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District Heating Sensitivity to Heat Demand Reductions and Electricity Market Dynamics

Licentiate Thesis

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Abstract

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Sweden and the rest of the EU member states have to reduce primary energy use and emissions of CO_2, and increase the use of renewable energy sources according to the EU climate change package "20-20-20". To do this, the energy systems need to use less fossil fuel and to utilise energy resources more efficiently. Reduction of energy use in buildings is an important part of this transformation. In Sweden, district heating is the most common technique to supply heat for space heating and domestic hot water to multi-family residential buildings in urban areas. Efficiency improvements in buildings connected to district heating systems should not be counterproductive from a systems perspective, e.g. causing less efficient total use of resources and increased global CO_2 emissions. A reduced electricity production in combined heat and power plants, which may be a result of reduced district heating demand, is sometimes seen as problematic with regards to emissions of CO_2, since this electricity is normally considered to replace electricity produced in less efficient fossil-fuelled condensing power plants.

This licentiate thesis summarises the first part of a PhD project that studies the possibilities for Swedish district heating systems to adapt to a reduced demand for heating in buildings, as well as to changes in energy markets. In this thesis the impact of building energy-efficiency improvements and electricity market dynamics on the operation of district heating systems and CO_2 emissions is investigated.

The energy system cost-optimisation software MODEST has been used to study the impact of heat demand changes on the heat and electricity production in the Swedish district heating systems in Linköping and Uppsala. MODEST optimisations were also used to investigate the impact of electricity price fluctuations on the operation of the Uppsala district heating system, and the interaction between the national power system and all Swedish district heating systems collectively.

The results show that energy efficiency improvements in buildings that reduce heat demand by up to 40 % do not increase global CO_2 emissions due to production of district heating. This is because heat-only production is reduced to a larger extent than combined heat and power production. The results also show that low electricity prices during winter and a large introduction of intermittent wind and solar power generation in the Swedish power system can be expected to induce use of electricity for district heat production and to hamper co-generation of electricity in combined heat and power plants.

Keywords:

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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 analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

PROGRAM ENERGISYSTEM
Forskning och forskarskola

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 as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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”Men då kan ju du sitta där i ditt vulkanträsk...”

Andreas Molin, Danmark 2011

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Åberg, M., Henning, D. (2011) Optimisation of a Swedish district heating system with reduced heat demand due to energy efficiency measures in residential buildings. *Energy Policy* 39: 7839–7852.

II Åberg, M., Widén, J., Henning, D. (2011) Sensitivity of district heating system operation to heat demand reductions and electricity price variations: A Swedish example. *Energy,* (Submitted for publication)

III Widén, J., Åberg, M., Henning, D. (2011) Impact of large-scale solar and wind power production on the Swedish power system. In proceedings of the World Renewable Energy Congress 2011, Linköping, Sweden, May 8-13 2011.

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Publications not included in the thesis

IV Karresand, H., Molin, A., Persson, J., Åberg, M. (2009) How passive are your activities? - An interdisciplinary comparative energy analysis of passive and conventional houses in Linköping.The Energy Systems Programme. Working paper 42. Linköping University.

V Åberg, M., Molin, A., Wäckelgård, E., Moshfegh, B. (2009) CO_2 emission from general district heat use in Sweden - an approach for justified comparisons in residential energy use. Energitinget, Stockholm, Sweden, March 2009.

Contents

Abbreviations

CC	Coal condensing
NGCC	Natural gas combined cycle
CHP	Combined Heat and Power
HWB	Hot Water Boiler
WIP	Waste incineration plant
SH	Space heating
DHW	Domestic hot water
PE	Primary Energy
EU	European Union
EU ETS	European Union Emission Trading System
MW	Mega-watt
MWh	Mega-watt hour
α	Electricity-to-heat output ratio for a plant
α_{system}	Electricity-to-heat output ratio for a system
SEK	Swedish currency

1. Introduction

During the 20th century the industrialised world has experienced a tremendous and historically unique transformation considering increasing economic wealth and technological development. This development has however also induced a parallel increase in the use of energy. There are indicators suggesting that the world is currently significantly overexploiting natural resources. These indicators are for example “peak-oil” and the climate change issue, stressed by the intergovernmental panel for climate change (IPCC). In order to reduce carbon dioxide (CO_2) emissions, decrease use of primary energy and prepare the world for a situation with reduced access to fossil oil, the established energy systems of today need to be shifted and adapted to present and future conditions. Saving energy is however not always a trivial task because the energy systems are dependent on factors such as climate, weather, business cycles and the access to primary energy resources.

Buildings constitute about 40 % of the total Swedish annual use of primary energy. In buildings, energy is used for space heating, domestic hot water, household electricity and electricity for building operation. Multi-family residential buildings represent a large part of the Swedish building stock and constitute 32 % of the total Swedish demand for space heating and domestic hot water. Most multi-family residential houses in Sweden are connected to one of the over 400 district heating systems within the country.

The “20-20-20” targets agreed upon by the European parliament and council legally binds the member states of the European Union (EU) to reduce primary energy use by 20 % until 2020, compared to the projected levels of 2020 [1]. Also, the Energy performance in buildings directive (2010/31/EU) requires that all new buildings will be nearly zero energy buildings in 2020 [2]. Further, buildings in general are considered to have a large potential for energy savings, mainly through possibilities to improve energy efficiency in building envelopes. Therefore are reductions in energy use for the buildings sector an important part of reaching the overall targeted 20 % reduction of primary energy use until 2020.

If energy efficiency improvements are made in buildings that are connected to a district heating network, the analysis of the effects of energy saving measures becomes a multi-factorial and a system based problem. This is because the energy savings in buildings affect the operation of the district heating system due to a lowered demand for district heating.

The consequences caused by reduced energy use also depend on factors such as fuel prices and electricity prices. The problem gets further complicated when CHP (combined heat and power) plants, electric heat pumps and electric boilers are considered since they connect district heating systems to the Nordic and the European power systems. The connection to the power grids has indirect global effects when electricity generation and use in both Sweden and other European countries is concerned. One important issue is the possible antagonistic effects of reducing energy use in buildings connected to district heating in Sweden. It has been highlighted that reduced use of district heating might hamper co-generation of electricity in CHP plants. Co-generated electricity is normally considered to replace electricity from less efficient power generation in continental Europe, either through export or reduced import of electricity. This could lead to the conclusion that energy efficiency measures in buildings induce increased global emissions of CO_2. These effects on local and global energy systems caused by large-scale energy efficiency measures in buildings are investigated in this thesis along with the sensitivity of district heating systems to electricity market dynamics. Also, because of the complexity in delimiting the Swedish power system from the Nordic and the European power systems the environmental evaluation of electricity use is discussed.

1.1 Aim of the Thesis

This thesis is a compilation of the first part of a PhD project that aims to investigate the system impacts of potential changes in heat demand on heat- and electricity production in Swedish district heating systems. The PhD project is performed under the auspices of the Energy Systems Programme, which is an interdisciplinary national research programme and graduate school. The Energy systems programme focus on interdisciplinary research on a wide perspective of energy system related issues.

The work so far in the project has been focusing on the influence of building energy efficiency on Swedish district heating systems and the impact of electricity price variations on heat- and electricity production. The main objectives of this licentiate thesis are:

- Determine the impact of energy efficiency measures in multi-family residential buildings on the demand for district heating.

- Investigate the effects of heat demand changes on heat- and electricity production in Swedish district heating systems, and investigate how reduced heat demands influence CO_2 emissions.

- Study the sensitivity of district heating system operation to electricity price variations, both for local district heating systems and on a national aggregated level.

The research is mainly performed using the energy system cost optimisation model MODEST to study different energy systems.

1.1.1 Scope and delimitations

The research is limited to include energy use for space heating and domestic hot water in Swedish residential buildings that are connected to district heating networks. Household electricity use is not included since it is not considered to have a direct effect on the operation of the district heating system. No economic analysis for energy efficiency measures in buildings is included.

CO_2 emissions are one of the focuses in this thesis since global environmental impact is studied. Local emissions, such as acidifiers are not considered in this thesis. However, CO_2 emission from local fuel incineration is accounted for and here referred to as local CO_2 emissions.

1.1 Systems Analysis

The idea to solve complex problems by using a wider perspective has become more and more attractive during the 20th century. The concept of *Systems Analysis* originates in operational research, or operational analysis, that was developed during the Second World War. Operational analysis was created when researchers were gathered to assist the military in strategic decision-making during the war. After the war operational analysis was continued to be used for solving civil problems, initially to a relatively small extent. The use of Systems analysis however emerged as sub-branches such as systems theory and cybernetics. And the increased use of computers during the second half of the century increased the possibilities for Systems Analysis to be used to a wider extent. [3, 4].

A central concept of Systems Analysis is *The Systems Approach*, i.e. the focus on the whole, the structure and the internal relations between system parts, rather than focusing on the individual parts themselves. Gustafson refers to a system as *"a set of components united to a whole"* [4]. Churchman, one of the most influential writers on the subject, defines the system slightly differently as *"a number of parts that have been coordinated to achieve a set of goals"* [3]. Lars Ingelstam stresses the importance of the *system boundary* which distinguishes the system from its *surroundings*. Ingelstam argues that these two additional concepts are crucial in systems analysis [5]. The system along with the system boundary, the surroundings and the interconnections between the system and its surroundings is illustrated in Figure 1.1.

What is part of the system and what is part of the systems surroundings is not necessarily obvious. The definition of the system boundary is sometimes trivial and sometimes complex and depends on what *purpose* the study of the system has. This also indicates that a system could be considered to be part of another system and also that a system contains a set of *subsystems*. These systems can be interconnected in several different ways [4].

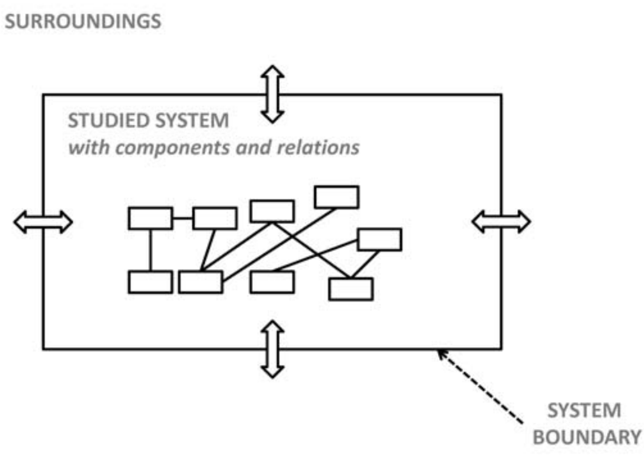

Figure 1.1: A general illustration of the system with components, relations, system boundary and the systems surroundings, after Ingelstam [5].

Systems can be directly connected, for example two buildings (each considered as one system), that are interconnected and related in parallel through the electric grid or the district heating network. However systems can also be related in the sense that one system is a part of the other. For example a building that is considered to be a subsystem of a larger local energy system that further is a subsystem of a national energy system, and so on. Therefore it is reasonable to think of a global system of which everything is part, on different system levels and in different subsystems. System levels and system relations are illustrated schematically in Figure 1.2.

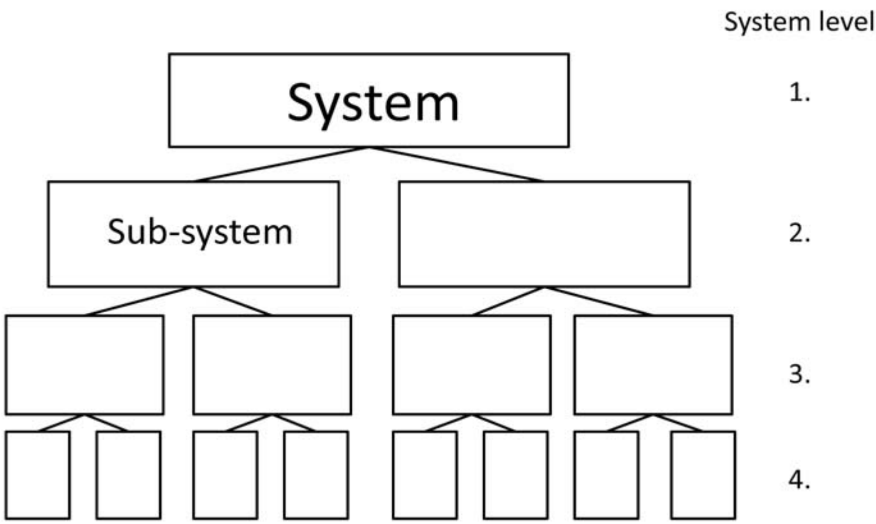

Figure 1.2: System levels and hierarchical system relations, after Gustafsson et al. [4].

For this thesis the systems perspective is fundamental. The systems studied are local Swedish district heating systems and the Swedish national power system. For these systems the distinction between the systems and their surrounding is relatively clear due to the technical nature of the systems. However, the complexity increases when system surroundings and relations to other systems and to other system levels are considered. One example is the impact of the European power system on both the Swedish national power system and the local district heating systems.

In *paper I* and *paper II* detailed models of two different local district heating systems have been used to study the impact of energy savings in buildings on the operation of district heating systems. Energy savings in buildings are studied in aggregated form and an aggregated impact of building energy-use changes on the local district heating systems is in focus. *Paper II* also includes an electricity price variation sensitivity analysis where the impact of seasonal and diurnal changes in electricity price levels on district heating operation is investigated.

In *paper III* the entire Swedish power system is studied. Within this system all Swedish district heating systems are modelled in an aggregated form and the effects of changes in power generation on Swedish district heating is studied. Thus, the studies presented in the thesis focus on different system levels, local energy systems and the Swedish national energy system. Also, the interconnection between the Swedish energy system level and the European energy system level is present in all three studies.

The actors within the energy systems are also of importance in the studies. Energy savings in Swedish buildings concern tenants and house owners, as well as local district heating companies. This means that energy savings in buildings, to a large extent are depending on two different, interconnected energy system-actors. These actors have different objectives, ambitions and possibilities to reduce primary energy use. On the national energy system level the Swedish district heating systems and the different types of Swedish power generation are aggregated and the actors in this study are all of the power generation companies and the district heating companies operating in Sweden.

1.2 Previous Research

There is previous research within this field that investigates the combination of improved building energy efficiency and district heating. Many studies are focusing on the problem with connecting new energy efficient buildings to an existing district heating system. Some of these studies find that district heating and planned new low-energy buildings have shown to be incompatible, this because the lower space heating demand in the buildings results in an unreasonably high cost for district heating. Not only because the fixed fee for heating subscription and installation becomes a relatively larger share of the heating costs in buildings with low heat demands but also that in some cases the subscription fee has been set higher for customers with significantly low heat demands [6, 7]. There are however also examples of newly-built passive houses that have been connected to district heating. One example is the semi-detached passive houses in the residential area Lambohov in the Swedish city of Linköping. In this case a special agreement was formed for district heating subscription fees and variable costs to suit the lower heat demands in the passive houses [8].

In this thesis the focus is however on energy savings in buildings that are already connected to district heating. This matter has been previously discussed in a study by Difs et al [9] where a MODEST model of the Linköping district heating system was used, similar to the one used in the study in paper I in this thesis. Difs et al. investigated, among other things, the impact of a 10 GWh heat demand reduction due to attic insulation on CO_2 emissions. The results presented show, in accordance with the results in paper I that heat demand reductions in the Linköping district heating system decrease global CO_2 emissions [9]. Also, in a study by Gustafsson et al [10] the effects of end-use energy efficiency measures on different types of district heating production systems is investigated. The study concludes that energy efficiency measures that reduce peak demand also reduce primary energy use to the largest extent, this since peak demand is generally covered by heat-only boilers. The analysis was performed on a case-study apartment building.

When studying the effects of a lowered heat demand in buildings that are already connected to a district heating system, the risk of an economic conflict is smaller than for buildings that need to be connected. However, a different issue addressed by Späth concerns the risk that district heating forces an energy system into a path dependency and latches the development of the system in a large and inflexible grid-based infrastructure [7]. This due to the fact that district heating is considered to be a monopoly and this reduces the power of the heat consumer and might inhibit energy savings in buildings. This, according to Späth, limits future improvements of the energy system. Thus, for example, if energy efficiency measures in buildings are considered incompatible with district heating and therefore left out, the system might be sub-optimised in terms of energy efficiency.

More generally, discussions concerning the environmental influence of low energy buildings and conventional buildings often tend to focus on the choice of heating system rather than on the energy efficiency of the buildings. Brunklaus [11], for instance, concludes that passive houses (see Section 2.2.1) heated with electricity and conventional houses heated with district heating contribute to global warming to the same extent due to the electricity use for space heating in passive houses. These conclusions rely on the assumption that the used electricity stems from coal-fired condensing power plants. However, Brunklaus also concluded that when the passive houses are connected to district heating they become distinctly “better” than conventional houses [11]. Further on, Joelsson [12] concluded that energy efficiency measures on the building envelope have less impact on CO_2 emissions and primary energy use than switching of domestic heating systems. Joelsson also concluded that electric resistance heaters are worse than other heating systems in terms of environmental impact and use of primary energy. This is regardless of the energy standard of the building envelope [12].

The discussion above suggests that there is a need to further investigate the effects of building energy efficiency measures in existing buildings on district heating system operation. In Gustafsson et al. [10] it is stressed that there is a need for research on large-scale implementation of building energy efficiency measures and its impact on district heating production. This matter is discussed in the appended papers of this thesis.

2. Background

The general background to the research presented in this thesis is given in this chapter. Section 2.1 briefly presents the district heating technology and provides an overview of the present situation for district heating in Sweden. In section 2.2 the primary energy use in Europe and Sweden is described along with the energy use in Swedish buildings. The concepts of low energy buildings and passive houses are also briefly described. Thereafter, an example of energy efficiency measures in existing buildings is given, followed by a presentation of policy measures aiming to reduce energy use in buildings. In Section 2.3 the power systems of Europe, the Nordic countries and Sweden are presented and this is followed by a discussion concerning the environmental evaluation of electricity use.

2.1 District Heating

District heating is a technical system characterized by a centralised facility used for heating of water, and a network of pipelines used to distribute the heated water to its consumers. When the heated water reaches the consumer (for example a residential building), the heat it is transferred through heat exchangers to supply domestic hot water and radiators for space heating. The centralised heat production within district heating systems generally takes place in one or several heat production units such as hot water boilers, heat pumps or CHP plants where heat is co-produced with electricity (see Figure 2.1). Different kinds of heat production processes use a variety of different fuels such as; bio mass, waste, peat, oil, coal, natural gas and electricity.

Figure 2.1 shows an outline of a district heating system with a CHP plant where biomass is used to produce heat and electricity simultaneously. Steam is produced in the boiler and used for electricity generation in a steam turbine. When the steam has passed the turbine the remaining heat is used to produce district heating in a heat exchanger and is thereafter distributed to consumers (red line). The district heating water is then returned to the plant to be re-heated (blue line).

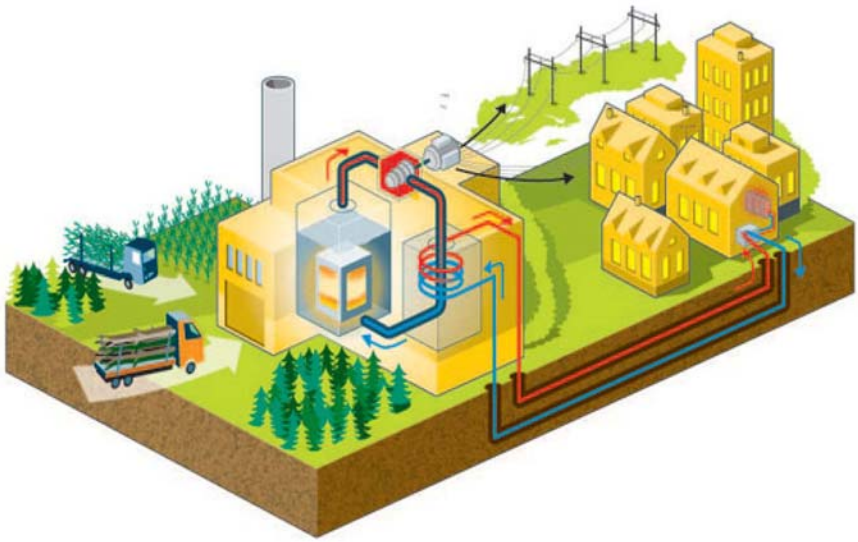

Figure 2.1: District heating and CHP plants [13].

2.1.1 District Heating in Sweden

The penetration of district heating in the world's heat markets is generally low. In Europe district heating's coverage of the total heat demand for space heating and domestic hot water is about 15%. But in Sweden, Denmark and Finland district heating supplies about 50 % of the total heat demands [14]. Thus, Sweden is one of the countries in the world with the largest share of the heat demand in buildings being covered by district heating. In 2009 a total of 52 TWh of district heating was distributed to Swedish heat consumers [15].

Sweden has over 400 different district heating systems of which most are small systems with annual heat deliveries below 100 GWh/Year. Instead relatively few systems provide most of the Swedish district heating. The three largest systems located in Stockholm, Gothenburg and Malmo together provide about 30 % of the total deliveries in Sweden [16].

District heating systems are by no means homogenous in terms of heat production utilities and use of fuels for heat production. The composition of heating plants in different Swedish systems differs vastly. Systems also differ when it comes to properties like; system size, fuel mix, access to and possibilities to use industrial waste heat and whether or not the system co-produces heat and electricity.

About 60 of the Swedish district heating systems have heat and electricity co-production in CHP plants. Most of these have an electricity-to-heat output ratio (α-system) between 0 and 0.3 for the entire system, on a yearly basis. This means that for each unit of delivered heat, the system produces 0 to 0.3 units of electricity in CHP plants annually.

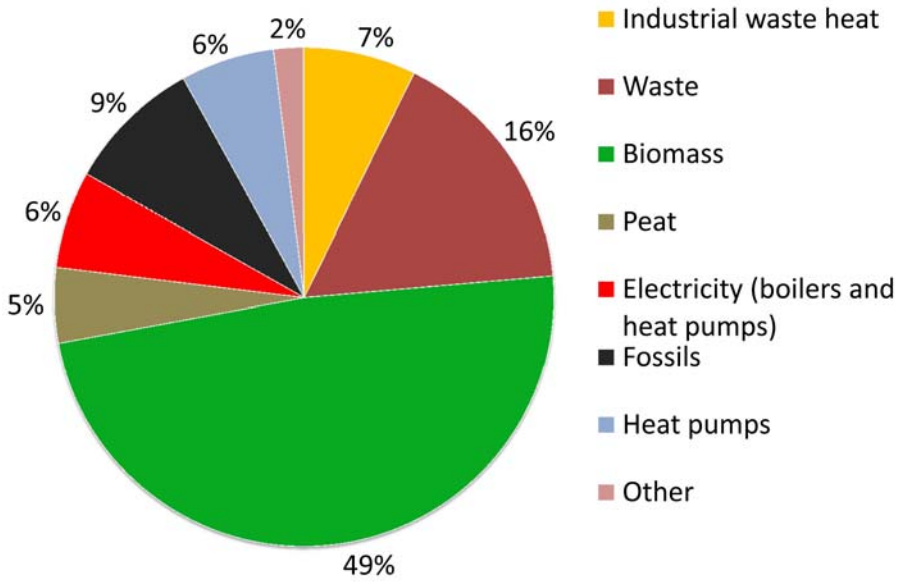

Figure 2.2: The Swedish district heating fuel mix in 2008, based on data from the Swedish district heating association [17].

The total use of fuels in Swedish district heating systems in 2008 is shown in Figure 2.2. Almost half (49 %) of the fuels used is constituted by different types of biomass, while the share of fossil fuel is 14 % (peat is here considered a fossil fuel). The use of electricity for electric heat pumps and electric boilers is together 6 %. 16 % of the total Swedish fuel use is waste. 7 % of the input energy in Swedish district heating systems is industrial waste heat.

District heating is most commonly used in multi-family residential dwellings in urban areas. The market for district heating in small detached single-family houses is however more limited due to the relatively small heat demands in detached houses, compared to multi-family buildings. Less heat demand and more geographically widespread buildings increase heat losses and therefore are heat deliveries to detached single family houses occasionally not considered beneficial by district heating companies. There are studies that indicate that the future demand for district heating in Sweden is about to decline. This reasoning is based on the assumption that existing Swedish buildings and new buildings will be made more energy efficient and that there will be an increased competition from heat pumps [18].

2.2 Energy Use

This section describes different aspects of energy use and energy efficiency in buildings. Building energy use is often referred to as specific energy use which includes energy for space heating, domestic hot water and electricity for building operation. Thus household electricity is not included

2.2.1 Overview of Energy Use in Swedish buildings

Sweden is a far stretched country in the northern part of Europe. The average temperature varies between +20 ˚C to +25 ˚C during summer in the southern parts and -15 to -20 ˚C during winter in the northern parts of Sweden. The differences in outdoor temperature between seasons in Sweden strongly influence the energy use in Swedish buildings. Swedish buildings in general have a need for space heating during the colder months of the year and there is also a demand for space cooling in some buildings during summer months.

In total, Swedish single-family detached houses constitute 44 % of the total building area. About 28 % is constituted by multi-family residential buildings. The remaining 28 % is found in other buildings, such as commercial and public buildings [19].

In Swedish multi-family residential buildings a total of 25.6 TWh of energy for space heating and domestic hot water was used in 2009. District heating alone provided 23.4 TWh (91 %) and is thus by far the most common technology for supplying heat to Swedish multi-family residential buildings. The remaining 9 % of the energy used for heating was covered by electric heating, oil, bio-fuels, natural-gas and other fuels [19].

The average energy use per multi-family building apartment and per square meter in Sweden was in 2009 10.9 MWh/apartment and 148.1 kWh/m^2, respectively [20]. The requirements of today for specific energy use in newly built residential buildings in Sweden is between 110 and 150 kWh/m^2 year, depending on the geographic location of the building. The concept of specific energy use includes space heating and cooling, domestic hot water and electricity for building operation. However, special requirements are defined if the space heating demand of a building is supplied by electricity and then the corresponding numbers are 55 – 95 kWh/m^2 year [21].

Low-energy buildings
It is hard to find a well defined concept for low-energy buildings. The low-energy building concept is being used to describe buildings that use small amounts of energy for space heating, domestic hot water and building operation electricity in a variety of contexts. The low energy concept has also changed over time. One definition that is presented by Karlsson [22] defines a low-energy building as a house that use considerably less energy than a house corresponding to present building regulations and building tradition. In this thesis the low-energy building concept is a generic name for buildings that use considerably less energy for space heating and to some extent domestic hot water than the present standard. A more strictly precise low-energy building type is defined by the passive house concept which is described below.

Passive houses
The first passive houses in Sweden were built in 2001 and until 2010 the number of passive houses in Sweden had reached about 1600 [23]. The Swedish forum for energy efficient buildings (FEBY) has defined specific requirements regarding needed heating capacity for the area of the building (including garage) that is heated above 10 C° in Swedish passive houses which is 12-14 W/m^2 depending on the geographical location. Along with these requirements FEBY also defined advice regarding the maximum amount of bought energy for domestic use (space heating, domestic hot water and building operating electricity). These advices aim to benefit the use of low-grade energy carriers that have a low exergy-to-weight ratio, which means that the amount of usable energy per weight is low. For example district heating is commonly considered a low-grade energy carrier, electricity is usually considered to be the opposite. An equation is used to calculate the weighted energy that is used where different types of energy are assessed differently. The advice is that Swedish passive houses should use no more than 60 – 68 kWh$_{weighted}$/m^2 for the area of the building heated above 10 C° depending on geographical location of the building [24].

In order to meet the defined requirements passive house building envelopes are generally different to conventional houses in the following aspects: low mean thermal losses (around 0.1 W/m^{2}K), optimal window orientation in combination with optimal solar shading, and finally high air tightness of the buildings [25].

Crucial in the passive house concept is the space heating system. The additional heat that is needed in the passive house could be supplied in different ways, either through extra heating of ventilation air or by using other heating systems.

An example of energy efficiency measures in existing buildings
Even if all buildings built today and in the future would be of passive house standard, the main part of building energy use would for a considerable amount of time still be found in the already existing buildings. Therefore it is natural to discuss what can be done in the existing building stock in terms of energy efficiency measures. This is also urgent considering that EU (see Section 2.2.3) calls for substantial reductions of energy use within the building sector.

In 2008, the Swedish national credit guarantee board stressed the need for renovation of the Swedish multi-family residential buildings built in the years between 1965 and 1974 [26]. During this decade the construction rate for residential buildings reached a level nearly twice as high as normal and this substantial extension of the housing stock in Sweden was part of a national plan called "the million homes programme", here referred to as the million-programme. This programme aimed to satisfy an increased need for housing due to rapid urbanization, growing prosperity and increased demand for higher housing standards [27]. In energy statistics for Swedish buildings the energy use in buildings from the period 1961-1980 is between 158 – 162 kWh/m^{2}year. These million-programme buildings are one large category of Swedish buildings that are in need for refurbishment and therefore it could be argued that energy efficiency measures should be taken in connection to other measures. This could also be an opportunity to increase energy efficiency in existing Swedish buildings.

There is an interesting example from the area of Brogården in Alingsås, a small town close to Gothenburg, where several million-programme multi-family buildings have been refurbished to passive house standard. In the initial demonstration part of the project one building with 18 apartments was refurbished. The specific energy use was decreased from 156 kWh/m^2 year to 45 kWh/m^2 year [25]. This project indicates that there is a great energy savings potential in this category of buildings. In paper I, the Brogården project is used to estimate effects of substantial reductions in the million programme buildings in the Swedish city of Linköping. This is further described in Section 3.3.1.

2.2.2 Energy Efficiency Policy Measures

Several policy measures have been taken in Europe to reduce energy use, on the EU-level and separately in the member states. These policy measures concern all different types of energy use in the different energy sectors. This section briefly presents the policy measures that are of importance for energy efficiency in the Swedish building sector.

In 2008 a directive was adopted within the EU that aimed to reduce all primary energy use by 20% until the year 2020. This is to be compared to the predicted energy use levels of 2020. Further, the emissions of CO_2 from the EU are supposed to be reduced by 20% until 2020, compared to the corresponding levels of 1990. And finally, in 2020 all energy supply within the EU should consist of at least 20% renewable energy. This package of targets for the European energy sector was named the 20-20-20 package [1]. The national goals set by the Swedish government states that total specific energy use per heated area in Swedish buildings shall be reduced by 20 % until 2020 and by 50 % until 2050 compared to the levels in 1995 [28, 29].

The Swedish emissions of CO_2 shall be reduced by 40 %, compared to the levels in 1990, until 2020. And 50 % of the total Swedish energy use shall stem from renewable energy sources [30].

In 2010 the EU launched a recast of "The Energy Performance of Buildings Directive" which requires all new buildings to be of nearly zero energy standard in 2020. This directive also included that all member states shall make national actions plans for how to increase the number of nearly zero-energy buildings and this is supposed to also apply to the renovation of existing buildings [20]. The Swedish Energy Agency proposed a plan where all new buildings were supposed to use no more than 55 – 75 kWh/m^2 year after 2020. Also the plan included a corresponding requirement of a maximum of 75-105 kWh/m^2 year after renovation of buildings [31].

2.3 The Power Systems of Europe and Sweden

As mentioned in Section 1.1 the systems perspective is crucial for the analyses performed in this thesis. This chapter introduces and briefly describes the relevant characteristics of the Swedish power system and its relation to the European power system. The focus is on Swedish, Nordic and European production of electricity, along with a description of the electricity transmission situation between the Swedish and the European energy system.

2.3.1 Power Generation

The electricity generation is important for this thesis since the environmental evaluation of electricity use have impact on the interpretation of the presented results. This is because the required amount of primary energy for different types of electricity generation varies significantly. Figure 2.3 shows the electricity generation mixes for Sweden, the Nordic countries (Sweden, Denmark, Norway, and Finland) and for Europe.

In 2008 Swedish power plants generated 150 TWh of electricity. Swedish hydropower constituted 46 % and nuclear power 43 % of the total production, respectively. The corresponding numbers for fossil thermal power and other renewable power generation (including biomass fuelled CHP and wind power), were 3 % and 9 % respectively [32]. The Swedish system also had a net export of electricity of about 2 TWh in 2008. However, the Swedish net import or export of electricity varies for each year due to changes in electricity demand and power plant availability, in both Sweden and the rest of Europe. In 2009 for example there was a net import of about 5 TWh of electricity to Sweden [15].

In the Nordic electricity generation mix the share of hydro power generation is clearly dominating. This is due to the large amounts of hydro power in Norway (98 % of the total Norwegian power generation) and Sweden. Nordic fossil thermal power constitutes 14 % of the mix which is larger than for the Swedish system. Nuclear power and non-hydro renewable power generation constitute the remaining part of the Nordic mix.

The European electricity mix differs significantly from the Swedish and the Nordic mixes. 3 351 TWh of electricity were generated in Europe 2008. The generation was dominated by fossil thermal electricity generation that constituted 55 % of the total. Nuclear power constituted 28 %, hydro power 10 % and other renewable electricity generation (such as wind and solar electricity generation) constituted 7 % [32]. Thermal power generation in Europe mainly use fossil coal and fossil natural gas and the average efficiency in thermal power stations in the European countries is about 50 % [32, 33].

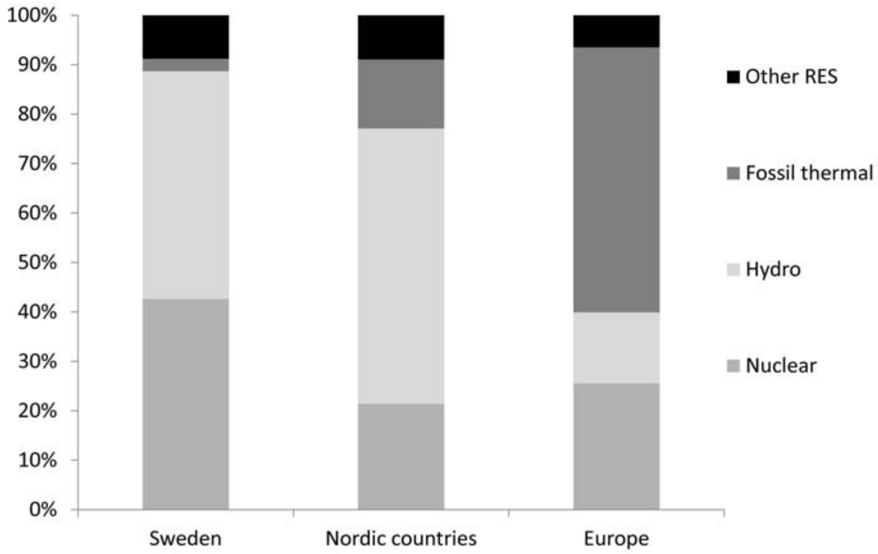

Figure 2.3: Electricity generation by type of power station in 2008 for Sweden, the Nordic countries and in the EU 27 countries, based on data from Eurostat [32].

2.3.2 Electricity System Interconnections

In order to describe the complexity of the Swedish electricity system and its part in the Nordic and the European electricity systems, the interconnections between the systems are briefly described in this Section. The physical transmission capacities between the Swedish electricity system and the Nordic countries along with the indirect and direct transmission connections to the European electricity system are visualised in Figure 2.4. The Swedish system is part of the well integrated Nordic electricity network which is connected to the European system directly and indirectly via Holland, Germany, Poland, Estonia and Russia. This means that changes in the Swedish power demand and supply could affect operation of power plants in the other Nordic countries and in other parts of Europe.

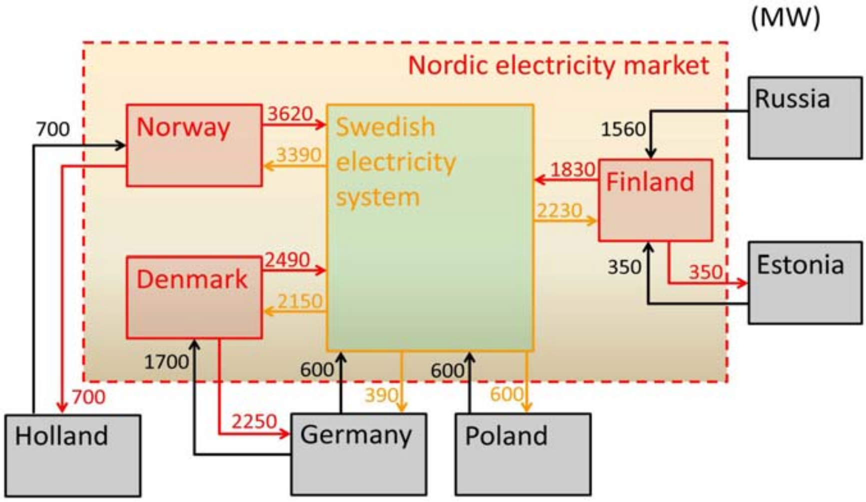

Figure 2.4: Electricity transmission capacity between Sweden, the Nordic countries and other neighbouring countries, after Swede Energy [34].

Figure 2.5 shows the direct electricity import and export from Sweden to neighbouring countries on a 24 hour basis for 2009 and 2010. It can be seen in the Figure that the import and export flow of electricity to and from the Swedish electricity system to the neighbouring countries is continuous. If also the indirect connections to Holland, Russia, Estonia and the rest of Europe is considered, it is clear that the origin of imported electricity to Sweden is significantly difficult to trace.

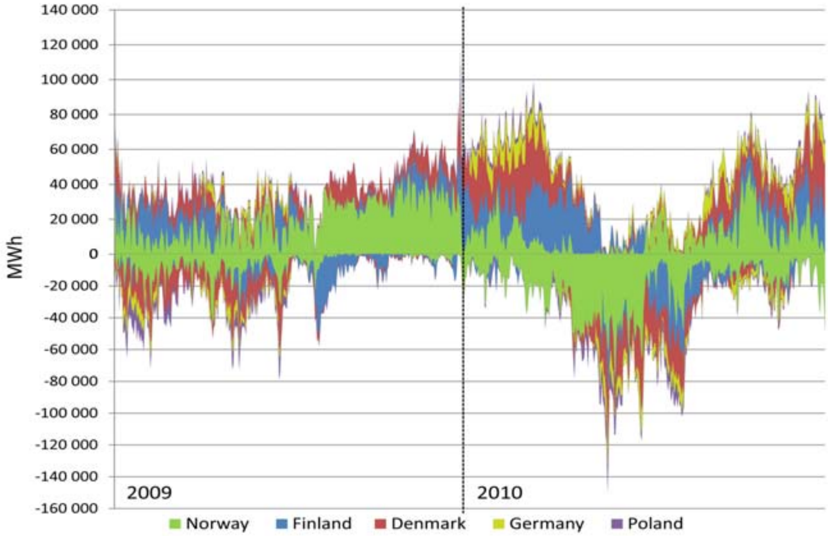

Figure 2.5: 24-hour mean values of electricity import (positive values) and export (negative values) from Sweden to the neighbouring countries in 2009 and 2010, based on data from Nord Pool [35].

2.3.3 Environmental Impact of Electricity Use

In the striving towards more efficient primary energy use and less emissions of GHG, the environmental evaluation of electricity use is crucial. The necessity of such evaluation lies in for example, the need of comparing different types of energy use and being able to approximate the environmental impact of taken energy efficiency measures and the resulting changes in primary energy use. The use of electricity is commonly evaluated in terms of CO_2 emissions, or CO_2 equivalents.

The complexity of the Nordic and the European electricity systems were briefly described in the previous sections. The estimation of climate impact from electricity use is strongly connected to this complexity. In order to be able to estimate the CO_2 emissions that are indirectly caused by electricity use, the knowledge of where the used electricity stems from is crucial.

There are several different approaches to approximate the origin of electricity use in Sweden. Most common are the using of average numbers for electricity production in a system or using the concept of marginal electricity production. Sjödin and Grönkvist [36] investigated the differences between these approaches. There is also an electricity use evaluation approach directly related to a system where an extra cost is paid by the consumer for the electricity to become labelled with for example “Swedish Good Environmental Choice”. This labelling guarantees that the purchased electricity stem from renewable power sources such as wind-, solar- and hydro power. The extra cost charged for the electricity is invested in future renewable power generation. Using this approach means that labelled electricity would be assumed to stem from the power generation sources included in the specific label [36]. This electricity labelling approach has not been used in the studies presented in this thesis, since it does not capture the actual electricity generation in the system and is therefore not suitable to assess momentary effects of changes in electricity demand and supply.

Another important aspect of accounting for CO_2 emissions is connected to the European Union Emission Trading System (EU ETS). This system gives all large emitting facilities within the EU an allowance to emit a certain amount of CO_2, also a fixed total amount of emissions is defined for the entire EU. Facilities with lower emissions than their quota can sell their allowance surplus to other facilities that have greater emissions than what is covered by their allowances. It can be argued that a consequence of this system is that a reduction of emissions from a local facility is considered irrelevant, since the rights to emit the corresponding amount of CO_2 is obtained by other facilities and the same total amount of CO_2 is emitted nevertheless [37]. However, emission reductions do have importance for the possibilities to lower the total amount of CO_2 emission allowances to the required level [38, 39].

In all three papers included in this thesis the marginal electricity production approach is applied when evaluating electricity use. In paper II, average production, i.e. electricity production mix for the Nordic electricity system, is also applied. These two approaches will be further explained and discussed in the following sections.

Electricity production mixes

Using a production mix to assess emissions from electricity use basically means that average emissions are calculated from recent year´s electricity generation in a particular system. For the Swedish national electricity system this means that every kWh of used electricity is assumed to stem from about 50 % hydro power, 40 % nuclear power and 10 % other power sources (mainly CHP, industrial power generation and wind power). This results in an emission factor of about 11 kg CO_2/MWh. And if the Nordic power system is considered the corresponding emission factor is about 100 kg CO_2/MWh (see Table 3.3) due to larger amounts of fossil based power generation in Denmark and Finland [32].

The average production mixes are according to Sjödin and Grönkvist [36] not useful to assess the effects of changes in electricity use or generation. This due to the fact that the average mix fails to account for the dynamics of the electricity system and the actual effects of variations in electricity use or production. In paper II the Nordic mix is used along with other evaluation approaches to illustrate the different results that are yielded with different accounting schemes.

Electricity production on the margin

When electricity supply and demand is changed in a short and a long term perspective it is not, as already mentioned, easy to describe and investigate the effects that these changes have on the power system. The use of a production margin approach to evaluate changes in electricity generation and consumption is recognised as the best available theoretical estimate for the electric system dynamics in [36]. This approach is also used in all three papers included in this thesis.

The principle of the production margin approach is that changes in electricity use and generation affects the, for the moment, most expensive electricity generation in the system. This however becomes further complicated when considering that limitations in transmission capacity within the electricity system also influence which electricity generation that constitute the marginal production at different times and in different parts of the considered system. This could for example mean that even if the most expensive generation that is supplying electricity to Sweden at a certain time is a low-effective Danish coal condensing power plant, the marginal production in for example northern Sweden might be wind or hydro power if the transmission lines within Sweden are utilised to a maximum.

Another reflection is that for the Swedish case the production margin generally can be considered to be located outside the Swedish system, or even outside the Nordic system as electricity is imported and exported to and from the Swedish and Nordic systems. However in the case when all transmission lines are fully utilised for export or import, the production on the margin is domestic electricity generation. Figure 2.5 in Section 2.3.2 indicates that this situation is not frequently occurring.

In the three papers included in this thesis the production margin is assumed to be constituted by coal condensing power plants (CC) in the short-term perspective with an emission factor of 950 kg CO_2/MWh of electricity. In the long term perspective natural-gas-fired combined cycle plants (NGCC) are considered to constitute the marginal electricity production with an emissions factor of 400 kg CO_2/MWh of electricity. (See Table 3.3) The short term perspective is based on the present electricity generation in the European system while the long-term perspective reflects the idea that the CC plants in Europe will eventually be replaced by NGCC plants. The CC assumptions is to be considered a worst case electricity production margin, since it is not likely that the electricity margin affecting electricity supply and demand in Sweden will at all times be constituted by CC. However since the accurate margin production is impossible to know in advance for a specific time, a worst case emission factor at least can tell us that changes in electricity generation and use will probably not have greater effects.

3. Methodology and Data

The methodology and data used in the appended papers are presented in this chapter. The performed research is based on modelling and energy system optimisation. Section 3.1 describes the overall characteristics of the modelling tool used in the three studies. The modelled systems structure and the data used in the models are presented in Section 3.2. The different studied scenarios are presented in Sections 3.3 and 3.4. Some conventional theoretical concepts for CO_2 emissions caused by energy use are presented in Section 3.5. Finally a concept for the environmental evaluation of district heating systems based on their electricity-to-heat output ratio is presented in Section 3.6.

3.1 MODEST

The modelling tool used in this thesis is called MODEST (Model for Optimisation of Dynamic Energy System with Time-dependent components and boundary conditions). MODEST is an optimisation model that uses the linear-programming method to find the cost optimal design and operation of the modelled energy system. Future costs are represented by their present values with respect to a real discount rate.

Linear programming is generally used to find the maximum or minimum values of a linear function constrained by linear relations. This method is frequently used in, for example business and economics to maximise profit or minimise cost.

A linear program is a problem with an expression to be minimised or maximised, i.e. the *objective function.* This function can be described as

$$c_1 \cdot x_1 + \cdots + c_n \cdot x_n \tag{3.1}$$

Further the linear program is defined by a set of *constraints (see Equation 3.2) [40].*

$$\begin{cases} a_{11}x_1 + \cdots + a_{1n}x_n = b_1 \\ \qquad\qquad \cdots \\ a_{m1}x_1 + \cdots + a_{mn}x_n = b_m \\ \qquad x_i \geq 0, all\ i \end{cases} \tag{3.2}$$

For energy system optimisation problems defined in MODEST the objective function is a system cost that is minimised to find an optimal system design and operation.

The MODEST model variables, $x_1, \ldots, x_n$ in Equation 3.1, are mainly energy flows, which connect different energy system nodes (e.g. boilers, turbines). Each node and flow can be constrained (see Equation 3.2) and related by definition of specific characteristics, such as energy balances, energy limitations, maximum outputs, flow-ratios and efficiencies. Each node and flow can also be associated with a cost, defined as $c_1, \ldots, c_n$ in Equation 3.1. These costs are for example fuel costs, taxes or maintenance costs. There can also be investment costs for new installations but that is not included the studies in this thesis. Other parameters are energy demand and electricity-to-heat output ratios of CHP plants.

The time division in MODEST is discrete and can be used in a flexible way to describe variations in for example energy demands and energy prices. A year is divided in seasons (or months) that can be further divided into diurnal periods (days, nights and specific hours). The flexible time division offers the possibility to include peak demands at a higher resolution than what is needed for off-peak periods. The model results include all energy flows for each time period (i.e. operation of all plants), the total cost and emissions.

MODEST can be used for local, regional and national energy systems. The model is similar to models such as MARKAL [41] and EFOM [42] but offers greater flexibility concerning time division and adaptability to different types of systems.

As previously mentioned, Difs et al [9] used MODEST to study the impact of a 10 GWh annual decrease in heat demand due to improved attic insulation in buildings. MODEST has also been used in many other applications, for example investigating the effects of industrial energy efficiency measures [43, 44] and the possibilities of a regional district heating market [45]. The model is described in detail by [46] and [47].

Unlike the studies mentioned above, the MODEST studies presented in papers I and II appended in this thesis are focusing on detailed district heating demand side changes of varying size. Also, the changes in space heating demand and domestic hot water demand are calculated separately. Further unlike previous MODEST studies, the national power system model presented in paper III has a time-division that is developed to especially capture wind and solar power variations.

3.2 Three Different System Models

Heat demand change analyses were performed using models of two different Swedish district heating systems. The overall aim of these studies was to investigate the effects on district heat production and electricity production in CHP plants caused by changed heat demand due to energy efficiency improvements in buildings. In order to analyse how building energy-efficiency measures affect the operation in different district heating systems case studies were performed on the two systems with similar objectives. In the appended paper I the effects on the district heating system in the Swedish city of Linköping was analysed, and paper II focused on the effects on the district heating system of the Swedish city of Uppsala. The two different systems have both similarities and crucial differences that make them suitable for a comparative analysis. The two systems and the case studies are described in more detail in the following sections.

3.2.1 The Linköping District Heating System

The City of Linköping is the fifth largest city in Sweden with 140 000 inhabitants. The city is located about 200 km southwest of Stockholm. The main characteristic of the Linköping district heating system is its large share of heat production in CHP plants. Between 80 and 90 percent of the annual heat deliveries in the Linköping district heating system is co-produced with electricity in CHP plants. The system also has a large share of heat production stemming from waste incineration plants. Waste is imported to the Linköping system from 30 different surrounding municipalities.

The share of fossil fuel in the Linköping system is about 14 %, constituted by 8 % oil and 6 % coal. The oil is used partly for peak demand heat production and partly for co-production of electricity in oil fired gas turbines that are integrated with some of the waste incineration boilers in the system. Coal is used in one of the CHP plants in the system. The fuel mix in the Linköping system is shown in Figure 3.1.

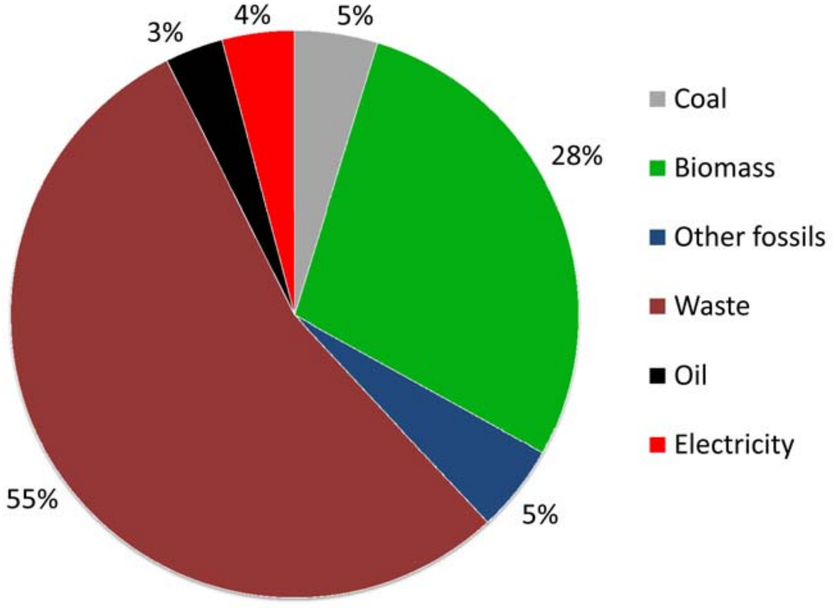

Figure 3.1: Fuel mix in the Linköping district heating system in 2008, based on data from the Swedish district heating association [17].

The total district heating production in Linköping in 2007 was 1625 GWh and the amount of produced electricity in the CHP plants was 259 GWh. Figure 3.2 shows the monthly heat demand in Linköping over the year and the plants that are used to meet the demand each month. The merit order is based on heat production cost. That is, the plant with the lowest heat production cost is found in the bottom of the bar and then plants are added according to increasing production cost until the heat demand is filled. The heat demand in the system is to large extent covered by the CHP plants. Heat only production in different plants is used from September until May. During the colder months of the year (December, January and February) electricity and oil are used in heat only boilers to supply peak demand.

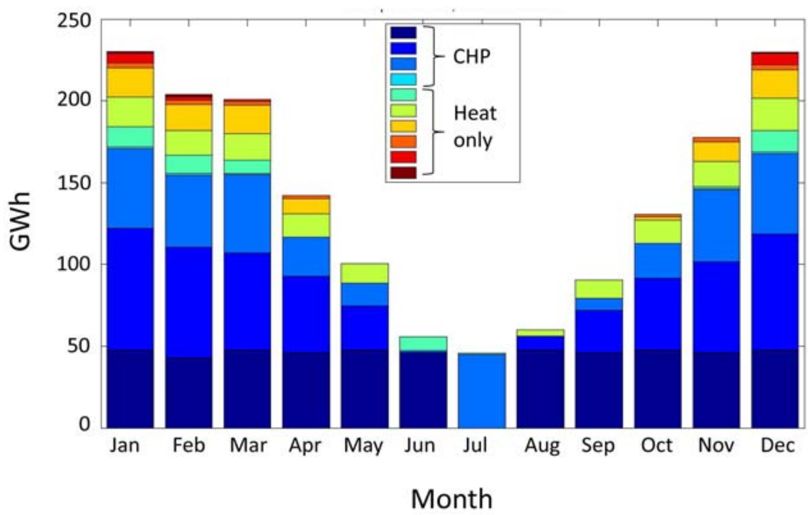

Figure 3.2: The heat demand and merit order of the Linköping district heating system. The figure is based on model result data from paper I.

About 90 % of Linköping's 46 500 multi-family residential apartments are connected to the district heating network [48]. About half of the heat produced in the Linköping system is delivered to multi-family residential buildings and the remaining half is delivered to single family houses (10 %), industry (15 %), public buildings (14 %) and other consumers (10 %) [49].

MODEST model of the Linköping system

Figure 3.3 shows the aggregated structure of the used model for the Linköping district heating system. The fuels are represented to the left and the demand and markets to the right. The heat and electricity production plants and the distribution system are represented in the middle of the figure. There is also a re-cooler to the right in the Figure which represents the possibility to waste heat. This means that the CHP plants in the Linköping system could also function as condensing power plants.

The hybrid CHP plant uses waste and oil for heat and electricity production while the central CHP plant primarily uses oil, coal and wood. There is also a small diesel fuelled CHP plant within the system and the heat only oil boilers and electric boilers are mainly used for peak demand and back up heat production.

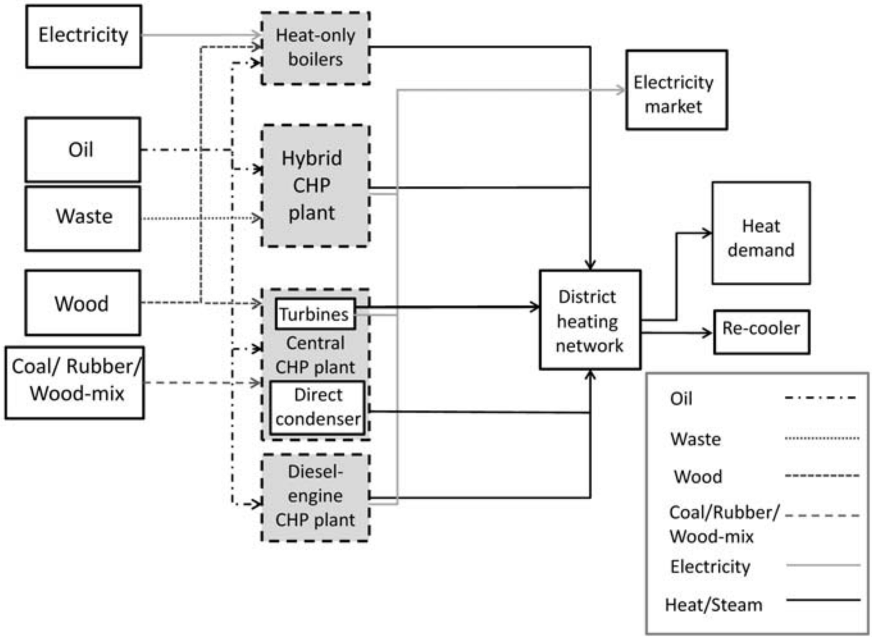

Figure 3.3: Aggregated presentation of the used model of the Linköping system.

3.2.2 The Uppsala District Heating System

The city of Uppsala is Sweden's fourth largest city and has nearly 200 000 inhabitants. The city is located about 80 km north of Stockholm. A similarity between the two systems is the large share of heat produced through waste incineration and that a large amount of heat is co-produced with electricity in the systems. In the Uppsala system about 60 - 70 % of the heat is produced in CHP plants. The fuel mix of the Uppsala system is shown in Figure 3.4.

A significant difference in the Uppsala fuel mix compared to the fuel mix in the Linköping system is the large share of peat. About 40 % of the total amount of fuel used in Uppsala is constituted by peat. The environmental aspects of peat as a fuel were described briefly in Section 3.5 and in this thesis peat is considered a fossil fuel. During the recent years the peat has been mixed with wood to reduce the environmental impact from the system. In 2009 the share of wood in the peat fuel was 2% and the corresponding share for 2010 was 6% [50*]. In the model described in paper II this wood is not included due to the small shares in the peat fuel mix.

The use of oil in Uppsala constitutes 2 % of the fuel mix and is only for supplying peak demand and back-up heat production. The electricity use for district heating production in Uppsala (4 %) is larger than for the Linköping system (1 %) due to the fact that within the Uppsala system electric heat pumps are used for heat production. Uppsala also has a smaller share of biomass in the fuel mix compared to Linköping.

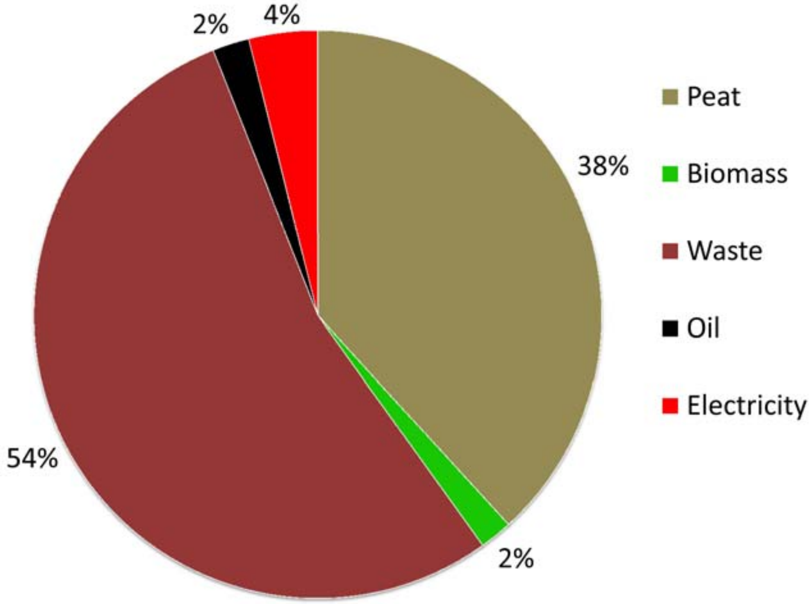

Figure 3.4: Fuel mix in the Uppsala district heating system in 2008, based on data from the Swedish district heating association [17].

A total of 1465 GWh of heat and 228 GWh of electricity were delivered from the Uppsala district heating plants in 2009. In Figure 3.5 a duration diagram visualises a template for the annual heat production in the Uppsala district heating system. The diagram shows the total heat output per hour in decreasing order. Thus, winter hours with the highest demand for heat are found to the left in the diagram, spring and autumn in the mid part and summer hours to the right. The merit order of the production plants is defined by the heat production cost with the most expensive plants covering the top of the heat demand level to the right.

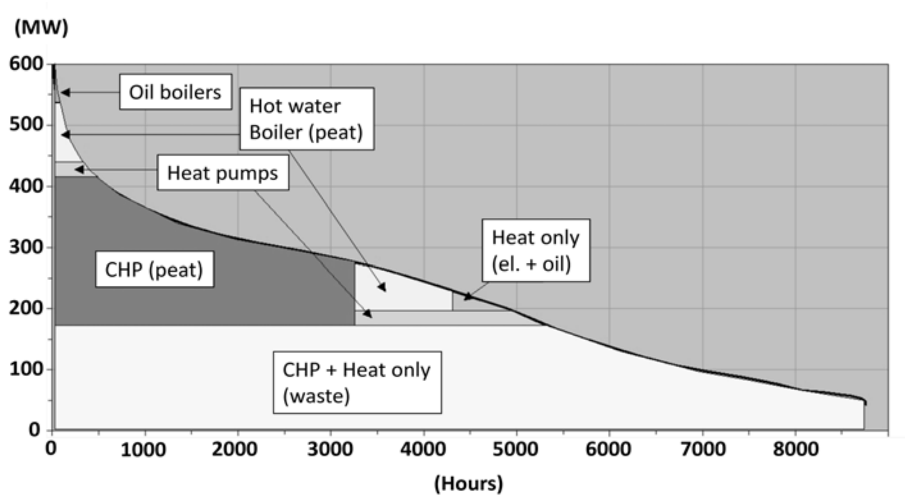

Figure 3.5: Duration diagram showing the merit order of the heat producing units in the Uppsala district heating system [51].

As for the Linköping system, the waste incineration plants have the lowest production cost. In both Linköping and Uppsala this is due to a reception fee that the district heating company charges for waste management. This means that household waste is actually a fuel with a negative cost, in other words an income. For more than 3000 hours per year the peat fuelled CHP plant is covering most of the heat demand that exceeds 170 MW. However the CHP plant has a minimum output of about 110 MW and is therefore not used when the total heat demand is less than about 100-110 MW above the output from the waste incineration plants. Heat only production in a peat fuelled boiler, oil boilers and electric heat pumps is used to cover peak demands and to replace the CHP plant when the output demand is less than 280 MW.

Similar to Linköping, about half of the Uppsala heat deliveries are addressed to multi-family residential buildings.

MODEST model of the Uppsala system

In Figure 3.6 an aggregated schematic illustration of the Uppsala system model structure is shown. The fuels used within the system are shown to the left. The heating and cooling demands and the electricity market are represented to the right along with the re-cooler for heat waste. The waste incineration processes are represented within the upper conversion box in the middle column. The box underneath the waste incineration contains the peat fuelled CHP plant along with peak demand oil boilers and the peat fuelled heat only boiler. The lower box seen in the mid column contains the electric heat pump facility for production of district heating and cooling.

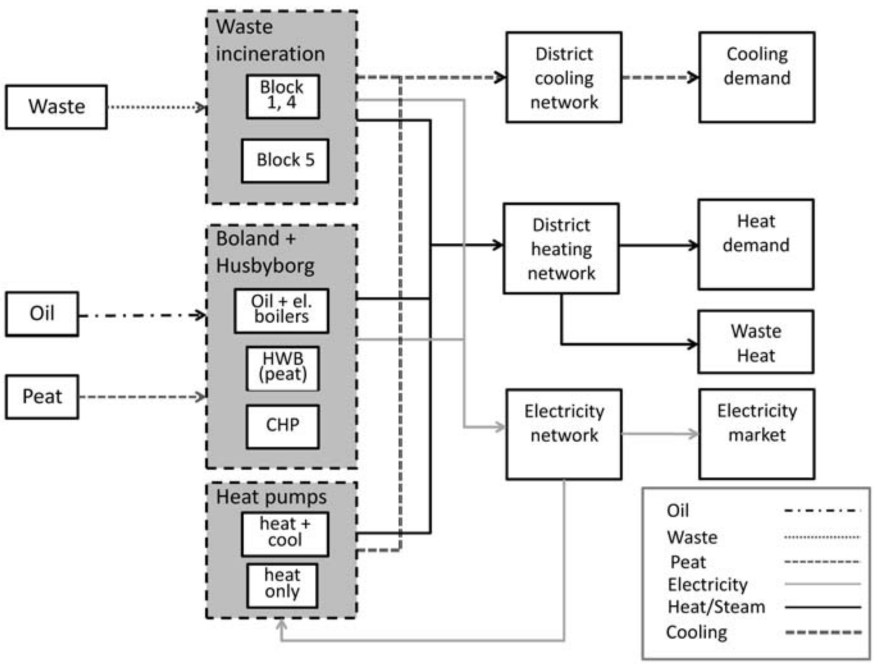

Figure 3.6: Schematic presentation of the Uppsala model.

3.2.3 The Swedish Power System

A MODEST model was built that represents and captures the important characteristics of the Swedish power system that was described in Section 2.3. The model includes an aggregated representation of the Swedish district heating systems. Figure 3.7 shows a schematic picture of the model with the used fuels for energy conversion to the left. The different energy conversion units are found in the mid column with electricity generation in the upper half and district heating in the lower half. The box for electric heating in between the electricity transmission box and the heat distribution box illustrates the possibility to use electricity for district heating production in electric heat pumps. Electricity purchase and sales can take place in the electricity market represented in the upper right part of Figure 3.7. A more detailed description of the model components is found in paper III.

The time division used in the model especially considers variations in wind and solar power generation. To reflect the possibility of various wind and solar power generation conditions to coincide or not, different power generation levels are assumed for the diurnal periods throughout the year. Also, the time division is represented with higher resolution during winter to capture electricity and heat demand peaks and a number of peak days are also included. The model was validated to fit data for fuel use in district heating systems obtained from the Swedish District Heating Association [17] and to fit data for electricity generation and Swedish electricity import and export obtained from Statistics Sweden [52]. All validation data were for 2008.

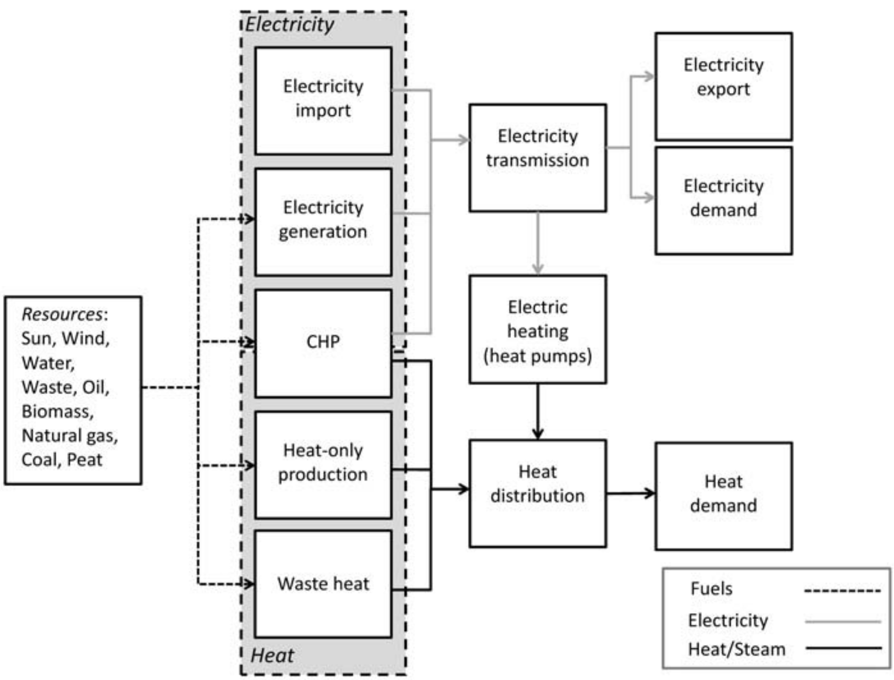

Figure 3.7: Aggregated MODEST model of the Swedish power system including district heating.

3.3 Heat Demand Change Scenarios due to Energy Efficiency Improvements in Buildings

When studying the effects of building energy efficiency measures, estimations of heat demand changes due to efficiency measures need to be made. This was done somewhat differently in the two studies of Linköping and Uppsala. This section presents the assumptions made and the calculations for heat demand changes. In all calculations of heat demand reductions due to energy efficiency measures in buildings, the reduction of space heating demand (SH) and domestic hot water (DHW) demand were done separately.

3.3.1 Heat Demand Reduction Scenarios in Linköping

For the Linköping study in paper I, a survey was initially made for the city building stock and all multi-family residential buildings built during the years 1961-1980 were identified. These buildings constituted 12 % of the total building stock in Linköping and were assumed represent the part of the Linköping building stock that were built within the Swedish million-programme (Section 2.2.1). Further, these buildings were assumed to be refurbished into an energy standard corresponding to the energy standard of the million-programme buildings renovated into passive houses in Brogården, Alingsås (Section 2.2.1). These renovations lead to an 8.3 % total annual reduction of the heat demand in Linköping.

The Linköping study also included a heat demand change sensitivity analysis where the total heat demand in Linköping was decreased step-wise by 5, 10, 15,…,50 %. The heat demand reduction analysis was performed for the district heating system as it functions today. No changes on the heat production side were studied.

3.3.2 Heat Demand Change Scenarios in Uppsala

For the Uppsala study in paper II, a heat demand change scenario was created where the total demand for district heating was assumed to be decreased by 1,5 % per year until 2030 based on the conclusions in a report published by the Swedish district heating association [18]. Also, 1000 new energy efficient residential apartments per year were assumed to increase the heat demand. The heat demands for the additional apartments were generated using the building simulation software VIP Energy [53]. These new houses were assumed to use 55 KWh/m^2 year in accordance with the suggested plan for energy efficiency in buildings from the Swedish Energy Agency (Section 2.2.2). 10 scenario stages were created for the years 2012, 2014, 2016,…,2030. As for the Linköping study the building energy efficiency measures in Uppsala lead to a reduced and more levelled annual heat demand.

3.4 Studying the Impact of Electricity Market Dynamics on District Heating

Figure 3.8 shows the hourly spot market prices in Sweden during the years 2006-2008. No obvious seasonal dependent pattern can be recognized. The electricity price is set on the Nord pool spot market and depends on several external factors, such as oil price and economic fluctuations. This makes it difficult to yield good approximations of the future electricity price which is needed when making scenarios for the future. Also, the electricity price is a critical parameter when studying future district heating scenarios since it has significant impact on the operation of the district heating systems, especially CHP production and electric heat pumps.

In paper I this problem was dealt with by using an hourly mean electricity price of the three years presented in Figure 3.8. The gain of this approach was that extreme peaks and lows were reduced and the results would not only be valid for one specific year. On the other hand there is nothing saying that the future electricity price will correspond to any of the prices in 2006-2008 or with a mean price.

In paper II an electricity price sensitivity analysis was performed where four different electricity price cases were defined regarding seasonal and diurnal variations. The impact of electricity price variations on the operation of the studied system in paper II was then analysed. This is further described in Section 3.5.

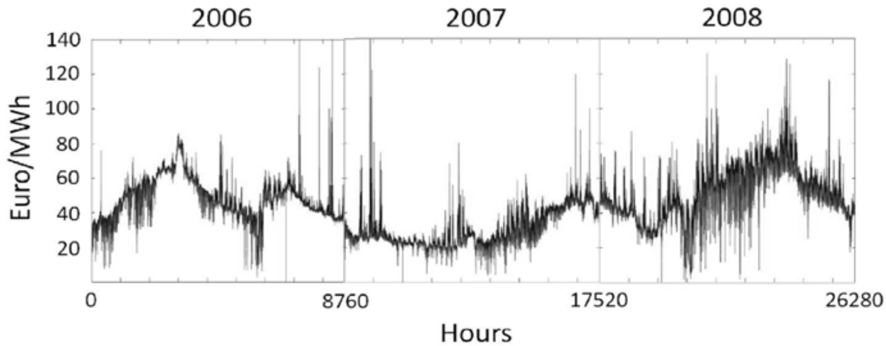

Figure 3.8: Hourly electricity prices in Sweden for the years 2006-2008, based on data from Nord Pool [35].

3.4.1 Scenarios for Renewable Power Generation in the Swedish Power System

Since renewable energy is targeted to cover 20 % of European energy use by 2020, the implementation of renewable electricity generation is an important part of this European energy system conversion. Paper III in this thesis investigates the possible effects of large scale renewable power generation on the Swedish power system and district heating systems.

Renewable power sources like solar and wind power are *intermittent*, which means that the output is systematically and randomly variable in time. This intermittence has impact on the balance, operation and reliability of power systems. An increase in intermittent power generation requires an increase in power generation reserves. An important aspect of increased levels of renewable intermittent power generation is that it has impact on electricity price levels [54, 55, 56, 57] Changes in electricity price levels also affect the operation of CHP plants, electric boilers and electric heat pumps in district heating systems. Wind and solar power generation is in practice not associated with a running cost and can therefore alter the merit order of electricity consuming and producing heating plants.

Two scenarios (A and B) were made to study the implementation of large amounts of renewable power generation in the Swedish power system. Scenario A is a reference scenario that represents the Swedish power system of 2008 with 2 TWh wind and 0.001 TWh solar power. In scenario B different levels of renewable electricity production is added to the system as shown in Table 3.1. The scenario is divided into four cases, all with the Swedish goal of 30 TWh of wind power until 2020 [58]. Further, for each case the amount of solar power is increasing. In the fourth case (B4) the amount of wind and solar electricity in the system is 60 TWh which is close to the level of the Swedish nuclear power generation.

Table 3.1: *Studied scenarios for renewable power integration in the Swedish electricity system. (Annual production)*

Scenario	**Case**	**Wind Power [TWh]**	**Solar Power [TWh]**
A	-	2	0.001
B	1	30	0.001
B	2	30	10
B	3	30	20
B	4	30	30

3.4.2 An Electricity Price Level Sensitivity Analysis

In paper II, electricity price sensitivity analyses are performed for the reference 2010 scenario case and for the 2030 heat demand change scenario stage, both described in section 3.3.2. Four different electricity price profiles are used to represent four characteristic situations. The profiles have been designed to capture electricity price fluctuations observed in the years 2006 and 2007 (see Figure 3.8). The profiles are different in terms of seasonal variations and diurnal fluctuations. Table 3.2 describes the features of the four cases.

Table 3.2: *The features of the four electricity price profiles in the analysis*

		Seasonal variation	
		low	*high*
Diurnal fluctuation	*low*	Case 1	Case 2
	high	Case 3	Case 4

The four different price profile cases in the analysis are shown in Figure 3.9. Case 1 represents an electricity price profile with low seasonal variation and low diurnal fluctuations. This is the least dramatic electricity price profile of the four and corresponds somewhat to the Swedish electricity price in the year 2007. Case 2 is a profile with high seasonal variation and low diurnal fluctuations. It reflects traditional Swedish electricity price variations with higher prices during winter. Case 3 is a price profile with low seasonal changes and large diurnal fluctuations, which somewhat corresponds to the current price profile on the European continent. Case 4 is the most extreme profile with high seasonal variation and large diurnal fluctuations. This profile could be the result of merging the traditional Swedish high seasonal variation profile with the European high diurnal fluctuation profile.

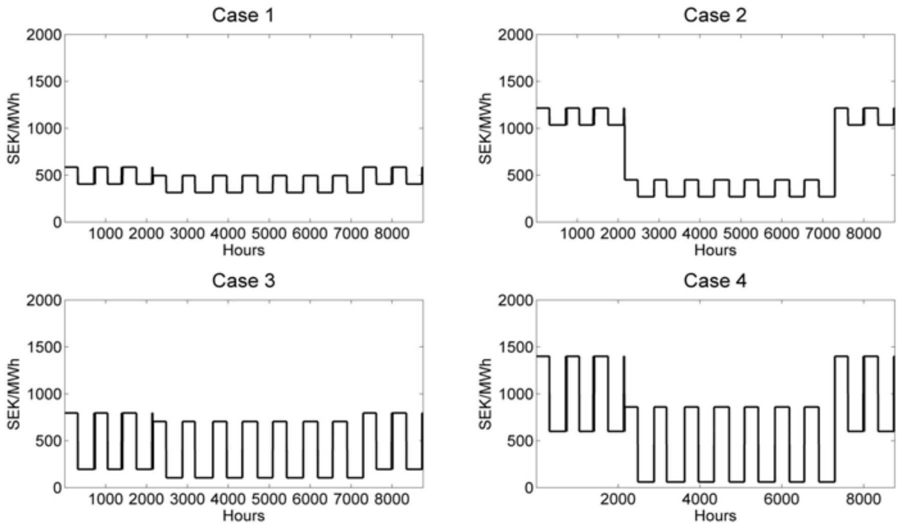

Figure 3.9: Electricity price profiles used in the electricity price sensitivity analysis.

3.5 Environmental Impact of Energy Use

In paper I and II both local and global CO_2 emissions are considered. The local emissions are from fuels incinerated locally while the global emissions are from both the locally incinerated fuels and the emissions associated to electricity consumption and production. This section will briefly present the approaches used in the included studies to assess energy use. Also, the complexity of evaluating energy use in general and electricity use in particular, is briefly discussed here.

Table 3.3 shows the CO_2 emission factors used in the studies. Slightly different emission factors were used for waste and oil in the two studies. This is because the figures for the Linköping system was obtained from the study of the Linköping system described in [47] and are specific for the Linköping system. The figures used in the Uppsala study are general emissions factors for the fuels.

Incineration of bio-fuels, such as wood in Table 3.3 is not considered to contribute to increasing CO_2 concentrations in the atmosphere since new plants and trees are assumed to assimilate the corresponding amounts of CO_2 that is emitted in the incineration process. Therefore are solid biofuels generally considered to be "climate neutral" in a relatively short time-perspective.

There have been discussions in Sweden regarding the environmental impact of peat use and whether it is to be considered a fossil fuel or not. This is due to the time perspective used to distinguish biofuels from fossil fuels. Peat incineration is, depending on decomposition conditions in nature, considered to add CO_2 emissions to the atmosphere several hundred, or even thousands of years in advance [59]. This is a significantly longer time-perspective than for bio-fuels but also a significantly shorter time-perspective than for fossil fuels, which places peat somewhere in between bio-fuels and fossil fuels. In this thesis however, peat is treated as a fossil fuel.

Table 3.3: *Emissions factors used in paper I and II [kg CO_2/kWh].*

Fuel	**Linköping**	**Uppsala**
Waste	100	90
Peat	-	370
Oil	280	270
Wood	0	-
Coal/rubber/Wood-mix	165	-
Electricity (heat pumps and boilers)	950/400/ -*	950/400/100*

* Depends on electricity origin
(CC/NGCC/Nordic mix)

The emissions factors for electricity use in Table 3.3 are based on the electricity on the margin approach and on the production mix approach for evaluation of electricity use (Section 2.3.3).

In paper II, local and global primary energy (PE) use is also considered along with the CO_2 emissions. PE use calculations are similar to that for CO_2 emissions. PE factors were assigned to utilisation of fuel and to electricity use. The PE factor for electricity use in paper II corresponds to the CO_2 emissions factor for the electricity on the margin concept with the CC perspective described in Section 2.3.3. The PE factors describe the amount of primary energy resources necessary for utilisation of energy in different forms. Energy that have been converted in processes with great energy losses, such as electricity from coal condensing power plants, typically has a higher PE factor than energy that can be utilised without conversion, such as coal or biomass [60].

3.6 The α_{system} value

The fact that district heating generated in CHP production units can be considered to have positive environmental effects, while this would not be the case for heat produced in heat-only production units, it is interesting to study the electricity-to-heat output ratio for an entire district heating system. The electricity-to-heat output ratio can be described as the quota of the co-produced electricity and all heat that is produced and utilised. It is important that wasted heat and electricity produced in condensing mode in CHP plants are excluded and not credited as co-production of heat and electricity. This electricity-to-heat output ratio is here denoted the α_{system} value. The α_{system} value provides an indication of the environmental performance of the system. A system with a large share of CHP production will have a higher α_{system} value than a system with a smaller share of CHP production. The α_{system} value depends of course on the electricity-to-heat output ratios (α-values) of the individual CHP production units in the system. Higher plant α values generates a higher α_{system} value.

The α_{system} value is not affected by the type of fuel used in the system because it is a measure of the converted energy forms rather than of the primary energy imported to the system. For a more complete analysis of the environmental influence of a system it is also crucial to consider the fuel mix.

4. Results

This chapter presents and summarises the results from the studies included in the thesis. The results from the heat demand change scenarios are presented in Section 4.1. Section 4.2 presents the results from the electricity market dynamics studies.

4.1 Results for Heat Demand Change Scenarios

This section presents the results from the heat demand change studies performed on the Linköping and the Uppsala district heating systems. The studied parameters are heat and electricity production, amount of wasted heat, local and global CO_2 emissions and the α_{system} value. For the Uppsala results the use of primary energy is presented as well.

First the results for the renovation of multi-family residential buildings built during 1961-1980 in Linköping system are presented. This is followed by the results for the heat demand reduction sensitivity analysis in Linköping. Further are the heat demand change scenario results for the Uppsala system presented.

4.1.1 Results - Linköping

The values presented in Table 4.1 represent the possible effects on heat and electricity production in Linköping caused by an assumed renovation to passive house standard of 15 700 multi-family residential apartments that were built in the years 1961-1980. The annual district heating production was reduced by 116 GWh while electricity production was reduced by 11 GWh. The amount of wasted heat was increased by 19 GWh. Thus, even though the electricity production is somewhat reduced and the amount of wasted heat while producing electricity is increased the effects on the system are dominated by the reduction in heat-only production and more effective use of CHP plants.

Table 4.1: *Results from the renovation of the million programme buildings scenario in the Linköping study, annual values.*

	Heat prod. (GWh)	**Electricity prod.** (GWh)	**Wasted heat** (GWh)	α_{system}	**CO_2 emissions** (kton)		
					Local	**Global** (CC)	**Global** (NGCC)
Reference	1663	475	23	0.286	244	-186	63
Scenario	1547	464	42	0.300	228	-203	46

The α_{system}-value (Section 3.6) also indicates that the heat-only production is decreased to a larger extent than the electricity production since it is increased when the head demand is decreased. This means that the amount of produced electricity per unit of delivered heat is higher in the system for the scenario case than for the reference case.

For the CO_2 emissions (also shown in Table 4.1), both local and global emissions were reduced due to the heat demand reduction. The reduction of local emissions mirrors the reduced use of fuels within the system. However, for the global emissions the CC-case yields negative emissions, explained by the assumption that all electricity produced within the system replaces electricity from coal condensing power plants in Europe, which means a reduction of 950 kg CO_2/MWh of produced electricity (Sections 2.3.3 and 3.5). Larger reductions of CO_2 emissions due to CHP electricity production than emissions from the fuels used within the system causes the negative global emissions. However, the reduction from -186 ktonnes of CO_2 to -203 ktonnes of CO_2 is, as for the local emissions, mainly due to the lesser fossil fuel use within the system since the electricity production is not affected to a large extent. The results for the NGCC case are similar and only differ in absolute numbers because this approach has a smaller emissions factor (400 kg CO_2/MWh of produced electricity).

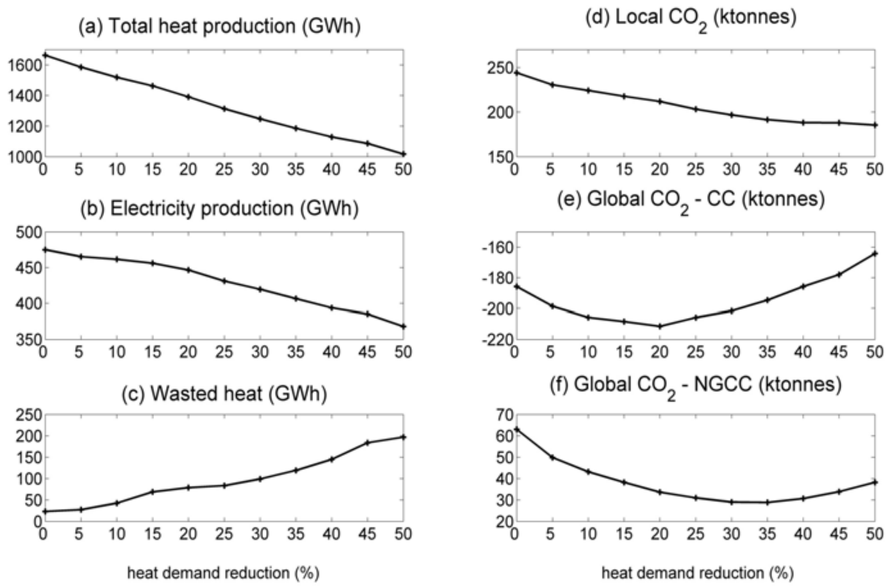

Figure 4.1: Effects on (a) total heat production, (b) total electricity production, (c) wasted heat and (d-f) CO_2-emissions due to heat demand reductions. Note that local CO_2 emissions are included in the global CO_2 emissions.

Figure 4.1 shows the results from the step-wise heat demand reduction sensitivity analysis performed with the Linköping model. Diagram (a) shows the total heat production that is decreased, (b) the electricity production, (c) wasted heat, (d) local CO_2 emissions, (e) global CO_2 emissions with CC-power plants on the electricity margin and (f) global CO_2 emissions with NGCC power plants on the electricity margin.

As the heat demand is reduced, the amount of produced heat and electricity is decreasing. The decrease in electricity production is however relatively small for heat demand reductions up to 20 %. The increase in wasted heat is explained by electricity production being profitable even though the heat cannot be utilised due to the lower heat demand.

The local CO_2 emissions are reduced along with the decreasing heat and electricity production, because less fossil fuel is used. Both diagram (e) and (f) in Figure 4.1 show that the changes in global emissions due to heat demand reduction, at a certain reduction level turns from being decreasing to increasing. This is because the reduction of local emissions from heat only boilers becomes smaller than the increase in emissions caused by reduced electricity production in CHP plants (Section 2.3.3). Thus, Global CO_2 emissions are higher at very large heat-demand reductions because electricity production is lower and less marginal electricity can be displaced. In the CC case, the turning point is at a heat demand reduction of 20 % while for the NGCC case this turning point appears at a heat demand reduction around 30-35%, this because of the lower emission factor associated with electricity produced in NGCC power plants then in CC power plants (Section 3.5). In the CC case, heat demand reductions larger than 40% result in *larger* global CO_2 emissions than today's level. A 20% reduction of the Linköping heat demand in the CC case and 30-35% reduction in the NGCC case generate the lowest global CO_2 emissions.

Figure 4.2 (a-b) shows the duration curves for; the reference case (a) as well as the case with a heat demand reduction of 40 % (global CC emissions yield emissions similar to today's level) (b). The solid bold lines in the duration diagrams represent the heat demand.

The heat only production in the 40 % reduction case is merely 0.1 GWh and is found in the demand peak to the far left in diagram b. The larger amount of wasted heat for the 40 % reduction case is clear in Figure 4.2. In the reference case 23 GWh of heat was wasted and the amount of wasted heat for the 40 % reduction case was 145 GWh. The wasted heat is assumed to stem from the operating CHP plant with the highest production cost, which would not be used if only a lower amount of heat could be produced.

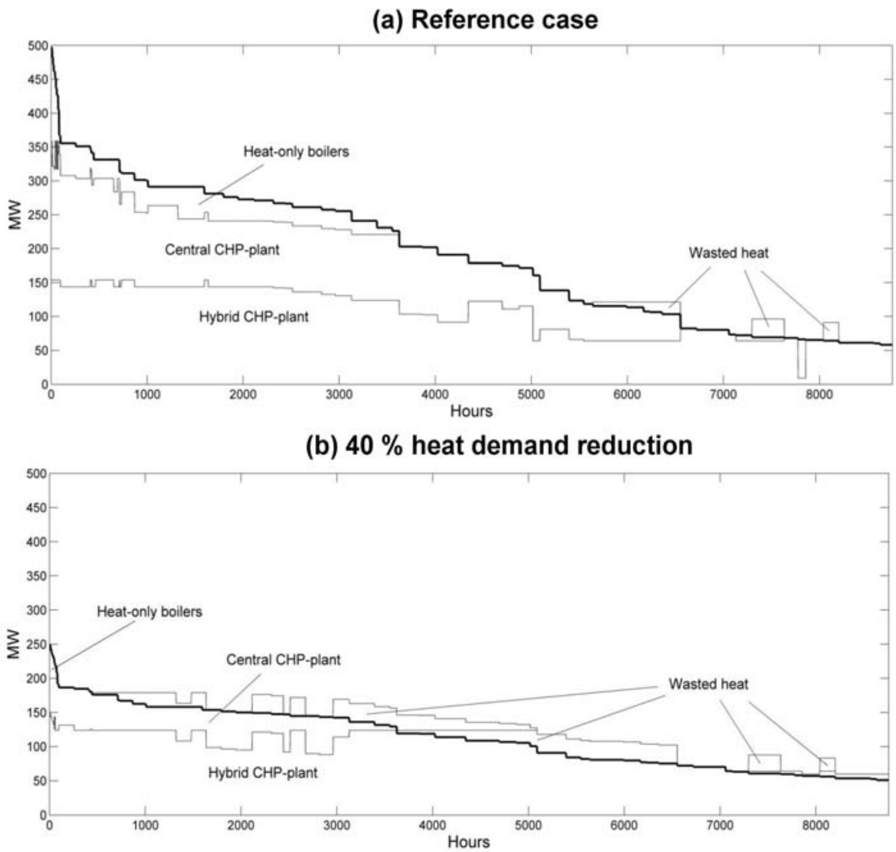

Figure 4.2: Duration diagrams for; (a) the reference case and (b) 40 % heat demand reduction case. The solid bold line is the heat demand and the thin lines indicate the heat production from different production units.

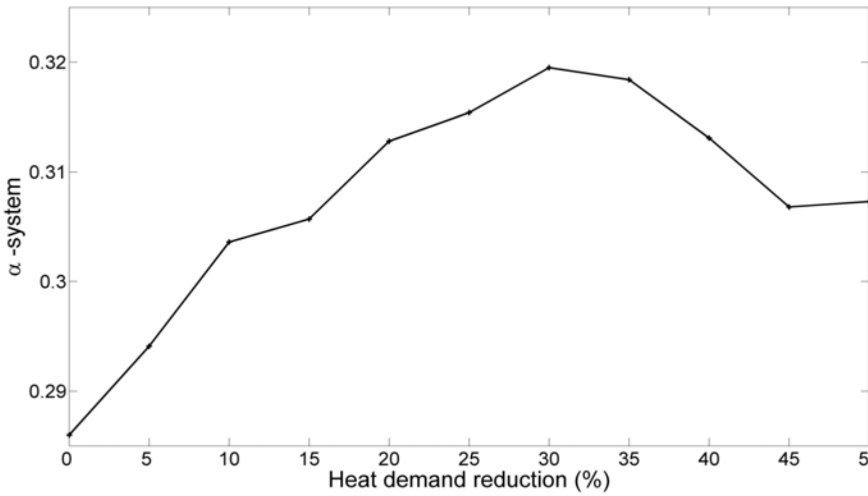

Figure 4.3 Electricity-to-heat output ratios for the district-heating system (α_{system}) depending on heat demand reduction. Note that only utilised heat is included in the ratio.

Figure 4.3 shows how the α_{system} value is increasing for heat demand reductions up to 30 % , which mainly influence the heat-only production units and has less impact upon CHP plants. By extensive demand reduction (above 30 %) the α_{system} value is reduced due to more CHP electricity production where the heat is wasted. The difference in α_{system} value is about 12 % between the reference value (0.286) and the peak value at 30 % heat demand reduction (0.32).

4.1.2 Results – Uppsala

In the Uppsala study a heat demand change scenario was optimised. The scenario included 10 stages representing the approximated heat demand for every second year from 2012 until 2030. In Figures 4.4 and 4.5 the results from these optimisations are presented.

Figure 4.4 (a) shows that both heat and electricity production in the Uppsala district heating system are decreasing for scenario stages 2012 to 2030 due to lowered heat demand. In (b) it is shown that CO_2 emissions are decreasing for all stages, both locally and globally, except with the CC-perspective where the emissions are nearly constant because the local emissions of CO_2 from CHP peat use are similar to the global-CC emissions replaced by CHP electricity. Note the differences in global emissions depending on the choice of electricity evaluation approach. The worst-case CC approach definitely yields the most favourable results considering global emissions from the

Uppsala district heating system. The differences in global emissions however decrease with the amount of produced electricity in the system.

Figure 4.4 (c) shows that the local primary energy use is reduced along with the decreasing heat demand mainly due to the reduced use of fossil peat in the CHP plant. This corresponds well to the local emissions in Figure 4.4 (b). The global primary energy use also shows a development similar to the global emissions when CC is assumed to be on the margin. This is because the primary energy factors for electricity use in the heat production plants are based on primary energy use in coal condensing power plants.

The α_{system} curve in Figure 4.4 (d) follows the ratio between the heat production curve and the electricity generation curve in 4.4 (a). As the electricity generation in the system decreases due to the reduced use of the CHP plant, the α_{system} value drops.

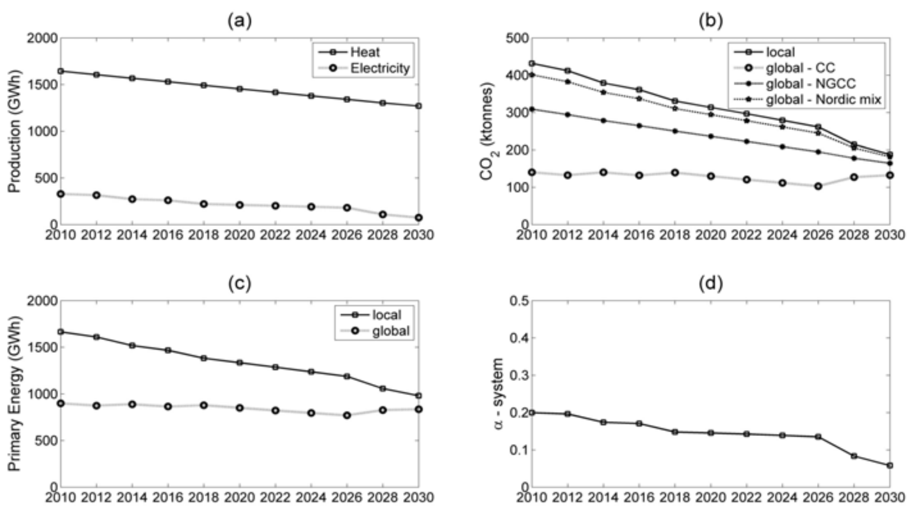

Figure 4.4: Results from the heat demand change scenario including; (a) heat and electricity production, (b) CO_2 emissions, (c) primary energy and (d) α_{system}-value for the system.

In Figure 4.5 (a) the duration diagram for the reference case is shown. The waste incineration plant, i.e. the base heat production, is operated all year. During the period November through March (about 3500 hours) the heat demand is sufficient for utilisation of the peat fuelled CHP. When heat demand is less than 260-270 MW the CHP plant is disabled and replaced by the peat-fuelled hot water boiler (HWB) and the heat pumps. The heat pumps also to some extent replace the waste incineration during summer. The operation of the heat pumps depend on, the electricity price, the demand for district cooling that is co-produced with heat and on the availability to wastewater in the water treatment plant.

In the 2030 scenario case shown in Figure 4.5 (c), the heat demand has been decreased to a level where the CHP plant is not operated at all. Instead the HWB and the heat pumps supply most of the heat demand that is not supplied by waste incineration. Oil boilers are used for the peak demand to the far left in the diagram. There is also some heat wasted from waste incineration units, occurring when electricity production is beneficial in the waste incineration even though the heat demand is already satisfied.

To summarise the results from the heat demand scenario cases in the Uppsala study, the optimisations show that the most cost-effective operation of the system following a reduction and flattening of the heat demand is to phase out the peat-fuelled CHP plant, which leads to less electricity generation in the system and a lower electricity-to-heat ratio. However, this does not increase the CO_2 emissions allocated to the electricity exports from the system even with the most unfavourable assumptions, since local CO_2 emissions from peat combustion in the CHP plant are similar to or higher than the global emissions replaced by CHP electricity.

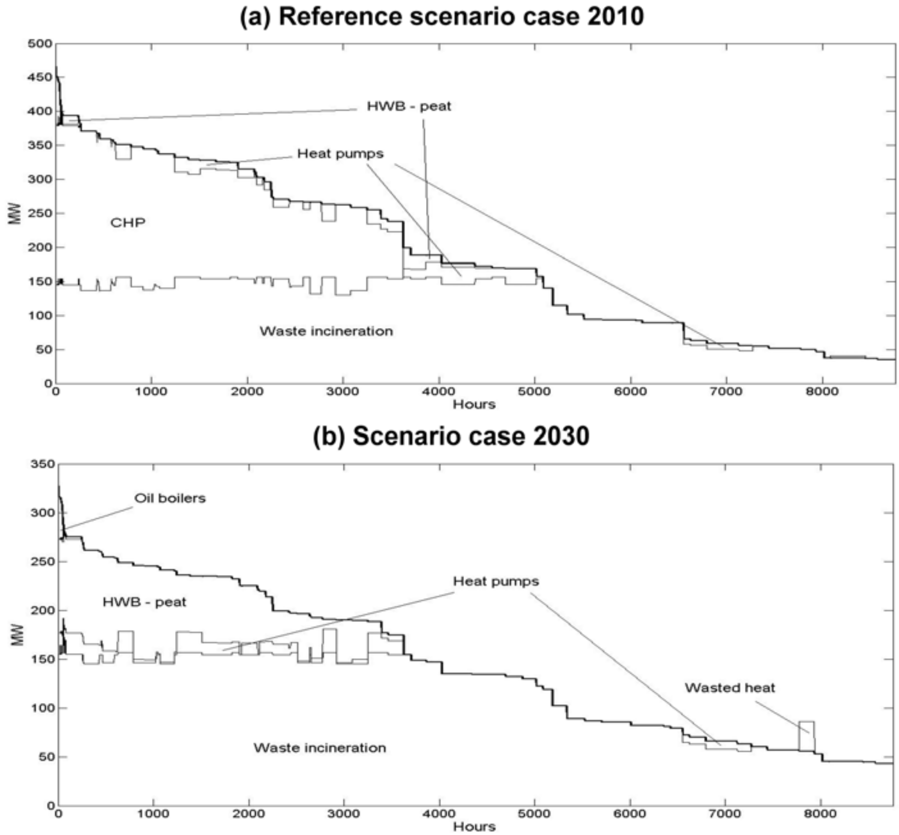

Figure 4.5: Duration diagrams and heat production unit operation for; (a) reference scenario case 2010 and (b) scenario case 2030.

4.2 Results from Electricity Market Dynamics Studies

This chapter presents a summary of the studies of the impact of electricity market dynamics. This topic was investigated in paper II and III. In paper II an electricity price profile sensitivity analysis is performed on the model of the district heating system in Uppsala. In paper III a model was constructed for the national Swedish electricity system including district heating and CHP electricity production. This model was used to study the impact of large scale intermittent renewable electricity generation on the use of fuels, heat production and electricity generation in Swedish district heating systems.

4.2.1 Results from the Electricity Price Level Sensitivity Analysis

In Figure 4.6 results from the sensitivity analysis for the reference scenario for Uppsala 2010 are shown. In Figure 4.6 (a) the amounts of used fuels are shown for the different cases. Waste incineration is favourable because of the waste reception fee and electricity price variations do not change the merit order of the waste incineration plant (WIP). Therefore the use of waste is the same for all cases. No oil is used in the system due to that the oil boilers are used only for peak demand and back-up heat production. This because the fitting of heat demand data to the model time-division reduces the peak demand hours in the model. Also, the back-up production to cover for malfunctions in other production plants is not included in the optimisation model. The use of peat depends on the electricity price variations and from (a) it can be seen that low seasonal electricity price variations (case 1 and case 3) reduce the use of peat compared to cases 2 and 4 with high seasonal variations. Electricity use is low in all cases but significantly lower in case 2, due to higher general electricity price levels during winter that inhibit use of heat pumps.

Figure 4.6 (b) and (c) show the heat and electricity production, respectively, from the different units of the district heating system. The results for cases 1 and 3 indicate that relatively low prices during winter lead to higher heat only production in the WIP and lower co-production of heat and electricity in the CHP plant. The smallest amount of produced electricity in WIP and the least overall use of peat are seen in case 3 and this is explained by the low electricity prices during nights and weekends throughout the year. Large diurnal price fluctuations however, do not affect the heat and electricity production to the same extent as large seasonal variations do, as seen in cases 2 and 4.

Further, in (b) and (c) it is shown that even though electricity production in the WIP is similar for cases 1 and 2, the heat production in the WIP is lower in case 2. This is explained by a reduced need for heat from the absorption heat pumps in the WIP, which is a consequence of higher electricity price levels during winter in case 2 that induce more electricity and heat co-generation in the CHP plant.

The results in Figure 4.6 further indicate that, for the electricity price profiles studied here, seasonal variations have more impact on the results than diurnal fluctuations. In general the production in the CHP plant benefits from high electricity price levels during winter, see cases 2 and 4 in (c). The levels of wasted heat while producing electricity seen in (d) are also higher for these cases to enable extended production of electricity. The limited use of heat pumps and the overall high electricity production in case 2 is explained by the generally high electricity price levels during winter that makes electricity expensive to use but profitable to produce.

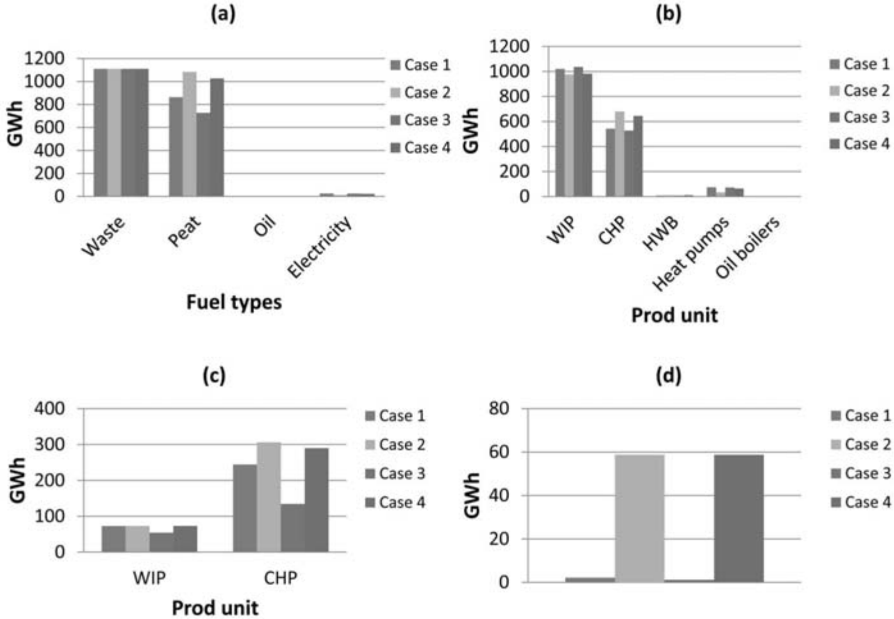

Figure 4.6: The electricity price sensitivity analysis for the reference scenario; (a) used fuels, (b) produced heat in different plants, (c) produced electricity and (d) wasted heat.

In Table 4.2 the α_{system} value for the four cases is presented. The first row includes the values for the reference (2010) scenario stage. The highest electricity-to-heat output ratio for the entire system is for case 2. This match the result shown in Figure 4.6, i.e. that high electricity prices during winter months are beneficial for co-production of heat and electricity in the CHP plant. Also, the α_{system} value for case 3 is significantly lower than for all the other cases, due to small amounts of co-produced electricity. In case 4, lower night-time prices than for case 2 hamper CHP production and this explains the lower α_{system} value in case 4. Again, low seasonal variations and high diurnal fluctuations in the electricity price, like in case 3, are hampering electricity production in the Uppsala system.

The second row in Table 4.2 shows the α_{system} values for the 2030 scenario. As a consequence of the non-availability of the CHP plant the α_{system} values are small compared to the corresponding values for the reference scenario. However, as in the reference scenario, the α_{system} value for case 3 is lower than for the other three cases which is, as before, explained by the low electricity price levels during winter and summer nights.

The system in the reference scenario case is naturally more sensitive to electricity price variations than the system in the 2030 scenario case since the peat-fuelled CHP plant has been phased out by 2030, and since the electricity generation capacity in the waste incineration plant is small compared to the capacity of the CHP plant.

Table 4.2: *Electricity-to-heat output (α_{system}) values for the different electricity price cases and for the scenario stages 2010 and 2030.*

	Case 1	**Case 2**	**Case 3**	**Case 4**
α_{system} *2010 (ref)*	0.19	0.22	0.11	0.21
α_{system} *2030*	0.06	0.07	0.04	0.06

To summarise the sensitivity analyses, low electricity price levels during winter and summer nights hamper electricity generation in co-generation units. This leads to lower α_{system} values and small amounts of wasted heat while electricity is generated. Also, low seasonal electricity price variations with relatively low winter prices lead to an extended use of heat pumps for district heating production while higher price levels during winter is an incentive for electricity production and also leads to larger amounts of wasted heat by co-generation.

4.2.2 Results for Renewable Power Implementation Scenarios

This section presents the results from the study presented in paper III where the impact of large amounts of solar and wind power generation in the Swedish power system on district heating production is investigated. The results for reference scenario A and scenario B (described in Section 3.4.1) are shown in Figures 4.7 and 4.8. Figure 4.7 shows the used fuels, the district heating production, the electricity production, and electricity import and export for the scenarios. Figure 4.8 shows duration diagrams for the district heating production in scenario A and scenario case B4.

In Figure 4.7 (a) it can be seen that for increasing amounts of renewable electricity in the system, the total fuel use in district heating is reduced. The largest fuel reductions are seen for biomass and oil, because of the higher production costs for these fuels when used for heat-only production. The total district heating production shown in (b) is constant for all cases due to the unchanged heat demand, but the shares of heat production for different production plant categories changes. This because increasing amounts of renewable electricity generation in the system leads to a surplus of generated electricity, which is beneficial to use in heat pumps for district heating production at times when export capacity utilised to maximum. And this is mainly at the expense of fuel-based heat-only production. Only in the most extreme case (B4), with 30 TWh of wind power and 30 TWh of solar power, do the renewable electricity generation reduce the production in CHP plants. This is confirmed in Figure 4.7 (c) showing electricity production. Large amounts of wind and solar power generation does not significantly reduce other parts of the electricity generation mix. For case B4 a small reduction is seen in electricity generation from CHP, hydro power and backpressure (industrial CHP). The implemented renewable electricity is instead exported to the Nordic and the European markets as seen in Figure 4.7 (d).

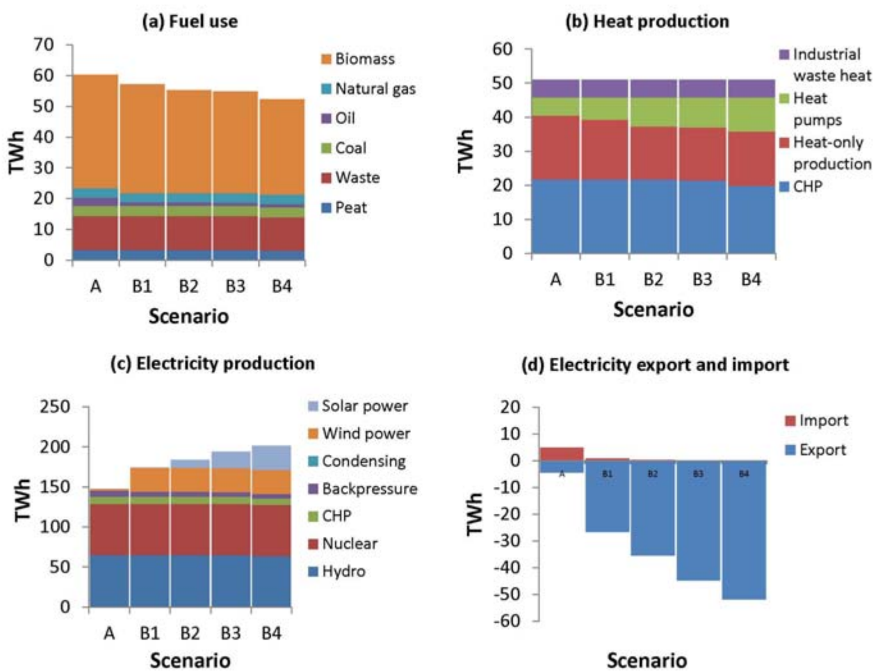

Figure 4.7: Results for (a) fuel use, (b) production of district heating, (c) electricity production, and (d) electricity import and export in the model of the Swedish power system. Scenario A is the reference scenario and B1 to B4 are the scenarios with different amounts of implemented solar and wind power generation.

In Figure 4.8 (a) and (b) duration diagrams for the district heat production over the year for the reference scenario A and case B4 is shown. The bold lines indicate national hourly heat demand levels for district heating in decreasing order. The other lines show output for different categories of heat production plants.

When a large amount of renewable power generation is implemented in the system the utilisation time of electric heat pumps for district heating production is increased. This is, as mentioned above, because vast increase in low-cost electricity generation combined with limited capacity for electricity sales to external markets yield an electricity generation surplus that can be used for heat production. This also explains the heat pumps displacement of CHP production during summer time, seen in Figure 4.8 (b).

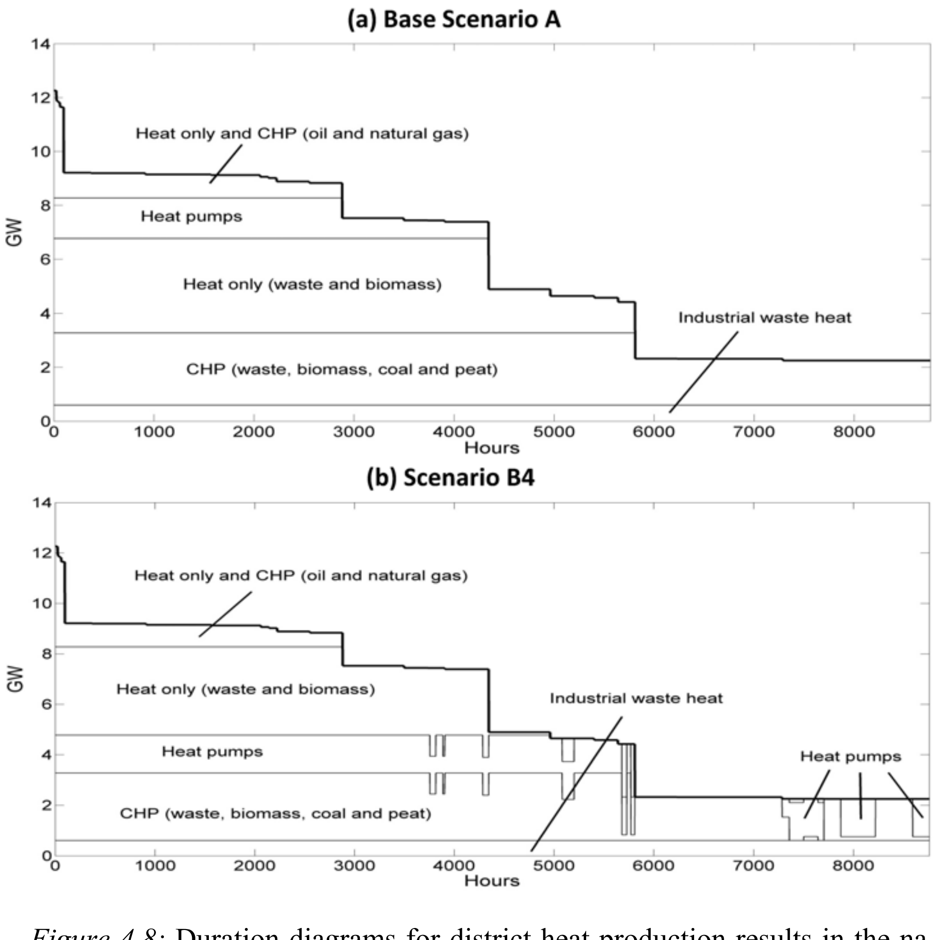

Figure 4.8: Duration diagrams for district heat production results in the national study. (a) shows the results for the base scenario A, and (b) show the results for scenario B4 with 30 TWh wind and 30 TWh solar power generation.

5. Discussion

Energy use per heated area in buildings is to be reduced by 20 % until 2020 and by half until 2050. Energy efficiency measures in existing buildings are crucial for reaching these Swedish policy goals. Therefore it is necessary for district heating systems in general to adapt heat and electricity production to an energy system with less heat demand in buildings. For this, investments in production plants and distribution networks might be needed. However, the decreasing heat demand in buildings that are already connected to district heating can to some extent be counteracted by the establishment of new residential, commercial and industrial heating demands.

The results presented here show that reduced heat demand due to energy efficiency measures in buildings connected to district heating systems does not imply increased global CO_2 emissions caused by reduced electricity sales from CHP plants. Even when using the most unfavourable assumptions regarding electricity origin with coal condensing (CC) power plants on the margin, the global CO_2 emissions from the Uppsala system was not increased. This because the CHP plant generates electricity to replace the marginal electricity generation and uses high-emitting peat fuel, thus a reduced utilisation make local CO_2 emissions decrease while global CO_2 emissions increase. If the CHP plant would use CO_2 neutral biomass instead of peat the global emissions in the CC case would have been increasing. The corresponding case for the Linköping system indicated that heat demand reductions up to 40 % yield global CO_2 emissions below current levels. In the Linköping system, the partly fossil fuelled CHP production was not affected to the same extent by heat demand reductions as it was in Uppsala, and the results showed that for heat demand reductions up to 30% the α_{system} value, that describes the electricity-to-heat output from the system (Section 3.6), was increased. This indicates that the structure of the district heating systems is crucial for the environmental impact of district heat use. Also, the use of CHP production does not alone imply a certain outcome of heat demand changes. The merit order of the heat production units within a system and the mix of used fuels are crucial for the effects of heat demand changes. This also indicates that comparison of results between different district heating systems requires structural similarities.

An important issue when working with energy system modelling and construction of scenarios is the result's strong dependence on assumptions made regarding future conditions for the system and its surroundings. Future fuel and electricity prices, heat demand and changes in properties of heat and electricity production plants are not known in advance. This requires that assumptions regarding future conditions are made with precaution while reflecting over the impact the assumptions have on the modelling results. In this thesis this issue have been dealt with by performing sensitivity analyses for electricity prices (paper II) and oil prices (paper I). Also, the studies presented here are focusing the impact of heat demand changes on operation of district heating systems as they function today. But the heat demand changes would take decades to realise and the results should be interpreted with that in mind. A developed approach would be to assume changes of heat production as well. An example of this would be to include the mixing of wood with the peat fuel used in the Uppsala system. If the share of wood in the fuel mix used in the CHP plant and the peat fuelled HWB reaches its technical maximum of 30 % this would probably have an impact on the CO_2 emissions result, since the emission factor for the fuel mix would be lower than for peat only. This would make global emissions increase with decreasing heat demand in the CC perspective, since increasing emissions from CC power would not be completely outweighed by decreasing local emissions.

In a decision-making perspective it is important to consider the long-term impact of decisions concerning buildings energy standards. Decisions concerning new buildings and refurbishments that are made today are valid for 35-40 years, i.e. until 2050. This should be considered in decision making that concern buildings. Lower future heat demands and lower heating output demands in buildings will become a challenge for the district heating companies and a situation that they will have to adapt to. For example, there is technology being developed for low tempered district heating networks and better insulated pipes [61, 62]. This to minimise heat distribution losses, which otherwise become relatively high in traditional district heating networks not designed for low-energy building heat demands. However, the investigation and analysis of such solutions have not been included in the studies presented in this thesis.

A situation where energy efficiency measures in buildings are not implemented in favour of heat and electricity production in district heating systems might result in a non-flexible and latched local energy system, with an un-necessary large energy demand for decades to come. Also, clean electricity production in district heating requires access to waste and biomass which are both finite resources. And as Europe is transforming a coal based energy system to a system with an increasing level of renewable energy sources the competition for biomass will probably increase from several sectors. Therefore should reduced energy demand generally be considered beneficial and considered to decrease the use of primary resources and the structure of district heating production should be adapted to the district heating demand rather than the other way round.

District heating as a system offers the possibility to utilise surplus heat from industrial processes and waste incineration. This heat use is however only desirable as long as domestic waste and surplus heat from industry do not gain value as resources. It is not desirable to fall into a situation where a path dependent sub-optimised energy system is the consequence of lost incentives for reducing the amount of domestic waste through re-cycling or where energy efficiency measures are not taken in industry, due to the utilisation of waste heat from processes. Therefore should industrial waste heat and incineration of domestic waste be utilised as by-products but not as primary products.

Heat demand reduction due to energy-efficiency measures in buildings, results in a more levelled demand over the year. An important issue concerning such efficiency measures is whether they lead to reduced production of electricity in CHP plants. Peak demand is commonly covered by heat-only units with relatively low investment costs, but high operating costs. A more levelled demand makes it possible to cover a larger fraction of the demand by CHP production, which yields revenues from electricity sales. A less variable heat demand with reduced peaks could also reduce the amount of peak-demand boiler start-ups and shut-downs.

To achieve a more levelled heat demand over the year, non outdoor temperature dependent applications such as industrial processes and household appliances (for example washers, dryers and dish washers) could be considered. Also, a combination of heat and electricity production with production of biofuels for vehicles could be a possible way to pro-long plant utilisation hours over the year and enable a larger CHP production.

The exact levels of future Swedish electricity prices are hard to approximate, but some seasonal differences due to the cold Swedish climate in winter and diurnal variations due to higher electricity demands during day-time are reasonable to expect. As the Nordic electricity network is increasingly integrated with the European network, the electricity price is also expected to adapt more to the higher European price level and larger diurnal variations. This issue is further complicated by the Swedish electricity market in 2011 being divided into three price regions which means that the electricity price within Sweden will be different depending on geographic location.

Increasing integration of the European electricity market means increased transmission capacities between countries. Therefore, the impact of implemented renewable intermittent electricity generation on the electricity prices could be expected to be decreased since export possibilities for electricity is expected to increase. However, export of electricity also requires a net demand in the area that electricity is exported to. The implementations of renewable electricity generation will also increase in the rest of Europe if the legally binding “20-20-20” targets are met and thus the possibilities to export surplus renewable intermittent electricity from Sweden will depend on the correlation of Swedish renewable power generation to that in continental Europe.

6. Conclusions

In the studies of the Linköping and the Uppsala district heating systems heat demand changes due to energy efficiency measures in buildings caused a more levelled annual district heating production. This because reduced demand for space heating in buildings to a large extent affect peak demand periods rather than low demand periods. The differences in heat and electricity production in the two systems meant that the results from the Linköping study and the results from the Uppsala study are complements to each other. Also, results from two different studies provide a more nuanced analysis of the effects of energy efficiency measures in district heating systems. The indications from the results are that building energy efficiency measures do have an impact on the operation of district heating systems.

In the Linköping study the results showed that heat demand reductions up to 40% lead to lower global CO_2 emissions than today´s level and also that the electricity-to-heat output ratio for the system is increased for heat demand reductions up to 30 %. These findings indicate that there is an environmental gain in levelling out the heat demand in the Linköping district heating system over the year. Also, the results show that heat demand reductions in the studied system reduce CO_2 emissions.

Less heat from heat only production to cover demand peaks were needed and a more efficient use with less share of heat only production was achieved for the CHP plants within the systems. The structure of heat production and the fuels used have crucial importance for the environmental impact from district heat use, even though substantial heat demand reductions in both systems are possible without increasing global CO_2 emissions and primary energy use.

The impact of electricity market dynamics on district heating system operation was studied on the local level in the study of the Uppsala system and on the national level in the study of the national Swedish power system. For the Uppsala system an electricity price sensitivity analysis indicated that high electricity price levels during the colder parts of the year promote heat and electricity co-production in CHP plants. Even generation of power while wasting heat is beneficial to some extent under such conditions. Low electricity price levels during winter on the other hand, hamper electricity generation in co-generation units and lead to lower total electricity-to-heat output ratios for district heating production. Also, low seasonal electricity price variations with relatively low winter prices lead to an extended use of heat pumps for producing heat.

In the study of the national Swedish energy system, incremental amounts of solar and wind power were added to the existing system. Some of the added renewable electricity generation capacity produce a surplus of low-cost electricity that is exported, however limitations in transmission capacities to neighbouring countries means that parts of the electricity surplus needs to be used domestically. The results indicate that utilisation of made investments in CHP plants are reduced, due to the competition from increased low-cost electricity generation. The electricity surplus that is not exported is instead used in heat pumps for production of district heating and, as a consequence, the use of solid biofuels for district heating is reduced.

The collective conclusion from the research presented in this thesis is that rather high levels of heat demand changes due to energy efficiency measures do not increase global CO_2 emissions from heat and electricity production in the district heating systems of Linköping and Uppsala. This indicates that it is possible to meet the Swedish and European targets for energy savings until 2020 and 2050 without significantly increase global environmental impact. Also, the operation of district heating is depending on the dynamics of the electricity market. Large amounts of renewable intermittent low-cost power generation can be expected to occasionally reduce electricity prices. Further, low electricity prices can be expected to induce use of heat pumps for district heat production and to inhibit co-generation of electricity in CHP plants. This was seen for both the local level in the Uppsala study and on the national level in the study of the Swedish power system.

7. Further Work

The results from the studies presented here have opened several doors for further research within the area. To continue the work with investigating effects on district heating system operation due to heat demand changes is a natural path to study the possibilities of performing more generally valid district heating system modelling. This can possibly be done through creating a set of typical system with different crucial characteristics so that the entire variety of district heating system conditions is represented. The studying of these typical systems would then yield results that are representing effects that can be expected in most Swedish district heating systems.

The studies within this PhD project so far have been rather technical and the ambition is to implement more interdisciplinary perspectives in forthcoming studies. An interdisciplinary collaboration with researchers from the research fields of business studies and economic history is planned. Within this collaboration the typical systems mentioned in the previous paragraph will be used to study actors, business strategies and the market situation in Swedish district heating.

Another continuation of the work presented in papers I and II is to also to further investigate the district heating companies' future challenges caused by energy efficiency improvements in buildings and their possibilities to adapt to them. For example the implementation of household appliances that use district heating. This could somewhat counteract heat demand reductions due to improved building envelopes and further contribute to a more levelled annual heat demand. These appliances are for example washers, dryers and dish washers. Time use data could be used to estimate the load of such appliances which then could be up scaled and implemented in the MODEST models of Linköping and Uppsala.

Also, the construction of an aggregated model for the European power system has been discussed. The model will be used to study the dynamics of the European power generation and to investigate the effects of changes in Swedish electricity demand and supply.

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