a Nordic European
(marginal electricity from Danish coal condensing power) all measures increase CO\textsubscript{2} emissions (Rolfsman, 2003).

6.3.2 How to affect energy supply and use

In Swedish municipalities energy planning is a legislated requirement. Shortcomings in energy plans and implementation were studied by Stenlund (2006), who found several possible improvements. One of the conclusions was that if energy issues are included in urban planning and a participatory planning approach is used, this could facilitate the implementation of energy plans. Mårtensson and Westerberg (2007) argue that to understand the processes of change within the energy system it is not sufficient only to use models that are based on technical developments or socio-economic analyses since these are based on the idea of rational economic decision-making. Three different paths of possible action; transformation through shared visions, transformation through networking and transformation through management culture, are presented as inspirational management tools for other actors when facing the possibility or need to transform local energy systems (Mårtensson and Westerberg, 2007).

When exploring the barriers to energy efficiency in case studies Thollander found that the most significant barriers were technical risks such as risk of production disruptions; lack of time or other priorities; lack of access to capital; cost of production disruption/hassle/inconvenience; other priorities for capital investments; difficulty/cost of obtaining information about the energy use of purchased equipment; lack of budget funding and that technology is inappropriate at the site. The principal driving forces, apart from cost reductions resulting from lowered energy use, were found to be the existence of a long-term energy strategy and people with real ambition (Thollander, 2008).

In economic theory, the problem of rational economic decision making is often explained by the lack of perfect information. Information programmes are one of the major means of overcoming barriers to energy efficiency such as behavioural barriers, imperfect or asymmetric information and split incentives. It has been shown that energy audits are an effective means, in terms of public money spent per kWh saved, of providing the industry with information on potential energy efficiency measures (Thollander, 2008).

6.4 Case studies

Studies of energy systems at municipal, regional or national level often bring to the fore not only a need to comprise technical issues but also the question of to what extent to include influences from organisations, companies, humans etc. One way of dealing with this is to broaden researchers’ knowledge base so that an understanding of possible benefits from multidisciplinary and interdisciplinary work is reached. This
can facilitate the crossing of disciplines and the use of different methods to gain new and beneficial knowledge.

Yin (Yin 2003) addresses the social scientist when describing the design of and methods for case study research and he also proposes triangulation of data sources (among different evaluators), perspectives of the same data set or of methods. This implies that studies of energy systems that focus on contemporary events, that do not require control of behavioural events and that have how and why questions can be appropriately carried out as case studies.

A case study is defined by Yin as an empirical inquiry that investigates a contemporary phenomenon in its real life context, especially when the boundaries between phenomenon and context are not clearly evident (Yin 2003).

Phenomena that appear at the boundary between a studied system and its surrounding often raise some of the most interesting questions (see also section 6.1). While researching these questions the distinct boundary for a system study can unfortunately be difficult to define. For example the question of whether an organisation that runs a technical system should also be included in a system study of the technical system and if so how social studies can be included.

Central to this thesis is whether a certain value can be addressed to the demand for heat in the light of the opportunity for increased electricity production through CHP that this heat demand can constitute. Since this sought value can have a different meaning and value for different actors at for example municipal, regional or national level, more than the physical system affects the research questions. Both case study techniques as described by Yin and system studies as described in section 6.1 have influenced this thesis.

6.5 Analyzing with models

Werner (1984) states that models for heating and electrical systems have different structures depending on different load characters. The major part of the load in a heating system has physical causes (space heating), while the minor part is caused by user habits (e.g. hot water preparation). The opposite situation appears in an electrical system, where the load mainly depends on user habits. Models for electrical systems are therefore to a large extent built on known load patterns for various categories of consumers. Load components with a physical background, such as lighting, complement the load patterns.

Optimisation models have been used in several studies of large and complex energy systems. Energy system optimisation models can have great technical detail of energy sources and supply and demand-side technologies (Henning, 1999). Such models can make a simultaneous consideration of the multitude of component configurations that may be constructed with the available menu of equipment. Energy system optimisation
models mostly use the optimisation method linear programming to select technologies and operation according to least total cost, under consideration of constraints, such as limitations on capacities and fuel supplies. The models present the system design and operation that best serve the objective, which normally is minimum cost for satisfying useful energy demand (Henning, 1999). Some energy system optimisation models are MARKAL (e.g. Unger and Ekvall, 2003), EFOM (e.g. Holttinen and Tuhkanen, 2004), TIMES (e.g. Remme et al., 2001) and MODEST (Henning, 1999; Gebremedhin, 2003; Henning et al, 2006).

MODEST (Model for Optimization of Dynamic Energy Systems with Time dependent components and boundary conditions) is a linear optimizing model, specially constructed to evaluate local energy systems and has been used for approximately 50 local utilities (e.g. Henning, 1999, Gebremedhin, 2003, Henning et. al., 2006). The model has been developed in order to find the best way to satisfy the demand for heat and possibilities for electricity generation in municipal or regional energy systems. A schematic picture of a MODEST application is in Figure 20. The properties of the fuels (e.g. cost) in the system are described and coupled to a conversion plant. The conversion plants can for example be different types of boilers with their own specific properties and, for example, combined heat and power alternatives. The heat from conversion plants is coupled to different demand categories and district heating pipes for connections between different district heating locations. The heat demand is defined as something that must be met, whereas the electricity generation from CHP can be sold in the electricity market place.
When the goal for the system is to minimise costs, the function describing this can be:

Minimize the function:

\[ \sum C_n \cdot x_n \]

Subject to the constraints:

\[ x_n \geq 0 \]

\[ \sum a_{mn} \cdot x_n \leq (or \geq, =) b_m \]
Chapter 6

The constraints formulate the energy balances for conversion plants and storages, dimensioning relations, output-power restrictions, fixed relations between flows ($x_n$), specified energy amounts, uniform energy flow, demand balance etc.

The costs ($C_n$) to be minimized are the total discounted system costs for the period under study. These may be energy costs, costs related to the output capacity and fixed costs. Energy costs can also be negative and represent revenues for example from selling electricity.

The optimum production is calculated and can be presented in, for example, a duration graph. Heat production over a year is presented so that the operating hours for each production unit can be seen (like in Figure 10 in section 4). Energy flows and marginal and system costs can also be analyzed in spreadsheets.

6.6 Scenarios

Scenario building has its roots in many different disciplines, such as military research, future studies, planning, and pedagogy and action research. Traditional scenario-building is often generated by scientific expertise and can be constructed as forecasts. In interactive scenario-building the scenarios are generated through the interaction between researchers and stakeholders. In this form scenarios are created as visions aimed at facilitating discussions and challenging current thinking on what is possible, thus opening up for new ideas and actions (Danestig & Westerberg, 2005, see also Ling et al 1998 and Svidén, 1989).

It can be difficult to use general scenarios in different places since the local conditions are different. If the scenarios are adapted to local conditions this can be a better starting point for discussions and further investigations. Three questions can be posed by scenario users; What will happen? responded to by predictive scenarios; What can happen?, responded to by explorative scenarios; How can a specific target be reached?, responded to by normative scenarios (Börjeson et al., 2006). Increased sustainability addresses the third question but in practice it may be important to address all questions. This means that scenarios that are partly predictive and partly explorative can be created. The purpose can be to increase knowledge, initiate interaction among researchers and practitioners and establish understanding of the energy system. Scenarios can show alternative energy solutions that are acceptable for local stakeholders, but the necessary steps towards the desired development must also be described and discussed.

The interactive creation of visionary scenarios is in itself a creative process, preparing the participants for decisions and change, but the process can be further enhanced by using such scenarios in interactive back-casting. In contrast to fore-casting – which often extrapolates current trends into the future – back-casting uses visionary scenarios as “given futures” and concentrates on the question of how such possible futures can be realised given the present situation (van de Kerkhof et.al., 2002). In interactive
back-casting this is done in co-operation between researchers and stakeholders and gives the participants the opportunity to shape ways to reach a desired future and to highlight the diversity of views and interests of stakeholders.
Chapter 7

7 PERFORMED STUDIES

The studies that were carried out are presented in the form of short descriptions of the resulting papers.

Most of the studies are carried out as case studies in municipalities with a common theme: heating. In paper II, the studied energy programme also comprises other energy efficiency measures than heating.

7.1 Paper I. Stockholm CHP potential - An opportunity for CO₂ reductions?

The study of the CHP potential in Stockholm focused more on policy makers and actors in the electricity generation chain than on energy users. Therefore, important properties to valuate are energy supply, demand and price, which will emphasize the central value of choice, mainly for energy suppliers. The carbon dioxide emissions are studied in the context of an assumed integrated well functioning European energy system. The study was performed in order to determine how this market will affect energy systems and if it impacts as intended from the perspective of the European Union’s ambitions.

A model of a large district heating system, containing the four major district heating networks with new interconnections, was developed in the MODEST optimization model. It is shown that this new large district heating network can be used to increase electricity generation from CHP in Sweden substantially and it therefore has a value that should be utilized. The economic value is more than 35 percent lower costs than now if bio-fuel CHP is chosen and the historical electricity prices from 2000–2005 prevail. If electricity prices increase by 100 percent from the historical level, the cost for satisfying district heating demand are transformed into a profit due to revenues from sales of CHP electricity. The profit, however, is largely supported by electricity certificates. The cost reduction due to a natural gas fired combined cycle CHP plant,
when gas prices range from 15 to 20 EUR/MWh at high electricity prices, ranges from 80 to 170 percent. The value of the heat demand for additional electricity supply is that electricity generation is four times larger than from the reference case of “present” generation.

The potential for carbon dioxide emission reductions states a value when emission reductions are required. As long as the cap for tradable emission permits is fixed, the benefit will be increased efficient allocation of carbon dioxide emissions but when the emissions allowed under the cap are decreased, the CHP potential in Stockholm can contribute to reductions. Available tradable emission rights can be of better use elsewhere and this study showed a potential for possible carbon dioxide emission reductions of up to 5 million tons CO$_2$ a year which is about 8 percent of total Swedish anthropogenic CO$_2$ emission.

7.2 Paper II. Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs

The most extensive action targeting the adoption of energy efficiency measures in small and medium-sized manufacturing industries in Sweden over the past 15 years was project Highland.

An evaluation of the first part of this local industrial energy programme shows an adoption rate of more than 40 percent after the programme when both measures that have already been implemented and measures that are planned to be implemented are included. Regarding which energy efficiency measures were implemented, it is seen from Figure 21 that the four most commonly used measures were related to generic processes, i.e. space heating, ventilation, lighting, and compressed air. In terms of implemented and planned measures, these four categories were also the most common measures. However, several suggested measures were not considered.
A comparison between this programme and a major ongoing programme for Swedish energy-intensive industry indicates that the approach used in project Highland aimed at small and medium-sized industries is an effective way to increase energy efficiency in Swedish industry. The evaluation of project Highland indicates that by using intermediaries like local authority energy advisors and regional energy agencies, the concept of local energy programmes seems to be an effective energy policy option in terms of public money spent in relation to energy saved. When comparing the local energy programme, project Highland, to the Long-Term Agreements programme, PFE, the outcome in terms of private money spent in relation to energy saved is approximately the same. However, when comparing public money spent in relation to energy saved, project Highland appears more effective. The major barriers to energy efficiency among the firms were related to the low priority of the energy efficiency issue.

### 7.3 Paper III. Industrial district heating applications

Knowledge of the potential for increased industrial district heating due to switching from electricity and fuels is limited. Different heat-driven processes can be considered and heat load duration curves for processes and lines of business can be studied. This

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**Figure 21. Implemented, planned and not considered energy measures about two years after energy audits in the project Highland evaluation.**

<table>
<thead>
<tr>
<th>Type of Measure</th>
<th>Implemented</th>
<th>Planned</th>
<th>Not Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Educational</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressed air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot tap water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Number of measures

![Graph showing implemented, planned, and not considered energy measures.](image)
method is helpful when analyzing what impact different processes have on the district heating system when switching to district heating.

The switchings in the study lead to lower electricity use by 11 percent and reductions in oil and LPG use by 40 percent. Together with energy efficiency measures also found in the energy audits, the energy end-use saving for Swedish industry could be substantial. Converting from electricity to district heating not only reduces electricity use but could also be a measure towards increased electricity generation when the district heating system contains CHP. When considering the extra electricity generation in CHP plants due to the increased district heating demand, and when assuming a deregulated European electricity market, the extra electricity generated in Swedish CHP plants could be sold in another European country, replacing electricity produced with higher environmental impact.

### 7.4 Paper IV. Increased system benefit from cogeneration due to cooperation between district heating utility and industry

In the Swedish town Örnsköldsvik a study was conducted focusing on how low costs and environmental impact can be achieved through cooperation between a municipal district heating utility and a pulp mill. The issues addressed in the study were: What is the optimal production plan for the analysed energy system? How are CO$_2$ emissions affected by different plans? Is there a conflict between waste incineration and cogeneration in the district heating system?

The background is that the local district-heating utility intends to build a CHP plant but is choosing location and may complement it with a waste incineration facility. Wood fuel is planned to be used in the CHP plant. A conflict between waste incineration and cogeneration may exist due to the use of the district heating system as a heat sink for both technologies.

Alternative cases have been evaluated with MODEST and the most profitable solution is to invest in a CHP plant and a waste incineration plant. Considering carbon dioxide emissions, the results from applying a local or a global perspective are remarkably different. In the latter case minimum global CO$_2$ emissions are achieved through maximal electricity production in a CHP plant. From this viewpoint, waste incineration should not be introduced because it would obstruct cogeneration.

### 7.5 Paper V. Modelling the impact of policy instruments on district heating operations – experiences from Sweden

This is a compilation of previous studies where policy instruments were modelled. Policy instruments should make individuals and companies choose the solutions that are most favourable for the whole society. The interplay among instruments is
important. Previous Swedish CHP taxation favoured fossil fuels for electricity generation but bio-fuels for heat production. Now, fossil fuel taxes for cogeneration are lower, but bio-fuel-fired CHP plants are promoted by green certificates. However, Swedish CO$_2$ taxes may be reduced for emitters who are included in the emission trading system.

CO$_2$ emission allowances can play a vital role in reducing GHG emissions. Current allowance price levels can accomplish a significant reduction of local CO$_2$ emissions from district-heating and electricity production but the impact may be highly dependent on the allowance price. A previous study showed that a natural-gas-fired CHP plant seems to be a beneficial investment in one district heating system when considering emission trading because electricity market integration and emission allowances increase electricity prices. Other studies showed that a waste incineration tax may make it less profitable to invest in waste incineration, which, like industrial waste heat, can be beneficial in some district heating systems but can obstruct electricity production in others.

District heating expansion is likely to be favoured by taxes and emission allowances that make individual heating with fossil fuel and electricity, respectively, more expensive. Adding heat demand that does not have the common outdoor temperature dependence may be promoted by green certificates because it can enhance electricity production in bio fuel-fired CHP plants. Policy instruments may have a decisive influence on energy use but fluctuations in energy carrier prices can have an even greater impact.

7.6 Paper VI. Local development possibilities for sustainable energy supply and use in Sweden.

Modifications of municipalities’ normal operations can contribute to a more ecologically, economically and socially sustainable society through, for example, the promotion of measures concerning energy conservation and renewable energy supply.

The Swedish Energy Agency’s ‘Sustainable Municipality’ programme includes how spatial plans of ground use and building development can promote local renewable energy sources and efficient energy utilisation. Energy issues can be integrated in spatial planning through scenarios of future energy supply and use, which are discussed by local stakeholders. It can be shown how wall insulation, solar heating and heat recovery can reduce primary energy demand and that switching from electricity to biomass can reduce CO$_2$ emissions.

The heat load density indicator depends on building structure and shows, for instance, preconditions for district heating. If the local energy utility is involved in spatial planning, it may facilitate the introduction of temporary solutions, such as pellets-fired
boilers, to make more customers choose district heating in areas where the network is delayed.

Scenarios can initiate discussions among local stakeholders on how possible and desirable it would be to achieve more efficient energy utilisation and a more sustainable energy supply in different ways.

Replacing electricity with biomass, for example, decreases CO\textsubscript{2} emissions due to the interplay in the European electricity market. Wall insulation, heat recovery and solar heating reduce primary energy use. Such energy conservation measures can be more suitable in areas of certain ages. The location of main district heating pipes is a strategic spatial planning issue. District heating should firstly be built in areas with large buildings and high heat load density but it may be hampered by recent installations of heat pumps.

7.7 Paper VII. Efficient heat resource utilisation in energy systems

Electricity generation from CHP in Sweden can be doubled just through expansion in existing district heating systems in Stockholm. Since CHP is dependent on a useful heat demand, additional heat loads outside the cold seasons should be beneficial. Especially, switching from electric heating and cooling to district heating and absorption cooling, driven by district heating that comes from CHP, has a dual impact on the electricity system through reduced electricity demand and increased electricity generation. Cooling demand is larger in summer and can supplement the space heating demand. Absorption cooling increases the possibilities for enhanced electricity generation in CHP plants during warm seasons when district heating demand for heating in buildings is low. The introduction of district-heating use for other new proposes can increase the annual running hours of efficient combined heat and power production plants, which can displace condensing power plants and their heat losses.

When switching from electricity use to district heating the primary energy use will be reduced due for example the reduction of heat losses in nuclear and coal-fired condensing power plants. Energy-carrier switching from oil and electricity to district heating is also possible for manufacturing processes, such as heating and drying of goods, which often are operating rather evenly throughout the year and, therefore, are a favourable heat sink for CHP production.

A problem in areas with low heat load density is that it is especially important to attract as many district-heating customers as possible because if too many heat consumers choose other heating options, the demand for district heating may become too low to make it economically possible to build a district-heating system. If the heat load density for district heating is too low to motivate district heating in an area, the possibilities for increased energy efficiency in buildings are large. Extensive additional insulation of walls and attic, new windows and ventilation with heat recovery could
reduce the heat demand by 50% in an average Swedish detached house. Therefore, both energy efficiency measures as well as good conditions for efficient electricity generation are needed to reduce carbon dioxide emissions from the energy sector.

Energy efficiency in buildings and district heating systems with CHP should, though, not be combined at the same place. Because district heating is unfavourable in districts with low heat load density, energy efficiency measures should be done there in the first place. If other heat resources that are difficult to utilise in other ways, for example, industrial surplus heat and heat from waste incineration, can be used in areas without CHP this could be effective. But systems with CHP and electricity generation may enhance the efficiency and reduce the environmental impact of the total energy system more effectively.

7.8 Paper VIII. A multidisciplinary and interactive method for exploring energy systems in municipalities

The Swedish town of Söderköping, with approximately 14,000 inhabitants, is located in the south-east of Sweden. One debated energy question in Söderköping is the heating of buildings and in particular the management of the district heating system. The municipality sold its electricity company in 1994 and its district heating company in 1998. Since the economy and management of the district heating company has changed several times since then, the discussion of the heating system has been both conflicting and complicated. Söderköping therefore seemed to be a suitable place for application and testing of a new working approach. The new method is called Multidisciplinary and Interactive Method for Exploring Energy Systems (MIMEES) and it was developed and tested in practice in Söderköping with a focus on space heating. A schematic flow of the method is shown in Figure 22.
When the municipal electricity and heating companies in Söderköping were privatized in the 1990s the organizational basis for energy issues in the municipality was split up and distributed to different departments. Since then, often isolated initiatives have been taken by politicians, planning departments and Agenda 21 and energy advisory bureaus. Before the MIMEES process there was a lack of both knowledge transfers and co-operation between those different initiatives.

After the back-casting sessions there is a greater awareness about competencies and projects among actors and departments creating the possibility for new coordinated projects. One such example is the co-operation between a municipal political body, the energy advisory bureau and the municipal housing company in the planning of several small district heating systems.

Dissolving the department that had earlier been responsible for energy issues within the municipality also meant that the task of keeping up with developments of space heating systems on the local arena became difficult. Through the background and field study phases of the MIMEES process the researchers could contribute with an up to date review of production, distribution and use in both separate and common heating appliances. This review was central to the development of scenarios but also interesting in itself, becoming a valuable material for further discussions on energy policy and infrastructural projects.

As mentioned above the back-casting session created greater awareness of different visions for the local energy system. This has led to a more open minded view on energy issues in political debates, especially concerning the necessity for new energy solutions in various geographical zones. On the positive side is also the continued co-operation between the municipality and one of the participating researchers, through an interactive PhD study on how energy issues are organized in the municipality.
Chapter 8

8 RESULTS

The results from the different studies are presented under the following themes; system perspective in the light of global warming, supply and demand of heat, heat loads in district heating systems, local planning and energy, impacts of economic policies, and impacts of local activities.

The demand for heating can be met in several ways and the supply can be converted from one energy supply to another depending on the physical, technical and economic conditions that are related to the demand. Heat demand can also be reshaped by for instance energy efficiency measures and new applications for heating which in turn can change the most suitable way to arrange the supply. This chapter presents the results from studies of the heat demand in individual buildings, in industries, in the planning processes in municipalities, in regional energy systems and concerning global carbon dioxide emissions.

8.1 System perspective in the light of global warming

Since the greenhouse effect is a global problem it is important to take this into consideration when studying carbon dioxide emissions. The emissions from the electricity generation plants originate from the local plants but the electricity distribution network covers a wide geographic area, where generation plants and electricity use are spread. Therefore, the emissions from the whole system must be considered. In papers I, IV, VI and VII the perspective based on marginal electricity in the European energy system has been adopted. General estimations and references to other studies using the marginal electricity perspective are made in paper III and V. In paper VI and VII the marginal electricity perspective is complemented with primary energy use scenarios. Electricity of Swedish origin is a complementary view, considered in paper VI. Both local and marginal perspective based scenarios were used when testing the MIMEES method in paper VIII. In paper II, no quantification of
CO₂ emission is presented but reduction of CO₂ emissions is an important motive for formulating policies aimed at energy efficiency in industries.

When considering the whole electricity generation system in Europe it has been shown that the potential for reducing carbon dioxide emissions by means of increased electricity generation in Stockholm is large. Paper I shows that bio-fuelled CHP in Stockholm can decrease global CO₂ emissions by more than 4 million tons/year if coal condensing generation is avoided. A benefit with CHP is that new electricity generation can be achieved at the same time as waste (surplus) heat from electricity generation can be utilized and replaces different heating fuels (Paper IV). The undertakings in the Kyoto protocol mean that carbon dioxide emissions must be reduced and the national goal set by the Swedish Government is a reduction in carbon dioxide emissions of 4 percent from the 1990 level by 2012 (Government, 2006), equivalent to a reduction of 3 million tons of carbon dioxide a year. Expanding the supply from CHP and increasing electricity generation in the Stockholm district heating system shows a solution which could exceed the Swedish obligations according to the Kyoto protocol. According to the present administrative and measurement methods for carbon dioxide emissions, however, this cannot be accounted for in the Swedish obligation.

The economic conditions for investing in CHP varies but according to the Swedish district heating association there are major plans for new investments in CHP in Sweden. The technical potential for increased electricity generation in Stockholm is higher when applying a natural gas combined heat and power cycle. Since natural gas is a fossil fuel the local carbon dioxide emissions increase. On the other hand, since more electricity is generated than in the bio-fuelled CHP plant, the amount of condensing generation avoided will be larger and the net CO₂ emissions in the European electricity system will decrease even more. The potential for decreased net carbon dioxide emissions, with natural gas CHP exceeds 5 million tons but depends on economic conditions. The concerns of increased national carbon dioxide emissions, since they increase with natural gas, can, however, obstruct a development which, at least in a limited time perspective, can make a major contribution to limiting CO₂ emissions.

Heat pumps driven by electricity have negligible carbon dioxide emissions in a Swedish energy system perspective, with almost no carbon dioxide emissions from electricity generation. Assuming a common European energy system perspective the results, considering global carbon dioxide emissions, support other solutions. Bio-fuelled CHP can generate electricity instead of having electricity as energy supply (via heat pumps) for district heating (Paper V). When encompassing more than the local interests in planning for electricity generation, better solutions for low CO₂ emissions can be achieved. In Örnsköldsvik a model with waste incineration was studied in combination with a new bio-fuelled CHP replacing heat pumps for district heating. Since electricity generation increased, through the new generation in CHP, the CO₂ emissions from coal condensing generation could be decreased. But if the waste firing
Chapter 8

heat-only boiler was not built, the electricity generation could be even larger. The local carbon dioxide emissions from waste incineration was at the same time smaller but due to the landfill ban on combustible waste the waste will be used as fuel elsewhere and still cause CO\textsubscript{2} emissions. The global CO\textsubscript{2} emissions from waste incineration will, however, decrease if the waste is used as fuel in a CHP plant (Paper IV).

The location of a new plant within a municipality can be of major importance since the distance to possible steam customers is crucial. When choosing a location for a new CHP near the Domsjö industries in Örnsköldsvik it is possible to supply the industries with steam. When the Domsjö industries’ steam demand is added to the heat demand in the district heating system, the operating time for the CHP is prolonged and more electricity is generated. The waste heat from CHP can replace other fuels and increase renewable electricity generation (Paper IV).

8.2 Supply of and demand of heat

Heat demand depends on how buildings are constructed, the outdoor temperature, users’ habits and the industrial processes that use heat. In paper I the demand is described simply by the district heating demand in each of the interconnected district heating networks. Since the district heating networks in some parts are also renewed and reinforced, heat distribution is slightly different than today but no major changes are achieved. In paper IV a major change in the possibilities for heat and steam sales is achieved when locating the new CHP so that the Domsjö industries can be supplied with steam, but the internal demand in the industries does not change. Paper III is about changing the demand characteristics if industrial heat loads were converted into district heating. Energy efficiency enhancement affecting the heat demand in buildings and industries is mentioned or used in papers II, III, VI, VII and VIII. The supply of heat is in most papers (I, III, IV, V, VI, and VII) focused on district heating but in papers VI and VII and in the project behind VIII other alternatives for heat supply are also studied.

When performing energy efficiency audits, switching to district heating is found to be a possible measure. In the Highland project measures concerning space heating were among the most commonly planned and implemented measure (II). The Highland project is one of the most extensive actions targeting the adoption of energy efficiency measures in small and medium-sized manufacturing industries in Sweden over the past 15 years. When production processes are converted to district heating and steam from CHP possibilities exist to increase the utilisation time for district heating production and CHP plants. Since the energy audits in the Highland project focused on the supporting processes it was, however, mostly space heating that was considered. More space heating by district heating in industries, on the other hand, could increase interest in utilizing district heating in other processes than for space heating. In paper III, production processes for heating, drying/concentration, cooling and melting were identified that could be converted to district heating. The possible switching of
industrial processes will increase the heat demand in district heating systems and thereby increase possible CHP electricity generation, often instead of requiring electricity to run the processes.

Converting space cooling to district heating driven absorption cooling was one of the most favourable measures in the industries. Space cooling demand is high in the warm seasons which can complement space heating demand in the cold season and thereby contribute to more efficient utilization of the production resources. Altogether, this indicates that there is a potential for increasing the district heating share of total energy supply to industries by 4 percent (Paper III).

The precondition for district heating varies between municipalities. In Stockholm, the demand in several locations exceeds the expansion rate for district heating while the heat load density is crucial to its expansion in small municipalities. This implies that energy issues should be integrated at an early stage in urban planning processes. The heat load density can be explored and illustrated in maps divided into different geographical areas in a municipality. The present heating alternatives as well as changes in different scenarios can also be illustrated in maps. This gives municipal planners an early understanding and knowledge of the energy use for heat which can be useful in the planning for new developments and other changes in the municipalities.

In low heat load density areas district heating is not always appropriate. Various alternatives are possible when planning new developments. In a large development, for example with several industries or multiple multi-family dwellings, it might be possible to introduce district heating immediately or soon after establishment. In the latter case, temporary solutions with a local common heat boiler in the new area might be appropriate. Examples of low energy buildings have been used when creating scenarios of possible energy demand in both new and existing developments in different municipalities. Energy efficiency scenarios have also been developed. The heat load density in most of these scenarios is very low compared to cases with conventional building techniques.

8.3 Heat loads in district heating systems

Since high district heating demand with long duration time is beneficial for CHP and low CO\textsubscript{2} emissions, district heating loads with characteristics supporting this should be promoted. When studying characteristics for different industries it has been shown that several industrial processes have a longer heat load duration time than is common for heat loads in present district heating systems. One explanation to this is that heat loads in district heating systems often have a large outdoor temperature dependent factor and a smaller social dependent factor. The outdoor temperature dependency leads to high district heating demand in the winter and low demand in the summer. The social dependent district heating demand factor is more evenly distributed through the year but the demand is smaller than for the outdoor temperature dependent heat load.
Industrial heat demand can, depending on industrial processes, have a larger fraction of a not outdoor temperature dependent factor.

In paper III it was found that the industrial heat loads had other characteristics than heat loads in households. Heat loads in some industrial processes can complement the primarily outdoor dependent heat demand in households so that production resources will be utilized in a more efficient way (Paper III). It was also shown that CHP can benefit from several industrial heating loads since the CHP operating time can be prolonged during the year. When switching heat supply to industrial processes to CHP steam and district heating, the benefit is not only increased CHP. There is also a potential for decreased electricity, oil and LPG use by converting to district heating in studied industries. When assuming that increased district heating leads to increased CHP electricity generation, the overall impact on global CO\textsubscript{2} emissions is substantial reductions (Paper III).

The switching potential from electricity and fuels to district heating in industries can be found when performing energy efficiency audits aiming at reducing energy use and cost. In the Highland project it was found that the use of waste (surplus) heat can be increased within industries while electricity, oil etc. are replaced and decreased by energy efficiency measures (Paper II). The energy efficiency audits resulted in a potential for converting to district heating being found and listed among the proposed efficiency measures. Switching from one energy carrier to another does not normally result in reduced energy use but when switching from electricity to district heating energy losses from electricity generation in condensing plants may be avoided.

8.4 Local planning and energy
The preconditions for combined heat and power generation are very different in different municipalities. In some large communities the floor space index per ground area is high due to a large amount of large multi family, office and service buildings. In other areas or small municipalities single family houses with large gardens and open spaces are more common which constrains the motives for spending resources on district heating systems and by this combined heat and power (Paper VI and VII). If industries are connected to district heating on a larger scale than at present, the incentives for extending district heating systems are greater (Paper II and III).

When energy issues are integrated at an early stage in urban planning, the possibilities for important strategic energy infrastructural decisions increases. When the MIMEES method (Paper VIII) was used to explore energy systems in a municipality, it was found that there were some predominant lines of thought as to the future energy system, but there were also less predominant ideas, not considered here, although such energy futures are very important in other municipalities. It was found that creating scenarios comprising energy use and supply in all different sectors in a municipality and to discuss this in seminars with local stakeholders can help change attitudes towards marginalized (i.e. formerly not accepted or thought of) heating alternatives.
When developing the method one of the most important lessons was that interaction between researchers and local stakeholders is important. The method also proclaims the useful benefits of a multidisciplinary mix of project members. Scenarios coupling urban planning and energy questions were created and used among other things to discuss the meaning of sustainability. The scenarios led to discussions such as that it may be possible to find satisfactory individual heating solutions, but at the same time the sustainability may largely be lost if the energy systems interplay with the surrounding world is not taken into account (Paper VI). Scenarios reflecting both energy supply and energy demand measures such as whether to invest in wall insulation, heat recovery and solar heating can help planners to discuss sustainable energy use. The main outcome of this project was greater knowledge of energy questions among urban planners and of planning processes among energy specialists.

8.5 Impacts of economic policies
The global warming resulting from use of fossil fuels is an important reason for policy makers to formulate and adopt energy policies which decrease the use of fossil fuels. Taxation has been one of the most efficient instruments for affecting the energy system in Sweden. Taxation on fuels such as the one on fossil fuels for production of district heating in Sweden has earlier inhibited cogeneration of heat and electricity but has in recent times been re-designed to be more supportive to CHP. Policy instruments intended to affect other fields than the energy sector may have a substantial impact on the energy sector. For instance, when a tax on waste as landfill was introduced followed by a landfill ban on combustible and organic waste, the profitability of using waste as a fuel in district heating systems increased. The effects of these policies led to a tax on waste incineration (2006) which was directed to the fossil fuel part in the waste and should dampen the increase in waste incineration. The policy instruments on waste incineration affect the competition between different heat supply possibilities. In a model of the Örnsköldsvik district heating system the competition between waste incineration and combined heat and power as heat supplier was studied. Waste incineration producing only heat led to less electricity generation in CHP (Paper V).

The green certificate system for renewable electricity has a major effect on which alternatives for electricity generation are favoured. In the Stockholm study (Paper I), green certificates help bio-fuelled CHP beating the natural gas alternative when comparing total system costs. It takes high electricity prices and low natural gas prices for the gas alternative to be competitive. However, when it comes to the potential for electricity generation the gas alternative is much better. Higher electricity market prices lead to lower global CO$_2$ emissions and lower system costs to satisfy the district heating demand in the studied Stockholm energy system.

8.6 Impacts of local activities
Since global CO$_2$ emissions depend on local actions, local actors must have knowledge of how this connection works. Energy efficiency programmes for industries can increase knowledge and lead to implementation of energy efficiency measures. In the
Highland project all energy efficiency audits were individually formulated and an evaluation of the implementation of suggested energy efficiency measures has been done. It has been difficult to find comparative programs when evaluating whether the implementation degree of energy measures was high due to the initiatives. It was, however, shown that the cost of each saved energy unit was far below the energy price and thereby very profitable. When evaluating the reasons for not adopting some of the proposed energy efficiency measures too long pay back times were mentioned but the two largest barriers were lack of time and other priorities for capital investment. The largest driving forces for implementing energy efficiency measures were a long term energy strategy, people with real ambition, an environmental company profile and an environmental management system (Paper III).

In the Swedish Energy Agency’s ‘Sustainable Municipalities’ project, one part was about integrating energy questions into spatial planning processes (Paper VI). Different methods were developed, presented and tested in workshops with municipal planners, energy companies and researchers from mixed disciplines. The fundamentals of high and low heat load density in different areas, for instance the fact that high heat load density is favourable for district heating but low density more suitable for individual solutions and energy efficiency measures, were discussed. The question of who can and should be able to decide on energy solutions and what various municipal actors can do was also discussed. Energy scenarios showing, for instance, how different solutions affect primary energy use and the local carbon dioxide emissions and how these can differ from the global carbon dioxide emissions were discussed.
9 DISCUSSION

This chapter discusses the results in order to throw light upon some questions at the same time as the view of the results is broadened.

When using models for energy system analyses the results often indicate economically favourable solutions, show the effect on CO$_2$ emissions of different alternatives, and compare technical solutions. In some cases results are also implemented. To find out how and why this happens requires broad studies and analyses by specialists in several research disciplines. This thesis has only touched upon this difficult question, but it may nevertheless be important to take it up for discussion.

It has been shown that local activities such as energy efficiency programmes aimed at industry give results such as, for instance, that suggested energy efficiency measures are in fact implemented. Some of the most important driving forces for energy efficiency are prioritisation of energy issues and a dedicated person with real enthusiasm for energy issues (Thollander, 2008). Experience from working with scenarios and back-casting includes, for example, that it can affect local actors and open up for a change in attitude towards formerly marginalised energy solutions. This implies that it could be possible to introduce information and knowledge from a broader energy system perspective to a local arena and that it could be possible to have understanding of this as long as the information can be adapted to local conditions. Considerations of the specific preconditions in each location are most important when planning for the local heating solutions. This is true for district heating and it is also true for the investment in CHP. Strategic and realistic investigations of future heating demand must be made so that good decisions can be made and risks of blocking efficient development can be avoided. Most probably the possibility for change will also be favoured by finding people who are interested, dynamic and committed.
Since activities have to be at a local level, it is essential that local actors have knowledge of energy. It is then also important that they have knowledge of how local activities affect the whole energy system, the primary energy use, and the CO\textsubscript{2} emissions. Studies have shown that results mainly based on local knowledge and concerns can obstruct the most appropriate solutions concerning reduction of carbon dioxide emissions. One of the basic problems when overcoming these problems is that it is difficult to design policies and market rules which give the right incentives. The best heating solution within a high-density heat load area can be very different from that in low heat load areas. Because of these differences, policy options and other information must be adjusted accordingly.

When the Swedish electricity market was deregulated, district heating was also excepted from the municipal prime cost rules and market price setting was introduced. A district heating price higher than the prime cost of production may make the alternative of choosing district heating less favourable for some energy users. This obstructs the possibilities for expansion of district heating networks since the heat load density available for connection to district heating is lowered. In district heating systems, which cannot expand, the possibilities for development of the CHP electricity generation potential is delimited. At the same time, condensing electricity generation plants are in the majority in the European electricity system, which means that heat that is needed for heating buildings in Europe, is wasted. If the electricity was produced in CHP systems instead, both heat and electricity could be used. Assuming a functioning European electricity market, it can be assumed that increased CHP electricity generation in Sweden can replace the most expensive condensing electricity generation in the system (the marginal electricity).

The actual possibilities to reduce CO\textsubscript{2} emissions are affected by the prevailing policy instruments. With a functioning CO\textsubscript{2} tradable emissions permit system in the EU the most carbon rich electricity generation method should also be most expensive and among the first to be replaced. The tradable carbon emission permits sets the limits for CO\textsubscript{2} emissions from the participants in the trading system. If CO\textsubscript{2} emissions are decreased from the coal condensing plants assumed to be displaced by, for instance, new CHP generation, the CO\textsubscript{2} emissions will increase somewhere else because the number of permits is constant over a period. The actual benefit when decreasing CO\textsubscript{2} emissions in one part of the trading sectors must then be that the amount of CO\textsubscript{2} emitted will be more efficiently utilized in the whole system. If the cap on the emissions is decreased in the future, the replacement of the most inefficient generation plants will help achieving a real decrease in CO\textsubscript{2} emissions.

One problem with the CO\textsubscript{2} trading system is that a large part of the total CO\textsubscript{2} emissions take place outside the system, where it can be assumed that several energy efficiency measures will lead to decreased emissions. But even here the freed energy resources could be redirected to other places and they are used anyway. The assumption that the redirection will lead to increased efficient use of the resources can also be made here. Increased efficiency e.g. higher benefit per resource used and CO\textsubscript{2} emissions.
Chapter 9

emitted is per see a good development. My opinion is that this also highlights the necessity to include a larger part of the total CO$_2$ emissions in the tradable emission permits system and then choose a cap for the emissions which will lead to the desired goals. The next difficult step is to decide the level of the goal and how allowances should be allocated. It is most important that the cap on emissions is set for the whole system, without national or regional caps, so that countries like Sweden, with relatively small CO$_2$ emissions, will also get incentives to increase efficiency.

One aspect of CHP is that it can generate more electricity when more district heating is being used. A problem occurs when deciding at which level the use of heat should be delimited and how much effort should be spent on energy efficiency. The question becomes even more complicated when considering all condensing electricity generation in the European electricity system, including nuclear generation in Sweden, and compares all this wasted heat with the possibilities offered by CHP. The conclusion must after all be that new energy solutions should be better adjusted to the fact that the natural resources are delimited. Even the renewable energy sources use limited resources in the form of materials etc. Biomass also has CO$_2$ emissions and can only be counted as CO$_2$ neutral as long as forest regeneration is just as fast as or faster than the consumption of bio-fuels. Efficient energy use and utilisation of waste resources are necessary in a long term perspective to secure that technical development and maintenance of important functions in society can continue while still considering the problems with an enhanced greenhouse effect, the limitation of natural resources, and the fact that the use of resources always has environmental effects that should be under control. Nevertheless, CHP has great benefits for heat production and electricity generation which should be utilised when it can be done efficiently. Close co-operation and knowledge transfer among national and local authorities, planners, energy users, entrepreneurs and energy companies should promote wisely designed local solutions.

The taxation regime for CHP in Sweden was changed in 2004, so that the fuels used for heat production in such plants are now taxed at the same low rate as these fuels when used in industry. Previously, district heating could hardly meet the competition from local heating solutions in the industries. It has been shown that industrial heat loads can increase efficient utilisation of production resources in district heating systems which can also increase electricity generation when CHP is in the system. This motivates greater efforts to find industries and processes that are suitable for district heating.

Since the typical district heating demand is highly dependent on the outdoor temperature during the year, it should be beneficial to find other complementary heating demands in order to achieve full utilisation of the heat production plants. Absorption cooling as well as different industrial heat loads are options for longer district heating demand duration times. Several studies have shown that increased electricity generation with CHP is penalised if, for instance, heat-only waste incineration is introduced in the same district heating system. The heat demand
becomes a scarce “resource” and the competition between different fuels and heat resources may hamper electricity generation and the possibility to replace carbon rich electricity generation.

In the Stockholm study the assumption regarding replacement of marginal electricity generation gives a result where global carbon dioxide emissions have major reductions if a combined cycle natural gas CHP is used. The use of natural gas, however, increases local CO\textsubscript{2} emissions, though only by a fraction of the total global reductions. So one question is if this small increase can be more important than the large decrease of CO\textsubscript{2} emissions. Another question when discussing natural gas introduction on a larger scale than at present in Sweden, is whether it will lead to a lock up into a non renewable alternative in the long run. Natural gas would also lead to import dependency since there are no natural gas resources in Sweden. How important are these aspects in relation to the available time to decrease carbon dioxide emissions?

Some of the most important policy instruments being promoted at present are designed as market based and should due to their construction leave it to the market to find the most cost-efficient solutions. The tradable emission permits have been claimed to increase electricity prices, which should be true when assuming electricity market price setting in a perfectly functioning European electricity market according to the marginal price setting principles. The emission permits have also increased electricity prices at today’s electricity market. In a perfect market, the right price signals will be sent to energy users and they in turn will adjust their behaviour and technical development in line with these signals. For district heating, the price signals in a system with CHP should have a different impact than in for example a heat-only boiler based district heating system. District heating prices in CHP systems should vary in the opposite direction to the varying electricity prices and with respect to the limitations of the system. One example is that district heating prices should be very low in daytime in the warm seasons when the industries’ electricity demand is rather high.
10 CONCLUSIONS

The conclusions presented in this chapter are based on the results of the research that has been presented and answer the research questions. The answers are the basis upon which the hypothesis is found to be true.

The aim of this thesis is to illustrate whether the heat demand in district heating systems can be seen as a resource that enables efficient energy utilisation, how this can be achieved and to discuss consequences of this assumption. This cannot be answered in a simple way and all matters concerning this cannot be included considering the limited time and resources available for the evaluation. An ambitious starting point has been taken when trying to embrace a relatively broad energy system and with both the supply and the use of energy for heating within the system. The hypothesis states that a common system approach for energy supply and heat will show climate and economic efficient solutions. To verify and delimit the study, five research questions were posed with the purpose of determining whether the hypothesis may be true or if it is false. The research questions are:

- How important are concerns about local carbon dioxide emissions in relation to global carbon dioxide emissions?
- What are the benefits of combined heat and electricity generation?
- How does a European energy perspective and assumptions of marginal electricity generation affect energy system studies?
- How can energy system studies comprising both industry and households be useful?
- How can a focus on knowledge and implementation of energy measures be reached?

The first research question focuses on the choice of system boundary that must be made when evaluating the changes in carbon dioxide emissions in the studied energy
system. Since local actions affect global carbon dioxide emissions, the choices made on a local plane always affect global emissions. The local emissions, however, can be increased at the same time as total global emissions decrease. Assuming a deregulated, functioning European electricity market, several studies show that increased CHP electricity generation in Swedish district heating systems has greater effects on global CO₂ emissions than it has on local emissions. This is also true when considering changed use of electricity, such as from energy efficiency measures, which decrease electricity use and have very little effect on local Swedish emissions but a much larger effect on global CO₂ emissions.

A known benefit of combined heat and electricity generation is that it decreases waste of energy resources and increases the energy efficiency from fuels compared to conventional condensing generation. Since electricity can be distributed over long distances, one of the main benefits of combined heat and power in Sweden is that the local heat demand can be met and the surplus electricity generation can replace condensing generation elsewhere in the European electricity system. The studies show that the higher the utilization of CHP can be the higher the benefits are when it comes to efficient use of energy resources and CO₂ emissions. Natural gas plants can generally yield more electricity than biomass-fired plants. In some cases, the cost of introducing a natural gas combined cycle CHP is not beneficial and demands a very high electricity price but not too high natural gas prices. The preconditions for building CHPs in Sweden should however be better than for building condensing generation elsewhere since revenues are collected from electricity and heat sales and the costs for many district heating systems are already sunk in Sweden.

When having a European energy perspective to studies of changes in Sweden, the outcome and results differ from when having for example a Swedish energy system perspective. With a local-only, for instance Swedish, energy perspective, increased renewable electricity generation and decreased electricity use in Sweden will only show low effects on CO₂ emissions. Having a European energy perspective and assumptions of marginal electricity generation such measures will have much higher effects. The marginal electricity generation assumption focuses on common European solutions for energy efficient and low carbon dioxide alternatives instead of focussing local concerns.

Since district heating systems in Sweden normally have a very high outdoor temperature dependency it would be beneficial to lower the temperature dependency and increase heat loads having other characteristics or opposite outdoor temperature dependency. Some industrial heat loads, suitable for district heating, have been found to have other characteristics than the common ones in district heating systems. Most district heating systems supply residential and service buildings with heat. Since these loads are mostly outdoor temperature dependent, measures to decrease this dependency can be found for instance by using district heating in absorption cooling and industrial processes. Adding such measures can be beneficial for the operation of district heating systems and increased electricity generation from CHP.
several different sectors with different heat demand and characteristics in energy system studies opens up for increased use of heat and electricity generation at the same time as electricity use is decreased.

To achieve beneficial changes in both the heat supply chain and in the demand for heat, local preconditions must be taken into account. Since district heating is more beneficial in areas with high heat load density and other solutions might be more suitable in low heat density areas, energy issues should be integrated at an early stage in urban planning processes. Knowledge can for instance be gained when working with scenarios and seminars where local and external experts from different disciplines participate. It has been shown that local energy programmes for energy efficiency can have good results leading to both implemented and planned energy efficiency measures.

Based on these answers to the research questions and on the studies included in this thesis, it is concluded that the hypothesis “A common system approach for energy supply and heat demand will show climate and economic efficient solutions” is true.
11 FURTHER WORK

Energy system studies comprise a broad spectrum of issues which raise far more questions than have been included in this thesis. Suggestions for further work related to this study are given.

Condensing power generation is the most common electricity generation in Europe. Concerning energy efficiency, it seems that CHP is more energy efficient, but since condensing power still is in the majority, even in Sweden, the question of cost efficiency should be studied further. Renewed studies of the external costs (due to e.g. environmental impact), not included today, in these systems should be of interest. The question of whether condensing generation at the same time as heat is demanded can ever be efficient should be evaluated.

Problems with “lock up effects” such as for major natural gas introduction in Sweden should be studied further. The “lock up” problems should be compared to and valuated against the effects of, and possible avoidance of, a fast climate change. Among other things, it should be interesting to compare the timescales as well as the geographical aspects of the lock-up and climate-change problems.

Further investigations of the possibilities for heat switching and other use of “waste” heat resources such as from thermal electricity generation should be made. The total potential is interesting but it is also of interest to determine how to carry out implementations.

The subject of where and to what extent different energy resources can and should be utilized is being studied by several researchers. Finding a way of ensuring that biomass resources are not being overexploited is important and may inspire some researchers. Should CO₂ emissions from biomass be included in the CO₂ accounting schemes?
The problems with outdoor temperature dependent heat loads in district heating systems which lead to heat load peaks were described in an earlier chapter. When studying industrial heat loads a large amount of the possible heat load switch from other fuels to district heating in industries is outdoor temperature dependent. Is it appropriate to avoid heat loads which have an outdoor temperature dependent load curve and instead focus on loads having “the right” profile to complement present district heating heat load curves?

The map over how natural resources are spread in the European energy system should be interesting to study when considering the possibilities for decreased CO₂ emissions. Where will the available bio-mass resources be most beneficial? Where should investments in for instance increased windpower and solar energy solutions be done? How should the European policies be designed to achieve the least use of limited resources?
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