System Effects of Improved Energy Efficiency in Swedish District-Heated Buildings

MAGNUS ÅBERG
To alleviate global warming, European-Union member states must reduce primary energy use, emit less carbon dioxide (CO₂), and increase renewable energy use. Buildings constitute a great potential for energy savings, but saving energy in district-heated buildings influences combined heat and power (CHP) production, other electricity generation, and global CO₂ emissions.

This thesis investigates the system effects from Swedish district heating production caused by district heating demand changes due to energy conservation in buildings. The cost-optimising linear programming modelling tools MODEST and FMS, the latter developed in the context of this thesis, are used to describe present district heating production and to investigate the impact of heat-demand reductions in twelve Swedish district heating systems, four of them representing all Swedish district heating.

Energy savings in district-heated, multi-family residential buildings yield a lower, more seasonally levelled district heating demand. These demand changes mainly reduce use of fossil-fuel and biomass for heat production. CHP production is significantly reduced if it supplies intermediate or peak district heating load. The α_system value (ratio between generated CHP electricity and produced district heating) increases by demand reductions if CHP mainly supplies base district heating load. CO₂ emissions due to district heat production depend on the approach used for CO₂ assessment of electricity, and are generally reduced with heat demand reductions, unless the share of CHP production is large and the reduced fuel use yields smaller emission reductions than the emission increase from power production that replaces reduced CHP generation.

In total, heat demand reductions reduce CO₂ emissions due to Swedish district heating, and the district heating systems even constitute a carbon sink at certain energy conservation levels. If saved biomass replaces fossil fuels elsewhere, a lower heat demand reduces CO₂ emissions for every studied district heating system.

Keywords: district heating, carbon dioxide emissions, building energy efficiency, combined heat and power

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ISSN 1651-6214
ISBN 978-91-554-8996-0
urn:nbn:se:uu:diva-229477 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-229477)
“Energy rightly applied and directed will accomplish anything.”
- Nellie Bly
This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that 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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List of papers

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


Other Publications


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My contributions

- **Paper I** - all the heat demand change calculations, some model adjustments, all optimisations, and most of the writing.
- **Paper II** - most of the modelling, about half of the calculations, all optimisations, and most of the writing.
- **Paper III** - most scenario calculations, all optimisations, and most of the writing.
- **Paper IV** - most of the model development, all calculations, all optimisations, and most of the writing.
- **Paper V** - all modelling, calculations, simulations, and writing.
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Nomenclature

CC  coal condensing
CHP  combined heat and power
CO$_2$  carbon dioxide
DH  district heating
DHW  domestic hot water
FGC  flue gas condensation
FMS  Fixed Model Structure
GHG  green house gases
HWC  hot water circuit
IPCC  Intergovernmental Panel on Climate Change
IWH  industrial waste heat
LP  linear programming
MFRB  multi-family residential building
NGCC  natural gas combined cycle
SDHA  Swedish district heating association
SEA  Swedish energy agency
SH  space heating
$\alpha$ value  electricity-to-heat output ratio for a CHP unit
$\alpha_{system \ value}$  annual electricity-to-heat production ratio for a district heating system

Typical system characteristics

For the reader of the summary short descriptions are given of the main DH production characteristics in the four typical systems investigated in paper V.

**typical system I**  no CHP production is used
**typical system II**  fossil fuels are the main fuels used for CHP production
**typical system III**  waste is the main fuel used for CHP production
**typical system IV**  biomass is the main fuel used for CHP production
1. Introduction

In the cold climate in Scandinavia a significant amount of energy is needed in the building sector to achieve a comfortable indoor temperature, especially during the colder seasons of the year. Energy for space heating (SH) can be supplied to buildings in different ways. Single in-house boilers or electric heat pumps are common solutions in detached houses or buildings located in the countryside. In urban areas where population density is high, large scale distribution networks are instead commonly used to supply centrally produced hot water to domestic and commercial buildings for SH and domestic hot water (DHW). These hot water distribution systems and central facilities for hot water production are normally called district heating (DH) systems. Among the technologies used for heat supply to multi-family residential buildings (MFRBs) in Sweden, Denmark, and Finland, DH dominates. DH systems have large-scale advantages compared to single building heating systems. A variety of heat sources, which are difficult to use elsewhere, can be utilised, such as municipal waste, industrial waste heat (IWH) and forest residue. DH also provides the possibility of co-producing heat and electricity in combined heat and power (CHP) plants.

The DH systems in Sweden are affected by prevailing policies and public opinion. During the period from the late 1980s until today, the Intergovernmental Panel on Climate Change (IPCC) has, in different reports, addressed the issue of global warming caused by green house gas (GHG) emissions from human activities [1]. Most researchers world wide agree that the global mean temperature is increasing and that this will have effects on our global climate. In order to prevent global warming, or at least minimise its consequences, the member states of the European Union (EU) are obliged to follow certain directives aiming to transform the European energy system into using less primary energy, emit less carbon dioxide, and utilising more renewable energy.

The building sector has been identified by the EU to constitute the greatest single area for potential energy savings, which means that buildings have an important role to play in efforts towards a more efficent total use of energy within Europe. During recent years energy standard requirements for new buildings in Sweden have become stricter, and there are guidelines for how to improve energy efficiency in existing buildings.

In 2008 the work presented in this thesis was initiated. At the time there was a discussion in Sweden concerning the possible negative climate effects caused by increased energy efficiency in district-heated buildings. Advocates of the district-heating (DH) sector argued that a reduced heat demand in buildings would lead to less co-generation of electricity in combined heat and power
(CHP) units, which would need to be compensated for through increased electricity imports. Electricity imported from other European countries is commonly produced in fossil-fuelled condensing power plants, which are large contributors to global carbon dioxide (CO$_2$) emissions. Therefore it was argued that improved building energy efficiency would actually increase global CO$_2$ emissions, even though little research on this subject existed. At the time research on efficient energy use in buildings mainly considered different types of heat supply and energy efficiency measures in single buildings. The effects of large-scale building energy efficiency improvements in regional building stocks were investigated less and a need for such investigations was addressed by, for example, Gustavsson et. al [2].

It is reasonable to expect that improved energy efficiency in buildings means less heat demand in DH systems. It is not obvious, however, to what degree district heat demand might be reduced. It is also not obvious how heat demand reductions might influence heat and electricity production in DH systems. DH systems are different from each other and use different types of heat production. The system effects from improved building energy efficiency also differ from one system to another. Estimating indirect global effects such as CO$_2$ emissions from changed heat demands in DH systems is even more complex. CO$_2$ assessments for electricity use and generation are difficult due to the complexity of the Nordic and the European power systems. Issues related to increased energy efficiency in district heated buildings and its impact on Swedish DH production are discussed in some detail in this thesis.

1.1 Aim of the thesis

The present thesis aims to investigate the system effects from Swedish DH production caused by changes in DH demand due to more efficient energy use in buildings, connection of new energy efficient buildings, and new DH applications. The main objectives of this thesis are:

- Determine the impact of changed heat use in MFRBs on the demand for DH
- Investigate the effects of heat demand changes on fuel use, heat production and electricity generation in Swedish DH systems
- Investigate indirect system effects of heat demand changes in terms of global CO$_2$ emissions

All three objectives are approached in all of the appended papers. Cost-optimising linear programming (LP) modelling is used to describe DH production and how it is affected by changes in DH demands. The results from the optimisations are used to calculate impact on global CO$_2$ emissions. Heat demand changes due to building renovation, addition of new buildings, and
conversion of electrically heated appliances to district heated appliances are investigated. Several different DH systems are investigated.

1.2 Systems analysis

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. Churchman, one of the most influential writers on the subject, defines the system as “a number of parts that have been coordinated to achieve a set of goals” [3]. What is part of the system and what is part of the system surrounding it is not always obvious. Identification of the system boundary is sometimes trivial and sometimes complex and depends on the purpose of the study. In addition, a system can both be considered a part of another system and at the same time contain subsystems. Systems can be interconnected in different ways [4].

The systems studied in this thesis are both local specific DH systems and typical systems representing a group of DH systems in an aggregated form. For local DH systems the system boundaries are defined relatively easily. The interconnections to other systems are generally more complex. DH systems interact with national and international power systems and fuel markets. DH is also in many cases interconnected with local or regional social service systems, such as waste management and water treatment. The system boundaries for typical DH systems, as the ones studied in paper V, are harder to define due to the different locations and varying features of the grouped DH systems. However, typical DH systems are treated as if they were local systems. Therefore interpretations of results from the typical and the single system studies are similar, even though the typical system studies yield more general results due to certain general system characteristics.

The appended papers contain investigations of system effects for the DH systems as they are presently structured in terms of heat production units and distribution networks. No long-term changes are investigated in the composition of heat production units to meet proposed future heat demand changes. No economic analysis of the costs for building energy efficiency improvements is made since it is beyond the scope of this thesis.

1.3 Thesis overview

The remaining part of the summary of this thesis is disposed as follows. Chapter 2 contains a description of current energy use in Swedish MFRBs along with a historical perspective and a future outlook. In Chapter 3 the Swedish DH sector is described. Swedish DH in retrospect is considered along with future challenges for DH in Sweden and in Europe. Chapter 4 briefly describes
the modelling tools used in the appended papers. Chapter 5 presents the DH systems that have been investigated. In Chapter 6 the calculated parameters used to assess DH system effects are defined. The heat demand change calculations are described in Chapter 7. Chapter 8 contains the main results of the studies and in Sections 9 and 10 the results are discussed and the overall conclusions presented. Here are the appended papers briefly presented:

- **Paper I** investigates heat demand reduction scenarios for the DH system in Linköping using a linear programming (LP) optimisation model. A scenario is studied in which all buildings constructed between 1961 and 1980 are assumed to be renovated into passive house standard. A step-wise heat demand reduction scenario series is also investigated.

- **Paper II** uses an LP optimisation model to investigate the impact of future heat demand changes for the DH system in Uppsala. Scenario stages for every two years between 2010 and 2030 are defined where renovation of existing buildings, as well as additional energy efficient buildings, are considered. An electricity price sensitivity analysis is also performed for the Uppsala DH system.

- **Paper III** uses the same model as was used in paper II to investigate the potential increase in CHP generated electricity from large-scale implementation of DH-fed hot water circuit (HWC) domestic household appliances in MFRB apartments in Uppsala.

- **Paper IV** presents a fixed structure LP optimisation model implemented in Matlab that requires little input data for modelling DH systems. In addition, a heat demand data approximation method is presented that uses outdoor temperature data, annual heat load, and a system capacity factor to estimate hourly heat demand levels for DH systems. The paper also investigates a scenario where heat demands for SH and DHW are reduced in six Swedish DH systems.

- **Paper V** uses the optimisation model presented in paper IV to model a set of typical Swedish DH systems that represent the Swedish DH sector. The typical system models are built to describe a variety of DH production technologies. A step-wise heat demand reduction scenario is investigated, similar to that investigated in paper I.
2. Energy use in Swedish buildings

The outdoor temperature in the south and central parts of Sweden varies between about +25°C in summer and -20°C in winter. In the northern parts of Sweden temperatures as low as -40°C occur during winter. These differences in outdoor temperatures strongly influence the energy demand in buildings where heat is needed during the colder months of the year, and cooling is to some extent used during warm summer months to maintain a comfortable indoor temperature. The heating and cooling demands in buildings are crucial for the short-term operation strategies and long-term development of DH production. This chapter aims to provide an understanding of the energy use in district-heated buildings through a presentation of current statistics and through a description of the expansion of the MFRB stock, which is largely supplied by DH. This chapter will also give a brief description of different aspects of future improvements in building energy efficiency. The energy policy goals and ambitions within the EU that aim to reduce energy use in buildings are presented. Finally, obstacles and social aspects of large-scale energy efficiency measures in buildings are presented and briefly discussed.

2.1 Current statistics

The total energy use in the residential and service sector is about 40% of the total Swedish energy use. The main posts for energy use in buildings are SH and DHW, which together amount to about 60% of the energy use within the sector [5]. Table 2.1 contains key data on the energy use in the Swedish building sector in 2012. Out of the total heated building area of 624 million square metres, MFRBs constituted 28% (175 million square metres), while detached houses and commercial and service buildings constituted 47% and 25%, respectively. The average energy use for SH and DHW in MFRBs in 2012 was 144 kWh/m² which is higher than for both small detached houses and for commercial and service buildings. The share of heat demand in MFRBs supplied by DH was as much as 85% in 2012, whereas the corresponding share for small detached houses was 11% [6]. This illustrates the fact that DH is better suited for urban areas with a higher heat density, than for single-family housing areas with less heat demand per land area unit. This also shows that in urban areas Swedish buildings are district heated to a large extent.
Table 2.1. Building types, heated areas and share of district heat supply in Swedish buildings 2012 [6].

<table>
<thead>
<tr>
<th>Building category</th>
<th>Heated area [million m²]</th>
<th>Average energy use [kWh/m² year]</th>
<th>District heated area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-family residential</td>
<td>175</td>
<td>144</td>
<td>85</td>
</tr>
<tr>
<td>Detached</td>
<td>292</td>
<td>113</td>
<td>11</td>
</tr>
<tr>
<td>Commercial and service</td>
<td>157</td>
<td>135</td>
<td>72</td>
</tr>
</tbody>
</table>

2.2 Swedish multi-family residential buildings in retrospect

The Swedish history of housing is important for understanding the current energy use in MFRBs, as well as for understanding the obstacles and possibilities of improving building energy efficiency. Less than 200 years ago Sweden was still to a large extent an agricultural economy. In the mid 19th century, about 90% of the population lived in rural areas. The industrialisation of Sweden slowly increased the number of people in urban areas. In the mid 20th century about half the population lived in cities [7]. However, in the 1950s (about the same time as the first Swedish DH systems were established) the urbanisation process in Sweden accelerated. This was during a time when the western world experienced what would later become known as "the golden age", characterised by increased prosperity, mechanisation of agriculture and forestry, and economic growth. This development resulted in a housing shortage. Demand for new housing in the cities arose. The problem became critical in the 1960s even though housing production was already relatively high [7, 8]. In 1965 the Swedish parliament set the target to build one million new homes within the forthcoming ten years, a goal that afterwards came to be known as "the Million Homes Programme". Actually, as can be seen in Figure 2.1, the production of new homes in MFRBs during the period between 1965 and 1975 does not differ significantly from the previous already strong pace of new housing construction. The ending of the Million Homes Programme in 1975 marks the end of a long period of a substantial expansion of MFRB apartments in Sweden [7].

In 1975 the large housing shortage of the 1960s had turned into a housing surplus and the Million Homes Programme buildings were questioned because of their exterior monotony as well as the lack of well-functioning local services and transport in these newly built residential areas. To some extent the Million Homes Programme became a symbol for alienation and isolation [7]. The golden years and the Million Homes Programme have had a great influence on the current Swedish multi-family residential building stock. This is visualised in Figure 2.2 where the living areas in MFRBs from different construction periods is shown, along with the present average energy use per square meter. An important aspect is that 68% of Swedish multi-family residential buildings were built before 1980. It is also clear that these buildings require more energy.
2.3 Improvements in building energy efficiency

The building sector in the EU has been identified as having a large energy saving potential. One important reason is that it is possible to reduce space heating demand without substantial interference with residential activities. Heat demand can be reduced by decreasing heat losses through the building envelope or the ventilation system, or both. This is done, for instance, by additional insulation and improved air tightness in walls, floors, and roofs. Windows and doors can be replaced by more energy efficient alternatives. A central ventilation system can be installed where heat is recovered through an air-to-air heat exchanger or a heat pump that utilises the heat in the indoor tempered outgoing air. For domestic hot water use, energy-saving water taps and shower heads can be installed to reduce the demand for heat.

The use of energy for space heating and domestic hot water in the Swedish building sector has decreased during the last decades. As shown in Figure 2.3, 22% less energy was used for SH and DHW in 2012 compared to 1985. Note that these figures represent the building sector as a whole, not only MFRBs.

Figure 2.1. New multi-family residential building apartments built annually in Sweden 1940 until 2012. Data are obtained from [9]
This reduction is explained by increased energy efficiency in existing buildings, primarily through improved building envelopes and ventilation systems. Increased use of electric heat pumps, which reduces the amount of energy purchased for the building, is also a part of the explanation. The latter is mostly concentrated to small detached houses [6].

2.3.1 Policy to improve building energy efficiency

Sweden is obliged to follow directives decided upon by the European Union, and Swedish energy policy ambitions are in many cases connected to the legally binding European energy policy goals [5]. Two EU directives directly aim to reduce energy use in buildings. One is a comprehensive directive on energy efficiency (2012/27/EU) and the other is a specific directive on energy performance of buildings (2010/31/EU).

The directive on energy efficiency states that the member states of the European Union are obliged to establish a long-term strategy to mobilise investments in renovation of national building stock. This obligation is motivated by the fact that the building sector has the largest potential for energy saving in a single sector in Europe. This sector plays a crucial role in reaching the EU
goals for reducing the use of primary energy by 20% within the EU by 2020 and for reducing CO₂ emissions by 80 - 95% by 2050 [11].

A recast of the Energy performance of buildings directive was launched by the EU in 2010. The new version states that the member states shall ensure that by December 31st 2020 all new buildings will be “nearly zero energy buildings”. The recast directive also contains requirements that major renovation of existing buildings shall include energy efficiency improvements so that national or regional minimum standards for energy efficiency are reached [12].

Until recently the Swedish parliament had a goal, besides the energy efficiency goals stated by the EU, to further reduce energy use in Swedish buildings by half, compared to the level in 1995, by 2050. This goal however was removed in 2013, ”in anticipation of new goals to be set” [13]. A strategic decision on the pace of reduction in building energy use along with established standards for nearly zero energy buildings will be announced in 2015 by the Swedish government and The Swedish National Board of Housing, Building and Planning [13].
2.3.2 Building energy balance

A brief description of the energy balance of a building is here used to illustrate the potential of improving building energy efficiency by implementing existing technologies, such as efficient building envelope components and energy saving ventilation systems. A building’s energy balance is the relationship between the energy that is supplied to the building and the energy that is lost. Energy is supplied to buildings for different purposes. Space heating is needed to maintain the indoor temperature during seasons with low outdoor temperatures and space cooling might be needed during warm seasons. The energy supplied for space heating needs to match the heat losses through the building’s climate shield and through ventilation. Hot water is needed for showering, hand washing and dish washing, etc. Electricity is needed for household appliances, electronic equipment, lighting and for building operative systems (ventilation, circulation pumps, elevators etc.).

Figure 2.4. Principal mapping of the energy flows constituting the energy balance of a building
Figure 2.4 shows the energy supply and losses that influence a building’s energy balance. The heat losses through the building envelope consist of heat transmission losses through walls, roof, floor, windows and doors, and infiltration losses through air leakage. Heat is also lost through the ventilation system. The heat in the out-going ventilation air can be recovered and to some extent re-supplied to the building through a ventilation heat recovery system. Heat is also supplied to the building as passive solar heat gains through windows and internal heat gains generated from appliances and human presence.

2.3.3 Obstacles and possibilities for improving building energy efficiency

Figure 2.2 shows that a large share of existing Swedish MFRBs were built before 1975. Within this category of buildings heat losses through the building envelope and ventilation constitute the largest part of the energy demand. About 20% of the energy demand in these buildings can be avoided by relatively small efforts, such as optimising heating and ventilation systems. To reduce the energy use further, building envelope improvements are necessary (e.g., new windows and additional insulation). However, the conditions for energy efficiency improvements vary between different housing owners and in different parts of Sweden. Large housing companies have generally better resources than small family-owned housing companies. Housing associations have better conditions for energy saving than tenancy compounds. Local district heating prices might also have an impact on the incentive to take energy efficiency measures in buildings [13].

As already mentioned, most buildings built before the end of the Million Homes Programme are in need of substantial renovation within the decades to come. This makes it possible to improve energy efficiency in these buildings at the same time at a relatively low additional cost. However, the tenants living in these buildings today are to a large extent people with a relatively low payment ability, and it can be discussed if these tenants are capable of bearing the costs of such a renovation. Increased rents and individual payments for heat and electricity might lead to situations with people living in energy poverty, previously uncommon in Sweden [14]. So, even if the potential for energy savings in the Swedish building stock is high from a technical perspective, there are still obstacles to overcome from a social perspective.

2.3.4 Energy efficiency in new buildings

The concepts of Low-energy buildings, passive houses and zero-energy buildings all describe buildings that use small amounts of energy for SH, DHW, and building operation electricity. The low energy building concept is not precise and has changed over time. In this thesis low-energy building is used as
a generic name for buildings that use considerably less energy for SH and to some extent also for DHW than the present standard. More strict requirements for different low energy building types are defined by the Swedish center for zero-energy buildings [15].

The present requirement for specific energy use in newly built residential buildings in Sweden is between 90 and 130 kWh/m$^2$ year, depending on the geographical location of the building. Specific energy use includes energy purchased for SH and cooling, DHW and electricity for building operation. However, special requirements are defined if the space heating demand of a building is supplied by electricity; then the corresponding values are 55 – 95 kWh/m$^2$ year. However, with instructions from the government, the Swedish National Board of Housing, Building and Planning has recently published a change in the requirements for new buildings which will apply from January 1$^{st}$ 2015. The change means that different specific requirements are set for detached houses and MFRBs. The specific energy use for these building types is not to exceed 80 - 130 kWh/m$^2$ and 70 - 115 kWh/m$^2$, respectively [16].

But, 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 long time still be in the already existing buildings. According to data published by Statistics Sweden the number of apartments in the residential building stock have been increasing by 0.5% per year between 2001 and 2010 [9]. If this increase continues, the apartments built from today until 2030 will constitute about 9% of the total Swedish building stock in 2030. Thus, even if all new residential apartments are connected to district heating networks, new buildings will not have a major impact on the total district heating demands. Therefore new buildings will only be marginally discussed in this thesis.
3. District heating in Sweden

This chapter briefly describes the fundamentals of DH and presents current figures for the DH sector. Swedish DH development is briefly described and some future expectations regarding DH are presented. Finally, previous research on the interaction between energy efficiency in buildings and DH production is presented.

During the last 60 years Swedish MFRBs have gone from being entirely heated by tiled stoves and in-house heating boilers to being mainly district heated. Today, there are between four and five hundred DH systems in Sweden that supply about half of the total Swedish demand for space heating and hot water. In MFRBs alone, DH is used to supply 85% of the heat demand [6]. About 50 TWh of DH is delivered annually in Sweden and the DH sector is thus an important part of the Swedish energy system [17].

An important aspect of Swedish DH for the analyses in this thesis, is that DH systems are different from each other; different in size, different in fuel use, and different in the types of heat production techniques that are used. Some of these differences can be explained by the geographical locations of the systems. For instance, the utilisation of industrial waste heat (IWH) is dependent on the availability of local industries with a surplus of heat. Another example is the system size that is limited by the local number of inhabitants and on how close together the residents live. Other differences between DH systems are more difficult to relate to local conditions. One example is differences in types of fuel used in heat production plants. The fuel use is more or less independent of the geographical site of the plant, because transport by railway, road and water is relatively cheap. Another example is the possibility of combining heat and power generation in CHP units, which is possible to do in many systems, even though this to some extent depends on the system size.

So, why do Swedish DH systems differ in non-geographically dependent aspects, such as fuel use and CHP production? The historical perspective is important for the understanding of the differences between DH systems. One probable explanation is that Swedish DH systems have been established at different times during the last 60 years. During this period the conditions for DH production have changed; and so have availability of fuels and electricity, policies for energy utilisation, and legislation concerning energy supply to buildings. These changes, together with investments in DH system plants (new plants or conversion of old plants), are generally associated with large investment costs with long pay-back times. This means that once a large investment is made, further investments are probably far in the future. Long-term changes
in the prevailing conditions for heat production (policies, and global finances) are therefore faster than DH systems are able to adapt to. Thus, DH systems are in many cases characterised by the time the systems were established, or when large investments were made.

3.1 Principles of District Heating

The heat production plants of DH systems are of great importance to the work presented in this thesis. A DH system in this thesis contains the production plants, the distribution network and the users. Werner describes DH as hot water produced in large plants and distributed through underground pipe networks to many different heat users [18]. In the Swedish law [19] a DH system, or DH business, is described somewhat differently as

"distribution of hot water, or other heat carrying medium, in pipes to an undefined group of allowed users within a certain geographical area."

(SFS 2008:263)

Thus, according to the law text, there is no DH unless there is a pipe network and possibilities for geographically close buildings to connect to the network, or for already connected buildings disconnecting from the network. The Swedish law clearly distinguishes the heat production plants from the distribution network. The law does not focus on heat producing units. Instead the distribution networks and the consumers are described as the crucial characteristics of DH systems.

Figure 3.1 shows a DH system. A DH system normally consists of a central heat production facility, or other available heat source, connected to a number of users through an underground heat distribution network of pipes.

The demand for DH cdepends mainly on demand for SH in buildings, which varies between seasons. These seasonal variations need to be considered by DH producers. Dimensioning one single plant to supply the entire heat demand throughout the year means that the maximum capacity of the plant will be only marginally utilised and that the plant is over-dimensioned most of the year. This also means that investment costs will be unnecessarily high and that the use of plant capacity is inefficient. Instead, different production plants are normally used to handle the varying demand levels of the year and to minimise production costs. Figure 3.2 is a duration diagram showing how different heat production plants can be combined to supply a typical DH demand. The curve is the DH demand during a year plotted hourly in decreasing order from left to right.

Base production plants (the bottom of Figure 3.2) are dimensioned to be operated more or less continuously over the year, often more than 8000 hours per year. Base production plants are, for example, high investment CHP plants
fired with low-cost fuels, such as municipal waste or forest waste, which are difficult to incinerate. If industrial waste heat is utilised it is also often used for base heat demand. When the heat demand exceeds the capacity of the base production plants, the intermediate production plants are used. The intermediate plants are generally more expensive to operate compared to base production plants. Intermediate plants may be old base production plants that are operated fewer hours per year when new base load plants with higher operational priority have been built. For the coldest parts of the year, and for back-up capacity, most DH systems have peak demand production plants. The peak demand plants are generally low investment cost units that require little maintenance but are the most expensive to operate. In Swedish DH systems peak demand plants are often simple, heat only, oil-fired boilers due to the fact that it is convenient to store oil and it does not require much storage volume and maintenance.

The commonly addressed advantages of DH compared to alternative heat supply technologies are large-scale efficiency in energy conversion and flue gas cleaning, heat source flexibility, and the possibility of utilising energy sources that are otherwise often wasted, such as waste from forestry, household waste, cooling heat from thermal electricity generation, and surplus heat from industrial processes. Another often mentioned advantage of DH is the reliability combined with operational convenience for the users (no in-house boiler to maintain) [20].

DH systems are concentrated to urban areas, the reason being that distribution losses are the main limiting factor for DH system expansion. DH systems require a certain level of heat density (heat demand per length unit of dis-
distribution pipe) to make heat delivery profitable. Therefore DH systems are suited for urban areas and the size of a DH system usually relates to the size of the urban region. But even though the local heat market is limited, DH systems are not isolated. The possibility of using varying heat sources means that DH systems are suitable for combining heat production with both community beneficial activities (such as waste incineration) and business activities (thermal power generation and biofuel production). Waste incineration, large-scale heat pumps, and CHP units are well established heat production techniques currently used in Sweden. The use of these techniques interlinks DH systems with the power system (through CHP plants and the use of electric heat pumps), various fuel markets, local industries (through utilisation of IWH and supply of heat for industrial processes), and local utilisation of heat from waste incineration and water treatment plants. The interlinkages between DH systems, the power systems and the biomass fuel market are considered in the present thesis when analysing the indirect effects on global CO₂ emissions caused by changes in DH production.

*Figure 3.2.* A duration diagram showing three principle plant types in cost optimisation of DH production.
3.2 Current figures for the Swedish district heating sector

The 140 member companies of the Swedish DH association (SDHA) make 98% of the annual deliveries of DH. The statistics obtained from the association’s website are used here to represent the DH sector and contain figures for heat production, fuel use, CHP electricity generation etc. for all 457 DH systems owned by the members [21]. The total delivery of DH in Sweden in 2012 was 50 TWh. About 45% of the heat was produced in CHP plants that in total co-generated about 7.5 TWh of electricity. Figure 3.3 shows the fuel mix in the DH sector as a whole in 2012.

Figure 3.3. Fuels used in the Swedish DH sector in 2012. Data obtained from [21]

Biomass, waste and wood waste constituted 61% of the total supply of heat sources to the DH sector in 2012. The biomass category includes both unprocessed biomass (wood, forest waste, etc.), processed biomass (pellets, briquettes, etc.), and different types of bio oil. The fossil fuels (oil, coal, natural gas and peat) constitute in total about 13%. Heat pumps constitute 6% of the supplied energy carriers; the heat can be low-tempered heat from water treatment plants or surplus heat from industrial processes. The 7% electricity is used for heat pumps, electric boilers and system operation (plant startup, distribution water pumps etc.). The FGC category represents heat utilised in flue gas condensation while incinerating difficult fuels that contain water (waste and unprocessed biomass). Finally, the utilisation of IWH constitutes 5% of
the total heat source supply. The large share of waste and biomass based fuels in DH systems is a result of the major policy efforts that have been made since the early 1980s to phase out oil dependency in the energy sector. In 1981 oil constituted 84% of the heat source supply to DH systems [18].

![Diagram of heat user categories in the DH sector. After [22]](image)

Figure 3.4. Heat user categories in the DH sector. After [22]

Figure 3.4 shows the shares of heat deliveries supplied to each user category (multi-family residential buildings, single-family detached houses, commercial buildings, industry and other). As mentioned in chapter 2, buildings in urban areas are the major users of DH. MFRBs alone consume 50% of heat deliveries whereas single-family houses use only 9%, mainly due to the significantly lower heat densities associated with residential areas with detached houses. Commercial and service buildings use 28% of the heat and industrial customers about 10%. DH is suitable for industrial processes that require low-tempered heat, such as drying processes. The ”other” category consists of, for example, heat used in winter for melting snow on soccer fields and city streets, green houses, and biogas reactors [20]. The fact that different types of buildings together constitute 87% of DH deliveries is important to the work presented here.
3.3 The Swedish district heating sector in retrospect

To enhance understanding of the differences between Swedish DH systems, this section gives a brief description of the development of the DH sector. Previous historical descriptions have been made by Werner [18] and Summerton [23]. Their descriptions cover the development until 1990. Here some light is shed also on the post-1990 development.

The DH technique was first developed in the United States in the late 19th century. Initially, steam was used instead of water as a heat carrier, which is still the case, for example, in the New York DH system that was built in the early 1880s. Inspired by the Americans, the first DH systems were built in central Europe in the early 1900s. In Sweden, examples of central heating systems exist from the 1920s in which hot water boilers supplied heat to a single or a few apartment buildings. In Gothenburg a central heat producing facility supplied hot water for an entire hospital area with 45 buildings in the 1930s [18].

In 1936, copper mining was initiated at a geographically isolated site in northern Sweden and a small community was established. The community became nationally known for its modernity. The 61 residential apartments were equipped with electric refrigerators, electric stoves, and running hot and cold water. The hot water was produced in the cellar of a central office building by four wood fired steam boilers, and distributed in underground pipes to the community’s residential buildings. In 1946 the copper mining closed down. The entire community was dismantled and today nothing remains apart from the building foundations and the water-filled mine.

Even though ideas for more extensive DH systems had been discussed in Stockholm, Norrköping, Malmö and Gothenburg during the first half of the 20th century, these had not yet been realised in the late 1940s [18]. In 1948, heat was delivered for the first time in a Swedish DH system that is still functioning. This was in the city of Karlstad, a mid sized town in the mid-west of Sweden. In 1948-1949 DH in Karlstad was only delivered to one local industrial facility, but in 1949 seven residential buildings with 120 apartments were connected. This became the starting point for the development of the Swedish DH sector. During the period of 1951 until 1956, eight more cities established DH systems, all owned and operated by the local municipalities. After the initial systems were built in the late 1940s and in the 1950s, DH systems were established continuously in urban areas up to the present day. Figure 3.5 shows the years of establishment for 380 of the DH systems. These data were assembled during the fall of 2013 from the owners of the systems, mainly through contact by telephone. The 380 systems constitute 96% of the total deliveries of DH in the sector, which means that the about 100 DH systems not included in the data are generally small systems. The bars in the figure are absolute values while the curve is a moving average for five years, included to compensate for some uncertainties regarding the exact years for DH establishment.
In 30 cases only approximate data were available, and in these cases specific year of establishment assumptions were made. For instance, if the information of establishment was given as "mid 1980s", this was registered as "1985" which partly explains the high peak in that particular year. Note that these data do not mirror the total development of the sector because investments in the expansion of existing systems are not shown.

Figure 3.5. Number of new established DH systems in Sweden per year 1948-2014. The curve shows a 5-year moving average of the data.

The overall pattern of DH establishments presented in Figure 3.5 shows that during the initial phase between 1948 until 1975 few systems were built. 1975 until the late 1980s is a period with large numbers of new DH establishments each year. Between 1990 and 1996 few new establishments were made. Finally, a second period with many new DH system establishments per year is seen after 1996.

The initial phase 1948 to 1975 is a period in the Swedish economy that is characterised, at least initially, by little governmental intervention in infrastructural development, both regionally and locally. The demand for electricity was expected to increase and yield a future power deficit as the potential hydro power capacity would not be sufficient. DH with CHP plants was considered an efficient way to increase the power generation capacity. DH systems were initially established in larger cities. Most DH networks in this period were either built with CHP units from the start, or were designed for preparation for future CHP production [18,24]. During this first period there was also the idea of using nuclear CHP units in DH systems. Ågestaverket in Stockholm
was one such plant that produced nuclear power and heat between 1963 and 1974 [18]. According to Werner, further plans for similar plants were discontinued when government investigations disagreed with the location of such plants close to urban areas [18].

The increasing power generation capacity in Swedish DH systems meant that CHP production became a competitor to the government-owned power producer Vattenfall. Vattenfall responded to this competition and tried to hamper the development of CHP and DH production in order to secure the company’s access to both the electricity market and the heat market when the planned nuclear power plants were built [18, 25].

In the late 1970s the number of new DH establishments increased rapidly and continued to be high until the late 1980s, despite the fact that co-generation of heat and power was no longer attractive. During the 1970s the world had experienced two oil crises which had resulted in significantly increased oil prices. This, combined with Sweden’s low electricity prices, resulted in few incentives to build new, or even to operate already existing oil-fired CHP units [18]. So, the initial main incentive for DH establishment, CHP production, was gone, but the number of new DH systems each year was higher than ever before. This is explained by extensive oil dependency in the building sector and the fact that the expansion of DH using alternative fuels (coal, electricity, waste, and biomass) was an efficient way to phase out oil dependency in municipalities [18]. In 1977, energy planning in Swedish municipalities was legislated. DH establishment became a component of the energy plans in many of them.

The great expansion of the DH sector in the 1980s had come with the appearance of attempts to regulate choices of building heat supply systems within DH systems [23]. By the end of the 1980s a large share of the oil dependency in the Swedish building sector had been effectively phased out and oil prices had decreased. In 1990 a carbon dioxide tax was applied to fossil fuel use. However, the tax did not include fossil fuel use in condensing power generation, only fossil fuel use in heat production. This put DH in an unfavourable position compared to the power sector because condensing power generation using fossil fuels was not subject to the carbon dioxide tax, while the share of fossil fuel allocated to heat in CHP production was. These three things together, the reduced oil dependence, low oil prices, and the introduction of the non-favourable carbon dioxide tax, can help to explain the period of few new DH establishments between 1990 and 1996.

In 1996, pricing in the Swedish DH sector was de-regulated, as part of power market deregulation. This increased incentives for private actors to enter the sector. Furthermore, the protracted debate on the future of Swedish nuclear power became topical again. The oldest nuclear reactor Barsebäck I was taken out of service in 1999. Uncertainty about the future for the other reactors meant that interest in CHP technology, and thereby also DH, increased once again. The incentives for CHP and DH investments increased even more
in 2003 when green certificates were introduced and applied to biomass-based CHP generation of electricity. These three factors, pricing de-regulation, uncertainties concerning the future for Swedish nuclear power, and green certificates, probably contributed to the increase in new DH systems after 1996.

3.4 Expectations for the future of Swedish district heating

Improving energy efficiency in buildings is an ongoing process, as was discussed in Chapter 2. The EU is also striving to increase the use of renewable energy in the European energy system, to reduce primary energy use and emissions of CO$_2$. These changes will significantly alter conditions for European DH production and distribution. Lower heat demands increase the relative distribution losses, and varying electricity prices due to intermittent renewable power generation affect the profitability of CHP production.

Lund et al. [26] defines and discusses the concept of "4th generation of district heating", which refers to new DH systems that are adapted to future energy systems with energy efficient buildings and significant amounts of implemented renewable energy sources. For example, the 4th generation of DH systems need to be operated with a lower supply and return pipe temperatures, to reduce heat losses and to use flexible CHP production plants that can be used to maintain balance in the power grid. The 4th generation of DH systems also need to be similar to smart electricity grids in the sense that heat loads can be shifted and that weather forecasts can be used to optimise heat use and heat production.

The EU directive on energy efficiency (2012/27/EU) states that the member states of the EU are obliged to present national potential for the implementation of highly efficient CHP production, DH, and district cooling no later than December 31st 2015. Member states shall also develop strategies that encourage local and regional consideration of CHP potential. When new thermal power plants are planned, or when existing power plants are to be rebuilt, analyses of the cost and benefit of building CHP plants are to be made. In addition, cost and benefit analyses are to be made for the use of IWH when new district heating networks are planned, heat production plants are rebuilt, or when industrial boilers are built, or rebuilt. [11] Thus, there is an intention in Europe to promote the use of DH, IWH, and CHP production. Heat demand for buildings within the EU is now covered by DH by merely 13% [27]. This can be compared to about 50% heat market shares in Denmark, Sweden and Finland. Connolly et al [27] judges that by increasing the use of DH, in combination with energy saving measures in European buildings, EU goals to reduce emissions of greenhouse gases by 80% by 2050, compared to levels in 1990, will be reached at a 15% lower cost than was previously estimated.
In 2009, Göransson et al. [28] presented a prognosis on the future level of the demand for DH in Sweden. A base case was defined using levels of improved building energy efficiency calculated for a suggested package of energy subsidy measures in the Swedish government energy efficiency investigation from 2008 [29]. Göransson et al. concluded that the demand for DH in 2025 should decrease by 10% compared to 2007. This corresponded to an annual heat demand reduction of 1.6% in MFRBs and commercial buildings, and 0.5% in small detached houses. In the long-term prognosis published by the SEA, the total use of DH is expected to increase slightly between 2007 and 2030. The SEA expects, similar to Göransson et al., that the DH demand in residential and service buildings will decrease, but the use of DH in industrial processes will increase [30]. It appears that the two future scenarios agree on a decrease in building heat demand, but disagree on the total future DH demand level. Nonetheless, a significantly decreased heat demand in buildings will reduce the outdoor temperature dependence of the DH demand and change its annual profile.

Even though the potential to increase the use of DH in Europe is estimated to be large, there are barriers to overcome in order to realise this potential. Henning and Mårdsjö investigated barriers for DH development in five different European countries (United Kingdom, France, Czech Republic, Ireland, and Romania). Significant barriers for DH development were identified in all five countries. The barriers vary between different countries. Financing is identified as an important barrier, due to the large investments associated with DH establishment in combination with long payback times. Other examples of barriers identified by Henning and Mårdsjö are regulations that hamper CHP production, competition from natural gas networks, a built environment not suited for DH (i.e., few MFRBs and no central heating), and corruption [31].

3.5 Building energy efficiency in district heating systems - previous research

Previous research that has investigated the effects of combining improved building energy efficiency and DH has often focused on the problem of connecting new energy-efficient buildings to an existing DH system. Some of these studies find that DH and planned new low-energy buildings are incompatible because the low SH demand in the buildings results in an unreasonably high cost per kWh of delivered heat for DH. Not only does the fixed fee for heating subscription and installation become a relatively larger share of the heating costs in buildings with low heat demands, but also in some cases the subscription fee is set higher for customers with significantly low heat demands [32, 33]. There are, however, examples of newly built passive houses that are connected to DH. 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 reached for DH subscription fees and variable costs to suit the lower heat demands in the passive houses [34].

This thesis focuses on heat demand changes in buildings that are already connected to DH networks. Such a situation was analysed in a study by Difs et al [35], where a model of the Linköping DH system was used, based on the same model used 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\textsubscript{2} emissions from DH production. The results show that heat demand reductions in the Linköping DH system reduce global CO\textsubscript{2} emissions [35].

Gustafsson et al [2] concludes that energy efficiency measures that reduce peak demand also reduce primary energy use to a large extent, because 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 already connected to a DH system, the risk of an economic conflict is lower than for buildings that need to be connected. A different issue addressed by Späth concerns the risk that DH forces an energy system into a path dependency and latches the development of the system in a large and inflexible grid-based infrastructure [33]. This would be due to the fact that DH systems are natural monopolies in which the power of the heat consumers is limited, which might inhibit energy saving measures in buildings and limit future improvements in the energy system. Thus, for example, according to Späth, if energy efficiency measures in buildings are considered incompatible with DH and therefore left out, the system might be sub-optimised regarding energy efficiency.

Investigations of the system effects on 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. For example, Brunklaus concluded that passive houses heated with electricity and conventional houses heated with DH contribute to global warming to the same extent due to the electricity used for SH in passive houses. However, Brunklaus also concluded that when the passive houses are connected to a DH system they become distinctly “better” than conventional houses [36].

Joelsson concluded that energy efficiency measures on the building envelope have less impact on CO\textsubscript{2} emissions and primary energy use than replacing the 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, regardless of the energy standard of the building envelope [37].
3.6 Identified gaps in research

The discussion above points to a need to investigate further the effects of building energy efficiency measures in existing buildings connected to DH systems. In particular, research on large-scale implementation of building energy efficiency measures and their impact on DH production is lacking (cf. Gustafsson et al. [2]). This matter is investigated in the appended papers of this thesis.

Another research gap that has been identified is the need to investigate how the influence of heat demand reductions on DH production differs among DH systems. This is the main investigation in the appended papers IV and V, but is also investigated in the present thesis as a comparison of the results from all the appended papers.

Calculation of global CO$_2$ emission system effects from Swedish DH production is also an identified area needing further investigation. Calculation of CO$_2$ emissions requires assumptions regarding what electricity generation is affected by changes in CHP production, which is crucial to the results. Therefore the effects of different assumptions regarding indirect system effects on global CO$_2$ emissions are investigated in the appended papers I, II, III and V. The analysis is also extended in this thesis to include credited emissions from biomass savings.
4. Energy system optimisation modelling

Energy system modelling and computational optimisation are central methodologies in the studies presented in the appended papers of this thesis. Two different energy system modelling tools that both use linear programming for optimisation were applied for the analysed DH systems. This chapter presents briefly the central concepts of the linear programming computational method, the energy system optimisation software MODEST (paper I, II and III), and the MATLAB based optimisation software FMS, which was developed in the context of this thesis and is described in detail in appended papers IV and V.

4.1 Linear programming

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, for example, in business and economics to maximise profits or minimise costs. A linear program is a problem with a function to be minimised or maximised, i.e. the objective function. The linearity of the objective function and that it is restricted by linear relations mean that the maximum, or minimum, value of the objective function is not found within its interior domain, but at some boundary point of the domain. The general description of the objective function is

\[ f(x_1, \ldots, x_n) = c_1 \cdot x_1 + \cdots + c_n \cdot x_n \]  

(4.1)

The linear program is further defined by a set of constraints [38] described as

\[
\begin{align*}
  a_{11} \cdot x_1 + \cdots + a_{1n} \cdot x_n & \leq b_1 \\
  \vdots \\
  a_{m1} \cdot x_1 + \cdots + a_{mn} \cdot x_n & \leq b_m \\
  x_k & \geq 0, \quad \forall \ k
\end{align*}
\]

(4.2)

For linear programming problems that concern district heating production, the objective function is normally the cost for a district heating company to produce the amount of heat necessary to deliver the given heat demand. The
variables, \(x_1, \cdots, x_n\) in Equation 4.1, are in this case energy flows, which connect different energy system components (e.g. boilers, turbines, networks, demands, etc.) and component output. Each energy flow and output can be constrained (see Equation 4.2) and related to other variables through, for example, energy balance, energy limitation, production unit capacity, flow ratio and efficiency. The constraints are defined by the factors \(a_{11} \cdots a_{mn}\) and \(b_1 \cdots b_m\). Each variable can also be associated with a cost (fuel costs, electricity prices, taxes, subsidies, etc.) defined as \(c_1, \cdots, c_n\) in Equation 4.1.

4.2 MODEST

MODEST is an energy system modelling tool that uses linear programming. MODEST is an acronym for "Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions". MODEST uses linear programming to find the cost optimal design and operation of a modelled energy system and can be used for local, regional and national energy systems. The model is similar to models such as MARKAL [39] and EFOM [40], but offers greater flexibility concerning time division and adaptability to different types of system.

The time division in MODEST is discrete and can be used to describe variations in, for example, energy demands and energy prices. A year is divided into seasons (or months) that can be further divided into diurnal periods (e.g., days, nights and specific hours). The time division offers the possibility of including peak demands at a higher resolution than those needed for off-peak periods. The MODEST time division is somewhat limited since the maximum number of consecutive time-steps (seasons) is 99, each of which can be divided into 99 diurnal periods. Therefore MODEST does not offer the possibility of optimising a full year with consecutive hours or days. The number of components and energy flows in MODEST is flexible and can be adapted to different system structures and different levels of system description detail. Models with 170 components were used [41]. Model results include all energy flows for each time period (i.e. operation of all plants), the total cost and emissions.

MODEST was also used for many applications, for example investigating the effects of industrial energy efficiency measures [42, 43] and the possibilities of a regional district heating market [44]. Difs et al [35] used MODEST to study the impact of a 10 GWh annual decrease in heat demand due to improved attic insulation in buildings. MODEST is described in detail in [45, 46].
4.3 FMS

The FMS (Fixed Model Structure) optimisation tool is a simple optimisation tool built up in the same way as MODEST, but requiring relatively small amounts of input data. The FMS is implemented in the conventional calculation softwares Matlab and Microsoft Excel, which makes the FMS more available for use than MODEST which is developed for Windows and not for Macintosh. MODEST also requires the purchase of a separate optimisation engine (Cplex) license. This means that the MODEST software is limited to the personal choice of computer and the possibility of financing an optimisation engine license. This section describes the characteristics of the FMS tool, which was developed in this PhD project.

The FMS is similar to MODEST in the sense that it uses linear programming to cost-optimise heat production in DH systems while satisfying a given heat demand. However, optimisation is performed separately for each time step in the FMS and not, as in MODEST, for all time steps at once. This means that the number of time-steps and the time-step lengths in the FMS is principally unlimited. On the other hand, it also means that for each time-step and optimisation, the FMS only considers the currently prevailing circumstances (heat demand, electricity prices, fuel costs and available heat production unit capacities).

*Figure 4.1.* Energy system components (boxes) and the interconnecting energy flows (lines) in the FMS tool.
The FMS tool is, unlike MODEST, based on a fixed model structure (hence the name), with a fixed maximum number of system components and energy flows. All nodes and flows are not necessarily used when DH systems are modelled. Figure 4.1 shows an overview of the 17 nodes (components) and 22 energy flows that constitute the FMS. The model is prepared to include (from left to right) three different fuels or fuel categories, six different "fuel-to-electricity and/or heat" conversion units, DH and electricity networks, electric heat pump or boiler, industrial waste heat (IWH) utilisation, demand for district heat, a heat re-cooler for wasting heat and market nodes for purchases and sales of electricity.

The input data necessary to describe a DH system in the FMS are maximum outputs for energy conversion units, conversion efficiencies, electricity-to-heat output ratios ($\alpha$-values) for CHP conversion units, heat demand, fuel costs and electricity prices. The FMS tool also contains a method for approximating heat demands using local outdoor temperature data. The FMS tool is described in detail in paper IV along with an investigation of how DH production is influenced by building heat demand reductions in six Swedish DH systems. The FMS is also used in paper V to model four typical DH systems.
5. Studied district heating systems

The present thesis contains individual investigations of 8 different Swedish DH systems and an investigation of the entire Swedish DH sector using a set of four typical DH systems.

The DH systems in Uppsala and Linköping (papers I, II and III) which are two similarly sized systems that use waste incineration plants for base load production were studied in detail using the MODEST tool. The intermediate and peak load production units are different in the two systems, which makes it interesting to compare them. The DH systems in Karlstad, Enköping, Borlänge, Malmö, Norrköping, and Umeå (paper IV) were studied using the FMS tool and were chosen to represent differences in geographical location, fuel mix, and use of heat production units. The typical DH systems in paper V are used to investigate the entire Swedish DH sector but with crucial heat production unit characteristics considered. This is to avoid unrealistic competition between different types of DH production units.

Figure 5.2 shows the geographic locations of the DH systems modelled and studied in this thesis. The typical systems are not marked on the map since they represent geographically spread groups of DH systems. This chapter contains descriptions of these DH systems, as well as the models used to represent them.

5.1 Linköping

The City of Linköping is Sweden’s fifth largest city and is located 200 km southwest of Stockholm. The first sections of Linköpings DH system were built in 1954 and it is one of Sweden’s oldest systems. DH in Linköping has been managed by the municipality since the start. About 1600 GWh of heat is produced annually in the Linköping system. Important characteristics for the Linköping DH system are that between 80 and 90% of the heat is produced through CHP production, and that the heat production in the system to a large extent consists of waste incineration CHP production. The fuel mix in Linköping is mainly waste and processed biomass (wood chips). The older CHP plant that is located in the city center also uses a coal-rubber-wood mix, and oil is used in heat-only boilers for peak demand hours and back up production. The total share of fossil fuels in the fuel mix was about 15% in 2008 [17]. The system also contains an electric heat-only boiler for back up production.
The Linköping DH system was analysed using and modifying an existing MODEST model of the system. The original model is described in detail in [46]. Figure 5.1 shows an aggregated scheme of the model, with fuels represented in the left node column, the heat and electricity conversion units in the gray-shaded mid column, and finally the nodes for DH network, electricity market, DH demand and the re-cooler shown to the left in the figure. The direct condenser in the central CHP plant provides the possibility of the plant producing heat only.

Figure 5.1. The Linköping MODEST model presented in aggregated form.
Figure 5.2. The geographical locations of the DH systems for which system effects caused by building energy efficiency were investigated.
5.2 Uppsala

The city of Uppsala is located about 70 km north of Stockholm and is Sweden’s fourth largest city with 200,000 inhabitants. DH was first established in Uppsala in 1961 and, similar to the system in Linköping, is among the older systems in Sweden. Initially the DH system in Uppsala used mainly oil and used the heat generated from waste incineration. In 1973 the first CHP plant was built [47] and today about 60-70% of the heat in the system is produced in CHP plants. About 1600 GWh of heat is produced annually in the Uppsala DH system.

The fuel mix in the Uppsala system consists mainly of waste and peat, which are used for CHP production and for heat-only production. Electricity is used in a heat pump facility that utilises the waste heat from the city water-treatment plant. Oil boilers and electrical boilers are used for peak load periods and back up production [48].

![Diagram of the Uppsala MODEST model](image)

*Figure 5.3. The Uppsala MODEST model presented in aggregated form.*
A MODEST model for the Uppsala DH system was built and is described in detail in paper II. The aggregated model structure is shown in Figure 5.3, with fuel nodes to the left, conversion units and network nodes in the two mid columns, and finally the demand, re-cooler (for wasted heat), and electricity market nodes to the far right. Waste incineration is used for heat production, CHP electricity generation and for district cooling production, in absorption heat pumps. The compressor heat pumps in the bottom of the production unit node column are also used to produce both heating and cooling, simultaneously.

5.3 Karlstad, Enköping, Borlänge, Malmö, Norrköping, and Umeå

In paper IV six different Swedish DH systems were modelled using the FMS model described in Chapter 4. The modelled systems are located in the six Swedish cities: Karlstad, Enköping, Borlänge, Malmö, Norrköping and Umeå. The mixes of fuels and types of production units are shown in Figure 5.4. The figure shows reference case results from the optimisations.

![Figure 5.4. Heat production mixes in the DH systems investigated in paper IV.](image-url)
The six systems are different in fuel use, production technologies, size and in geographic location (Figure 5.2), but there are also similarities between them. Biomass for example, is used in all systems, in different ways. In Enköping 100% of the fuel mix consists of biomass [49], while the share of biomass used in the Malmö system is small. CHP units are also used in all systems, but to different extents. The heat output capacity of the CHP plants in Norrköping covers the heat demand even at peak hours and the share of CHP production in the Norrköping system is thus close to 100%. In Borlänge only a small share of the heat load is covered by CHP production. Instead, a waste incineration heat only boiler and utilisation of industrial waste heat is used to cover a large share of the heat load. The Borlänge utility also purchases heat from an external industrial biomass-fired boiler. In Malmö a natural gas-fired CHP plant is used with an electricity-to-heat output ratio ($\alpha$ value) of 1.6, which means that the main product from this plant is electricity and not heat. Further, in the Malmö system, heat from waste incineration is bought from an external waste treatment company. In Borlänge and Umeå electric heat pumps are used to a significant extent in the heat production mixes. In all systems oil heat-only boilers are available for peak load production. In the FMS models of the six DH systems, prices for the reception of municipal waste and utilisation of IWH represent the prices for an average Swedish DH system, since these prices vary between different systems and are difficult to obtain.

The FMS DH system models for the systems investigated in paper IV are less detailed than the MODEST models of the DH systems in Linköping and Uppsala in papers I-III. This means that certain DH production plant characteristics have been left out of the FMS models. The idea behind the FMS models was to build as detailed DH models as possible using easily obtained data such as plant capacities, $\alpha$ values, total annual heat production, and outdoor temperature data. This way the main DH system characteristics are captured with little effort. This enables the modelling of many different DH systems in order to investigate how DH system effects depend on DH production plant characteristics and composition, which is part of the aim of the present thesis. The results for the heat demand reduction scenario in paper IV show how system effects vary between different types of DH systems. If, however, single DH systems are investigated in detail, it is recommended that a modelling tool is used that offers more flexibility in system structure description, and allows the use of more complex relations between energy flows. MODEST is one example of such a tool.
5.4 Typical system representation of the Swedish district heating sector

In paper V four typical DH systems were defined to represent the entire Swedish DH sector with significant differences in fuel use and heat production technologies taken into account. The 441 Swedish DH systems represented in the statistical data from 2011 published by the SDHA [50] were divided into four groups. Group I contains all systems without CHP plants, group II-IV contains the systems with CHP production and where the respective main CHP fuel is waste, fossil and biomass. Figure 5.5 shows the total heat production mixes for each group and the shares of produced heat and electricity.

Figure 5.5. Heat production mixes and productions shares of heat and CHP electricity in the typical DH system groups.

Four typical models were built using the FMS model to represent the aggregated systems in each group shown in Figure 5.5. General plant efficiencies were used, obtained from [51], and output capacities and $\alpha$ values were adjusted to make model results agree with the annual heat and electricity production values in the aggregated statistics for each group of systems.

This chapter presents the system performance indicators used to investigate the DH system effects caused by improved energy efficiency in Swedish residential buildings. The direct indicators, i.e. fuel use, heat production, and CHP electricity generation, are described initially. Thereafter the indirect indicators, system electricity-to-heat production ratio ($\alpha_{\text{system}}$) and CO$_2$ emissions due to DH production are presented.

6.1 Fuel use, heat production and CHP electricity generation

DH system model optimisations yield the amounts of fuels used for heat production in different units to supply a given heat demand in a cost-optimal way. Optimisation also yields results for the amount of generated CHP electricity. In this thesis these results are considered to be the direct indicators of system performance, indicating the actual effects on DH production caused by heat demand changes.

The optimisation models used in the appended papers calculate the heat produced and electricity generated in different production units for each time period separately. This is important for investigation and analysis of the impact of seasonal and diurnal variations in heat demand and variations in electricity price level on the yearly cost-optimal production of DH. The direct indicators are further used in the calculations of the indirect indicators described below.

6.2 The $\alpha_{\text{system}}$ value

The $\alpha_{\text{system}}$ value is the ratio of the annually co-produced electricity and the annually produced and utilised heat. The $\alpha_{\text{system}}$ value provides an indication of the co-generation intensity of the system, and depends on the share of the heat that is produced in CHP units and on the $\alpha$ values of the individual CHP units in the system. A DH system with a large share of CHP production generally yields a higher $\alpha_{\text{system}}$ value than a system with a smaller share of CHP production. In addition, CHP units with high $\alpha$ values enable a high $\alpha_{\text{system}}$ value while CHP units with low $\alpha$ values limit the $\alpha_{\text{system}}$ value.

The $\alpha_{\text{system}}$ value is not directly affected by the type of fuel used in the system because it is a measure of the converted energy forms but not of the
primary energy supplied to the system. The type of fuel used, however, has an indirect influence on the $\alpha_{\text{system}}$ value since different fuels are differently suited for electricity generation. Normally natural gas-fired CHP plants have higher $\alpha$-values than, for example, waste-fired CHP plants.

Werner [18] presents a curve for annual electricity-to-heat production ratio, similar to the $\alpha_{\text{system}}$ value used here, for the DH system in Malmö between the years 1953 and 1985.

6.3 CO$_2$ emissions

The CO$_2$ emissions associated with energy use are important in energy system studies due to their essential role in the climate issue. Both Swedish and European energy policies are focusing to a large extent on the reduction of CO$_2$ emissions, with the intention of moderating the effects of global warming in the future. The member states of the EU emit about 5000 million tonnes of CO$_2$ equivalents per year [52]. Sweden alone emits about 66 million tonnes of CO$_2$ [53].

The calculation of CO$_2$ emissions due to heat production in DH systems is, however, complex. The reason is mainly that DH systems are connected to national and international power systems through CHP plants, electric boilers and heat pumps. The complexity of the power systems causes difficulties in assessing CO$_2$ emissions associated with electricity use and generation. In this section calculations of CO$_2$ from DH production in the investigated DH systems are described.

The total amount of CO$_2$ emissions ($X_{CO_2}$) from DH production are calculated as

$$X_{CO_2} = f_1 \cdot Q_{f_1} + \cdots + f_n \cdot Q_{f_n} + f_{el} \cdot (Q_{el.use} - Q_{el.prod}) \quad (6.1)$$

In Equation 6.1 emissions from the incineration of different fuels in heat production units are calculated by associating CO$_2$ emission factors, i.e., kg CO$_2$ per MWh, ($f_1 \cdots f_n$) to the annual use of each fuel ($Q_{f_1} \cdots Q_{f_n}$). The emission factor $f_{el}$ is used to assess CO$_2$ emissions per unit of electricity use and production. This factor is multiplied by the total amount of used electricity $Q_{el.use}$ and produced electricity $Q_{el.prod}$. Co-generated electricity in CHP plants is considered to replace an equally sized quantity of electricity that otherwise would have been generated at a higher cost in normally less efficient power plants elsewhere in the system. The emissions associated with CHP produced electricity are credited and thus subtracted from emissions due to fuel and electricity use. The assessment of CO$_2$ emissions from electricity use is further explained in Section 6.3.1.
Table 6.1. CO\textsubscript{2} emission factors used for the studied systems.

<table>
<thead>
<tr>
<th>Energy carrier/ fuel category</th>
<th>Linköping paper I</th>
<th>Uppsala papers II and III</th>
<th>Karlstad, Enköping, Borlänge, Malmö, Norrköping, Umeå paper IV</th>
<th>Typical system I-IV paper V</th>
</tr>
</thead>
<tbody>
<tr>
<td>waste</td>
<td>100</td>
<td>90</td>
<td>118</td>
<td>90</td>
</tr>
<tr>
<td>biomass</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>fossil</td>
<td>-</td>
<td>-</td>
<td>267/204\textsuperscript{1}</td>
<td>283/265/284/307\textsuperscript{2}</td>
</tr>
<tr>
<td>wood</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>peat</td>
<td>-</td>
<td>370</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>oil</td>
<td>280</td>
<td>270</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>coal/rubber/wood-mix</td>
<td>165</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>electricity (CC/NGCC)</td>
<td>950/400</td>
<td>950/400</td>
<td>930/400</td>
<td>930/400</td>
</tr>
<tr>
<td>Biomass savings</td>
<td>302</td>
<td>302</td>
<td>302</td>
<td>302</td>
</tr>
</tbody>
</table>

\textsuperscript{1} 204 is used for the DH system in Malmö due to the extensive use of natural gas. 267 is used in paper IV for the other DH systems for which oil is the main fossil fuel.

\textsuperscript{2} Individual factors are calculated for the typical DH systems to mirror the weighted averages of different fossil fuels used.

The emission factors for fuels and electricity used in the appended papers are presented in Table 6.1. CO\textsubscript{2} emissions from the incineration of biomass are, according to European Union standards, assumed to be zero as they are considered to be carbon dioxide neutral [54]. The viability of this assumption relies on the condition that the use of biomass does not exceed the regrowth.

The CO\textsubscript{2} emissions associated with the use of peat in, for example, the DH system in Uppsala (paper II and III) have been discussed as peat is a fuel with its origins somewhere between biomass and fossil fuels. The time to regrow peat is about 2000 years [55]. Peat is here considered to be a fossil fuel since the regrowth time of peat lies beyond the time-horizon to where the climate effects of CO\textsubscript{2} emissions are considered to be non-reversible.

6.3.1 Assessment of electricity

Because of the complexity of the Nordic and the European power systems, electricity use and generation are difficult to assess in terms of CO\textsubscript{2} emissions. The Swedish power system is nearly fully integrated with the power systems of the other Nordic countries, which means that the transmission capacity between the countries is high. Thus, the demands for electricity in Sweden, Norway, Denmark and Finland are not necessarily met by the respective country’s electricity supply. Further, the Nordic power system is also part of the European power system through transmission links between the Nordic countries and Russia, Estonia, Holland, Germany, and Poland. These links are used to maintain power grid balance and they handle mis-matches between electricity demand and supply within the European countries. The effect of
this power system complexity is that it is difficult to track the exact origin of the electricity that is used, or the exact use of generated electricity within the system. This means that it is difficult to assess the CO₂ emissions due to electricity use since electricity can be produced using different technologies, which yield significantly different CO₂ emissions.

Several different approaches are used to assess the CO₂ emissions associated with electricity use and production. Common approaches are to use average electricity generation (i.e. power generation mixes) and marginal electricity generation [56]. The average electricity generation approach means that changes in electricity use and production affect all electricity production units in the system equally. This is, however, an approach with few nuances [56,57]. The reason is that power generation technologies are differently suited for regulation according to demand, and together with the Nordpool trading control mechanisms, this makes it unrealistic to assume that all power generation is equally affected by changes in electricity demand and production. Two different average perspectives are used in papers II, III and V, mainly for comparison with other approaches. However, the average approaches should not be used exclusively due to their incapability to capture electricity market dynamics.

Instead, the marginal approach is in focus in the present thesis. Marginal approaches are based on the assumption that the co-generated electricity replaces electricity produced in the power plant with the highest electricity production cost in operation at the moment. This is the power plant considered to be on the electricity generation margin. The marginal approach is used for assessment of the credited CO₂ emissions from CHP produced electricity and for emissions caused by electricity used in electric boilers and heat pumps. Due to the integrated Nordic power system and its connections to the European power system, the power plants in Europe considered to constitute the power generation margin are currently coal-fired condensing power plants.

![Figure 6.1](image-url)  
*Figure 6.1.* Monthly power generation in the European power system (a) and the Nordic power system (b) in 2013. Data provided by ENTSO-E [58].
In papers I, II, III and V, two different marginal approaches for CO$_2$ assessment of electricity use and generation are used. The first is a short-term approach representing today’s situation, with coal condensing (CC) power plants on the production margin. Figure 6.1 shows the monthly power generation mixes in the European and the Nordic power systems in 2013. In both diagrams it is clear that fossil power generation is operated all year around, which motivates the assumption that CC power plants are on the margin. The second approach uses a long-term perspective, where today’s coal condensing power plants are assumed to have been replaced with more efficient and less CO$_2$-emitting, natural gas-fired combined-cycle (NGCC) power plants.

6.3.2 Global CO$_2$ emission calculation with credited biomass savings

Within the EU, the use of biomass is, as already mentioned, not considered to contribute to the concentration of CO$_2$ in the atmosphere. Therefore conversion to biomass based fuels constitutes an attractive path to reduce CO$_2$ emissions in fuel based sectors such as transport and electricity and heat production. The conversion of the previously fossil fuel dominated Swedish DH sector to the present situation with biomass as the main fuel is an example of this. This reasoning implies that increased, or decreased, use of biomass has no effect on CO$_2$ emissions, which would be reasonable if biomass was an unlimited resource. Biomass is, however, not an unlimited resource, even though the Swedish biomass supplies are relatively large [59]. Limited biomass availability is normally not considered in CO$_2$ calculations. It is reasonable to apply similar reasoning as that applied for co-generated electricity in CHP plants to calculations of global CO$_2$ emissions when biomass savings in Swedish DH systems are considered. Each unit of conserved biomass in DH production can be assumed to replace fossil fuels elsewhere in the European energy system. Here, this reasoning is applied to the six Swedish DH systems studied in paper IV. Global CO$_2$ emissions are calculated for the heat demand reduction scenario, where biomass savings emissions are credited for.

The assessment of CO$_2$ emissions associated with conserved biomass requires a few assumptions. It is assumed that each unit of saved biomass in Swedish DH is used in a new European biomass-fired CHP unit. It is also assumed that the heat produced in the CHP unit replaces heat from an in-house natural-gas-fired water heater. It is assumed that the co-generated electricity replaces electricity from a NGCC condensing power unit. The CHP unit is considered to be equipped with a flue-gas condensation step and thus the efficiency of the unit is assumed to be 110%. The electricity-to-heat output ratio of the plant is assumed to be 0.4. Further, the efficiency of the natural gas-fired water heater is 90% and the natural gas used in this boiler is assumed to emit
204 kg of CO₂ per MWh. For the replaced electricity from the NGCC plant an emission factor of 400 kg CO₂/MWh is used. These assumptions yield a calculated CO₂ emission factor of 302 kg CO₂/MWh for conserved biomass in Swedish DH production.

The CO₂ emissions with credited biomass savings are calculated as

\[ X_{CO_2} = f_1 \cdot Q_{f_1} + \cdots + f_n \cdot Q_{f_n} + f_{el} \cdot (Q_{el\text{-use}} - Q_{el\text{-prod}}) - f_{bs} \cdot Q_{cb} \quad (6.2) \]

Equation 6.2 shows how the biomass conservation emission factor \( f_{bs} \) is multiplied by the total amount of conserved biomass \( Q_{cb} \) and subtracted from the emissions calculated using Equation 6.1.

A different approach for assessing CO₂ emissions from changed biomass use in Swedish DH systems have been used in [60], in which a changed biomass use is assumed to affect co-firing of biomass in CC power plants or production of Fischer-Tropsch diesel. These assumptions yield CO₂ emission factors of 336 and 118-152 kg CO₂eq/MWh for conserved biomass.
7. Calculations of heat demand changes due to improved building energy efficiency

This chapter describes how the heat demand changes in the scenarios investigated in the appended papers are calculated. The calculations differ slightly between the papers. In papers I, IV and V, only energy efficiency measures in existing building stock are investigated for the studied systems, while the heat demand changes investigated for the DH system in Uppsala in paper II and III consider both building energy efficiency measures and future additional heat demand in buildings. More detailed descriptions and equations for the heat demand change calculations are presented in the appended papers.

For all the studied DH systems the demands for SH and DHW are reduced separately in the calculations, as SH demand depends strongly on the outdoor temperature. The share of the demands for DHW and SH also need to be estimated because heat demand data are provided in total figures, i.e., information for the shares of SH and DHW demands are not given in data.

It is assumed that SH demand in residential buildings is reduced by, for example, additional wall and attic insolation, exchanging windows and installing ventilation-air heat recovery. DHW demand is primarily reduced by implementing water-saving taps and shower heads.

7.1 Linköping

The heat demand reduction calculations for the Linköping system presented in paper I were performed separately for summer months (June to August) and winter months (September to May). SH demand during summer months is assumed to be zero and the average demand during the summer time periods is used to estimate DHW demand during the winter months. Thereafter the heat demands for SH and DHW are reduced separately.

The reductions of the SH and DHW demands in the Linköping DH system were based on the measured heat demands before and after the extensive refurbishment of the first renovated building in the Brogården project described in [61]. The SH demand and the demand for DHW in the Brogården building were reduced by 75% and 61%, respectively. These demand reduction factors were multiplied by the share of total heat demand in the DH systems affected by heat demand reductions.

Paper I contains investigations of two different scenarios, one scenario where all existing MFRBs in Linköping built between 1961 and 1980 (about 17 400
apartments) are renovated to passive house standard, which reduces the total annual heat demand in the DH system by 8.3%. Figure 7.1 shows the heat demand reduction per month for the Linköping DH system for this scenario.

The second scenario is a step-wise heat demand reduction scenario, i.e. a heat demand reduction sensitivity analysis. The Brogården reduction figures for SH and DHW demands were also used for this scenario. The share of the total heat demand being reduced were adjusted for each reduction step so that the total annual heat demand in the system was reduced by 5, 10, 15,..., 50%.

![Figure 7.1. Calculated heat demand reduction in the Linköping DH system after renovation of all MFRBs built in 1961-1980.](image)

7.2 Uppsala

For the Uppsala system (papers II and III) a possible future DH demand was calculated that included energy efficiency measures in existing buildings, as well as, the addition of heat demands in new buildings. The future heat demand scenario consists of a series of stages with an intermediate period of two years, i.e. stages for 2012, 2014,..., 2030. To determine the heat demand reduction in the scenario stages, a relation between the relative reductions for SH and DHW in a building, the relative amount of DHW and SH in a building, and the fraction of buildings being renovated was established. The advantage of this relation is that relative numbers of buildings can be used and the exact amount of buildings being renovated and the exact amount of heat use in each building does not necessarily need to be known. Seasonal variations in DH
distribution losses are here accounted for. The calculations are described in detail in paper II, Equations 2 to 7. The heat demand in the year 2010 is used as a reference. The 2010 heat demand was assumed to be reduced by 1.5% annually in each scenario stage, due to assumed energy efficiency measures in the existing building stock. Figure 7.2 shows heat demands for the reference case and the scenario stages 2020 and 2030. The stair-case shape of the duration curves is caused by the time step division used in MODEST for this system.

For the Uppsala DH system, calculations were also made to add heat demand, due to new district-heated buildings. An additional hourly heat demand for one MFRB was generated using the building simulation software VIP Energy [62]. The heat demand represents a low energy building with an average energy use of 55 kWh/m$^2$ year for SH and DHW. The single building heat demand is scaled up by the number of new buildings added to the system for each scenario stage and added to the remaining heat demand after energy conservation in existing buildings. In the scenario, 1000 new residential apartments per year were added because Uppsala is a growing urban area.

![Figure 7.2](image-url)  
*Figure 7.2. Reference heat output demand and scenario heat demand duration curves for stages 2020 and 2030 in the Uppsala DH system.*
In paper III a large number of hot-water-circuit (HWC) domestic household appliances that use DH instead of electricity are implemented in Uppsala for scenario stages 2020 and 2030. In 2020 all new apartments and 57% of existing multi-family residential apartments were equipped with HWC appliances. In 2030 all new apartments and all existing apartments were equipped with HWC appliances. The diurnal and seasonal heat demand variations for district heated household appliances were calculated using a set of time-use data, which show daily activities for a large number of individuals and their activities, based on diaries [63].

The heat demands for the reference year 2010, and scenario cases 2020 and 2030, are shown in Figure 7.3, with and without introduced HWC appliances. It is clear that the main impact on the heat demands is due to the energy efficiency measures, and that the additional heat demands from new buildings and HWC-appliances are relatively small. In total however, the calculated heat demand changes yield a lower annual heat demand and a more levelled heat demand profile over the year.

Figure 7.3. Heat output demands in the Uppsala DH system for the reference year 2010 and the scenario years 2020 and 2030, with and without introduced HWC household appliances.
7.3 Karlstad, Enköping, Borlänge, Malmö, Norrköping and Umeå

In paper IV a heat demand reduction scenario was made for the six studied DH systems in Karlstad, Enköping, Borlänge, Malmö, Norrköping and Umeå. The hourly reference heat demand data used for these systems were estimated using local outdoor temperature data and the number of produced GWh of heat per year for each DH system. The heat demand approximation method is described in detail in paper IV. In the heat demand reduction scenario, DHW demand in MFRBs is reduced by 20% and their demand for SH is reduced by 50%. These reduction levels for SH and DHW demand were considered reasonable assumptions for building energy efficiency measures such as implemented energy-saving water taps and shower heads, additional building envelope insulation, new energy-efficient windows, and the installation of ventilation-air heat recovery systems. The MFRBs are assumed to constitute 50% of the system’s heat demand. The scenario calculations for heat demand reductions are similar to the calculations for the Linköping system in paper I, but with different reduction factors for the demands for DHW and SH.

Figure 7.4 shows the approximated heat demand based on outdoor temperature data and the scenario heat demand for the Karlstad DH system. The reference and scenario heat demands for Enköping, Borlänge, Malmö, Norrköping and Umeå are different in size but similar to the Karlstad DH demands.

Figure 7.4. Approximated reference and scenario heat demand duration curves for the Karlstad DH system.
7.4 Typical systems

For the typical systems representing the entire Swedish DH sector studied in paper V, a similar step-wise heat demand reduction scenario was investigated as for the Linköping system in paper I. The total heat demand is reduced by 5, 10, 15, ..., 50%. The total annual heat demand reduction is adjusted by the share of the heat demand affected by the reductions, and the demands for DHW and SH are reduced by 30% and 50%, respectively. The reduction levels for SH and DHW demands were based on calculated potentials for energy efficiency in Swedish buildings by the National Board of Building, Housing, and Planning [64]. Figure 7.5 shows the reference heat demand for typical system III, along with heat demands for all scenario stages with 5, 10, 15, ..., 50% heat demand reduction. The heat demand reduction curves for typical DH systems I, II, and IV are similar to those of typical system III, in relation to system size.

![Figure 7.5. Reference heat demand (upper bold line) and scenario heat demands (dotted lines) for typical system III. Each line represents an additional 5% heat demand reduction of the reference heat demand.](image-url)
8. District heating production sensitivity to heat demand changes

This chapter presents the results obtained in this PhD project that are relevant to the scope of the thesis, which was to investigate the change in DH demand due to energy savings in Swedish MFRBs and its effects on DH systems’ fuel use, DH production, CHP electricity generation, and global CO₂ emissions.

Reference case results representing the current DH production for all the investigated DH systems are presented along with scenario results for a total heat demand reduction of 17 to 20%, which is a reduction level reflected in all papers. This is also comparable to the 20% energy use reduction agreed upon by the EU member states in the 20-20-20 climate-target package [65]. The heat demands for the six DH systems studied in paper IV are reduced by 17% to 19%, depending on the size of the annual total shares of DHW and SH demands. Scenario stage 2026 for the Uppsala DH system (papers II and III) yields a total heat demand reduction of 18.5%. For the Linköping DH system (paper I) and the typical DH systems (paper V), the most representative heat demand reduction level for comparison to the other results, is for 20% heat demand reduction. These results from the appended papers, including CO₂ emissions for papers I-III and V, are complemented with results for CO₂ emissions for the six DH systems in paper IV. CO₂ emissions are also calculated with biomass savings taken into consideration for all investigated DH systems.

Initially the direct system effect results, i.e. fuel use, heat production and CHP electricity production, are presented. Then the $\alpha_{\text{system}}$ values and the CO₂ emissions are presented. Finally, fuel use and CO₂ emission results are presented for the Swedish DH sector as a whole, with step-wise heat demand reductions.

8.1 Results for fuel use, heat production, and CHP electricity generation

Figure 8.1 shows the supplied energy to DH and CHP electricity production in the twelve studied DH systems for the reference cases, and the 17-20% heat demand reduction scenario cases.

The use of fossil fuels is reduced in all DH systems that use fossil fuels because they are the most expensive fuels. The incineration of municipal waste is nearly unaffected or reduced by only a small extent in all systems apart from
Figure 8.1. Energy supplied annually to the studied DH systems in the reference and heat demand reduction scenario cases.
Malmö. This is because heat from waste incineration in the Malmö DH system is delivered from an external part and is associated with a higher cost than waste incineration in the other investigated DH systems. The high $\alpha$ value of the natural-gas-fired CHP plant in Malmö, which yields large electricity revenues, combined with the relatively high cost for purchased heat from waste incineration, explains the small change in fossil fuel use and the larger reduction in the use of waste. Biomass based heat production is generally more expensive than heat utilisation from waste incineration and is therefore also reduced to a larger extent than waste when the heat demand is reduced. The results show that the use of biomass is reduced for all DH systems apart from Uppsala where biomass is not used. The electricity use is cut by about half for the systems that use heat pumps (Uppsala, Borlänge, Malmö, Umeå and all the typical systems). In Linköping electricity is used in a heat-only boiler which is no longer needed when the heat demand is reduced. The use of IWH is reduced when it is used to supply an intermediate load and it is combined with low-cost CHP production, as in Karlstad, Borlänge, Malmö, and typical system IV. IWH usage is less affected by demand reduction when supplying base load and when it is not combined with, for example, biomass-fuelled CHP production, that is within the same range of production cost (typical systems I and II).

Figure 8.2 shows that CHP electricity generation is affected by demand reduction to different extents depending on the share of CHP in the heat production mixes and on the type of CHP and other DH production used. The DH systems in Enköping and Norrköping reduce their CHP electricity generation significantly when heat demand is reduced, since these systems have little other heat production. CHP electricity generation in Uppsala and typical system II is affected by the heat demand reduction to a large extent due to expensive CHP production in fossil-fuelled CHP plants that supply the intermediate load, which is significantly reduced. CHP electricity generation is reduced less in DH systems with cheap CHP production that is not used to supply peak and intermediate loads to a large extent, such as typical system III and the DH systems in Borlänge and Umeå. In Linköping more heat is wasted while producing electricity in CHP plants when the DH demand is reduced. This is because of occasionally high enough electricity revenues that make CHP production beneficial even though the heat is not needed. It does, however, also require the possibility of wasting heat, which is not the case in the models of the other investigated DH systems. The main characteristic of typical system I is that heat is not produced in CHP plants, which explains the absence of generated electricity in Figure 8.2.

Implementation of hot-water-circuit (HWC) household appliances in the district-heated MFRBs in the Uppsala DH system slightly increases total heat demand. This small change in heat demand contributes to an increase in operation time for the peat-fuelled CHP plant in the system. The implementation of HWC appliances enables the CHP plant to be operated for one month instead
Figure 8.2. Annual DH production and CHP electricity generation for reference and scenario cases in all studied DH systems.
of not being operated at all in 2030. Thus for the Uppsala DH system, small changes in heat demand can significantly affect the peat use and generation of CHP electricity.

8.1.1 Summary of direct indicator results
Heat demand changes due to building energy efficiency improvements mainly affect the use of fossil fuels and biomass because these are commonly used for peak-load and intermediate-load DH production. Waste use in heat-only and CHP plants is generally affected to a lesser extent because it is normally associated with low heat production costs and therefore used in base-load DH production.

The generation of electricity in CHP plants is affected differently in the studied systems because CHP plants are used to supply different parts of the heat loads. CHP production is more affected if the share of CHP production in a system’s heat production mix is large, or if the CHP production is expensive and used to supply intermediate or peak load. Otherwise, if CHP production is used mainly for base load production, it is only marginally reduced by heat demand reductions.

8.2 $\alpha_{\text{system}}$ value results
The ratio between annual CHP electricity generation and annual heat production, i.e. the $\alpha_{\text{system}}$ value (Section 6.2), indicates the intensity of co-generation in DH systems and reflects how changes in heat production and electricity generation in DH systems relate to each other. Figure 8.3 shows the $\alpha_{\text{system}}$ values for the reference cases and the 17-20% heat demand reduction scenarios in the studied DH systems.

Since typical system I is not producing heat in CHP plants, the $\alpha_{\text{system}}$ value is zero. For the other DH systems the level of the $\alpha_{\text{system}}$ value depends on the share of CHP production in the system and on the individual $\alpha$ values of the CHP plants. The high $\alpha$ value ($\alpha = 1.6$) for the natural-gas-fired CHP plant in the Malmö system is crucial to its high $\alpha_{\text{system}}$ value. The close to 100% CHP production in the Enköping and Norrköping DH systems explains the relatively high $\alpha_{\text{system}}$ values for these systems. In Linköping, Umeå, and typical systems II and IV, the shares of CHP production are also relatively large and so are the $\alpha$ values of the individual CHP plants. The low $\alpha_{\text{system}}$ values seen for Uppsala, Karlstad, Borlänge, and typical system III are explained either by small shares of CHP production, or by CHP plants with low individual $\alpha$ values, or a combination of both, as in the Borlänge DH system.

The $\alpha_{\text{system}}$ values are increased with the heat demand reductions for all DH systems, apart from Uppsala, Norrköping and typical system II. An increased $\alpha_{\text{system}}$ value indicates that the CHP electricity generation is reduced
Figure 8.3. Reference and heat demand reduction scenario $\alpha_{\text{system}}$ values for the studied DH systems.

to a smaller extent than the heat-only production, and thus for Uppsala, Norrköping and typical system II the opposite is indicated.

For the DH systems in Linköping, Karlstad, Borlänge, Malmö, Umeå, and Typical systems III and IV, the $\alpha_{\text{system}}$ values are markedly increased with decreased heat demand. This is because these systems use CHP plants for the mainly unaffected base-load production, while peak loads, and to some extent also intermediate loads, are supplied by heat-only production plants that are affected to a larger extent by the heat demand reductions. The increase in $\alpha_{\text{system}}$ value for the Malmö DH system is explained by the high $\alpha$-value of the natural-gas-fired CHP plant and that CHP electricity generation is only marginally affected by heat demand reductions.

For the Uppsala system and typical system II, the $\alpha_{\text{system}}$ values are significantly decreased when the heat demand is reduced. Typical system II has a similar heat-production-plant composition and merit-order as Uppsala with fossil-fuelled CHP production supplying intermediate load, while the base load to a large extent is supplied by heat-only production. Therefore heat-demand reductions affect CHP production more than the heat-only base load production, which decreases the $\alpha_{\text{system}}$ value for these DH systems.

For Norrköping and Enköping the differences in $\alpha_{\text{system}}$ values are small between the reference case and the scenario. This is because CHP plants supply nearly 100% of the heat load. Heat-demand reductions thus almost only re-
duce heat from CHP plants. Therefore the electricity generation and the heat production are reduced to an equal relative extent and there is little change in the electricity generated per unit of produced heat. The $\alpha_{\text{system}}$ value for Norrköping is slightly decreased with the heat-demand reductions because the CHP plant that is mainly affected by demand reductions has a higher $\alpha$ value than the less affected CHP plant supplying the base load. The slight increase in $\alpha_{\text{system}}$ value for Enköping on the other hand is because DH production in bio-oil-fuelled, heat-only plants used to supply high demand peaks is relatively more reduced than the CHP production when the DH demand is reduced.

8.2.1 Summary of $\alpha_{\text{system}}$ value results
The impact on the $\alpha_{\text{system}}$ values due to a reduced DH demand depends on the extent of CHP production in the heat production mix, CHP-plant $\alpha$ values, and the kind of heat load supplied by the CHP plants. The results indicate that if CHP production is used for peak and intermediate heat load, but not base load, the $\alpha_{\text{system}}$ value decreases when the heat demand is reduced. For DH systems with a share of CHP production close to 100% the $\alpha_{\text{system}}$ value is only marginally affected. Furthermore, if CHP production is mainly used to supply base load the $\alpha_{\text{system}}$ value is generally increased by heat demand reductions.

8.3 CO$_2$ emission results
CO$_2$ emissions are calculated in papers I, II, III, and V. In the present thesis summary, CO$_2$ emissions are also calculated for the six systems studied in paper IV. This provides data that enables a comparative analysis of the studied DH systems in all appended papers. Further, global CO$_2$ emission impact where biomass savings are credited for, have been calculated for all the studied DH systems.

CO$_2$ emissions are calculated in three different ways. The first two ways are when the CC and NGCC approaches for electricity CO$_2$ assessment are used (Section 6.3.1). The third way of calculating CO$_2$ emissions is by using the NGCC approach, along with the crediting of biomass savings.

8.3.1 CO$_2$ results for the coal-condensing approach
The results in Figure 8.4 show that the contribution to CO$_2$ emissions from DH production for all DH systems apart from Uppsala and typical system I is negative when the CC approach is used. This means that the global CO$_2$ emissions are less than what they would be without DH production in these DH systems. Using the CC approach means that the level of credited CO$_2$ emissions per unit of produced CHP electricity is high (Section 6.3) and that this
significantly affects the impact on global CO\textsubscript{2} emissions. Large $\alpha_{\text{system}}$ values ($\geq 0.25$), as in Linköping, Enköping, Malmö, Norrköping, Umeå, and typical systems II and IV, generally yield low CO\textsubscript{2} emissions per unit of produced heat. Small $\alpha_{\text{system}}$ values ($\leq 0.2$), as in Uppsala, Borlänge and typical systems I and III, yield higher levels of CO\textsubscript{2} emissions, apart from the DH system in Karlstad, where a low $\alpha_{\text{system}}$ value (0.17) yields low CO\textsubscript{2} emissions per unit of produced heat because of the large share of biomass in the fuel mix.

The DH systems in Uppsala and Malmö and typical system II use fossil-fuelled CHP plants to a large extent but yield different CO\textsubscript{2} emissions per unit of produced heat, especially when the CC approach is used. Malmö yields the least CO\textsubscript{2} emissions per unit of produced heat of all the studied individual DH systems despite the extensive use of fossil fuels in the system. This is because of the large amount of CHP electricity generated per produced unit of heat, i.e. the high $\alpha_{\text{system}}$ value. Uppsala, on the other hand, yields the second highest level of CO\textsubscript{2} emissions per unit of produced heat when the CC approach is applied. This is explained by the low $\alpha_{\text{system}}$ value and the high level of emissions from local use of municipal waste and fossil peat. The largest amount of CO\textsubscript{2} emissions is seen for typical system I, due to the large amount of DH systems included, as well as the absence of CHP production and hence the lack of credited emissions for co-generated electricity. This also highlights the importance of CHP production for the level of CO\textsubscript{2} emissions when the CC approach is applied.

The 17-20\% heat demand reduction scenario results show that CO\textsubscript{2} emissions decreased for eight out of the twelve studied DH systems when the CC approach was used (Figure 8.4). The largest CO\textsubscript{2} emission reductions are seen for DH systems for which the main part of CO\textsubscript{2} emissions comes from DH production plants that supply peak and intermediate demand. This is the case in Uppsala and for typical systems I and III where fossil-fuelled heat-only boilers are used to a large extent to supply the peak and intermediate demands.

If the part of the heat demand being reduced was previously supplied by a DH production mix with low net emissions, the changes in CO\textsubscript{2} emissions due to reduced heat demand are small. DH production mixes with low emissions can, for example, consist of biomass-fuelled heat-only boilers and IWH utilisation or a mix of heat-only production and CHP production where the emissions from the used fuels are similar to the credited emissions from co-generation of electricity. Small CO\textsubscript{2} changes are seen for Linköping, Karlstad, Borlänge, Malmö, Umeå, and typical system IV.

For the DH systems in Enköping and Norrköping and for typical system II the CO\textsubscript{2} emissions are significantly increased with a reduced heat demand when the CC approach is applied. The emissions are increased for the DH systems in Norrköping and Enköping because the heat demand reductions mainly reduce DH production in the biomass-fuelled CHP plant. The emissions from the fuels used in Norrköping are therefore not reduced much and in Enköping only biomass is used and emissions from fuel use are zero. The credited CO\textsubscript{2}
Figure 8.4. Annual CO₂ emissions due to DH production for reference cases and heat demand reduction scenarios when the CC approach is used for CO₂ assessment of electricity.
emissions from CHP electricity generation is, however, reduced for both systems and therefore the net change in global CO\textsubscript{2} emissions shows an increase. For typical system II the heat demand reduction significantly affects the fossil-fuelled CHP plant with an $\alpha$ value of 1.0. Even though fossil fuel use is significantly reduced, the lower crediting of emissions due to CHP-produced electricity increases the total emissions from DH production.

8.3.2 CO\textsubscript{2} results for the natural-gas combined-cycle approach

The assumption that in the future natural-gas combined-cycle power plants will have replaced coal-condensing power plants on the European power generation margin means that less CO\textsubscript{2} emission is credited per unit of produced electricity in Swedish CHP plants (Section 6.3.1). The use of the NGCC approach for electricity assessment therefore yields different results for global CO\textsubscript{2} emissions than was seen for the CC approach. Generally, the emissions from local fuel use affect the global CO\textsubscript{2} emissions to a larger extent and the $\alpha_{\text{system}}$ values have less impact with the NGCC approach compared to when the CC approach is used. Figure 8.5 shows the reference case and 17-20\% heat demand reduction scenario results for the DH-production contribution to global CO\textsubscript{2} emissions when the NGCC approach is applied. The figure also includes scenario results when emissions are credited for biomass savings (Section 6.3.2).

Use of the NGCC approach leads to generally higher levels of CO\textsubscript{2} emissions for all DH systems with CHP production compared to when the CC approach is used. The difference in CO\textsubscript{2} emission levels per unit of produced heat between the different approaches for CO\textsubscript{2} assessment of electricity is large for the Malmö DH system since the credited emissions due to CHP electricity generation with the NGCC approach are more similar to the emissions from the local fuel use than was the case when the CC approach was used, and the system’s contribution to global CO\textsubscript{2} emissions was lower. The opposite results are, however, seen for typical system I, where a higher level of emissions per unit of produced heat was seen for the CC approach compared to the NGCC approach. This is because CHP plants are not used and the NGCC approach entails less CO\textsubscript{2} emission for the use of electricity in heat pumps compared to the CC approach. Linköping, Borlänge, Malmö, and typical systems II and III yield positive contributions to global CO\textsubscript{2} emissions due to the lower influence of CHP electricity generation on emissions for the NGCC approach compared to the CC approach for which these systems yielded negative emissions.

The heat demand reduction scenario results show that CO\textsubscript{2} emissions are reduced when the NGCC approach is applied for all the investigated DH systems, apart from the DH systems in Enköping and Norrköping where the emissions are increased. This is similar to the results for the CC approach and for
Figure 8.5. Annual CO₂ emissions due to DH production for reference cases and heat demand reduction scenarios when the NGCC approach is used. Further are scenario results presented where biomass savings (BS) are credited for.
Enköping and Norrköping due to the fact that nearly all heat is produced in CHP plants and less CO2 emission from NGCC plants are displaced after demand reduction. The CO2 emissions for typical system II on the other hand were increased by heat demand reduction when the CC approach was used, but with the NGCC approach the emissions decreased instead. This is due to lower CHP production by lower demand and the extensive use of fossil fuels in CHP plants yields larger emissions than those credited for CHP electricity generation with the NGCC approach.

Figure 8.5 also shows the results for the calculated contributions to global CO2 emissions when biomass savings are credited for (Section 6.3.2). The reduction in CO2 emissions due to biomass conservation means that global emissions become less than they would have been if heat demand was not reduced in the district heated MFRBs. Thus, more biomass can be used in CHP plants elsewhere in the power system to replace the use of fossil fuels. This means that CO2 emissions from biomass savings only apply when a possible change in biomass use is considered, which is why the reference CO2 emission levels in Figure 8.5 for the investigated DH systems are not different when biomass savings are credited for. It is clear that with credited biomass savings, and building energy conservation measures, CO2 emissions are reduced to a larger extent for all DH systems apart from Uppsala where biomass is not used in the fuel mix. For the Norrköping and Enköping DH systems, heat demand reductions cause decreased CO2 emissions when heat demand is reduced, which is different to when biomass savings were not credited for.

8.3.3 Changed CO2 emissions due to implementation of HWC appliances

The impact of implementing hot-water-circuit (HWC) household appliances (Section 7.2) on global CO2 emission also depends on the electricity assessment approach applied. The results presented in paper III for the Uppsala DH system show that emissions are slightly reduced with the CC approach when electricity use in household appliances is reduced and DH demand in HWC appliances is added to the heat demand reduction scenarios. However, with the NGCC approach, the results are the opposite and implementation of HWC appliances yields higher levels of global CO2.

CHP electricity generation is slightly increased due to the added heat demand in HWC appliances, and so is the use of peat. The high CO2 assessment of electricity with the CC approach yields a net negative addition of CO2 emissions, while the smaller credited emissions from electricity generation with the NGCC approach yield a net positive addition.
8.3.4 Summary of results for CO₂ emissions

The CO₂ emissions due to DH production depend to a large extent on the approach used for CO₂ assessment of electricity. The characteristics of DH production plants (CHP plant α values and fuel use) also influence the emissions significantly. CO₂ emissions for a DH system without CHP production depend solely on the fuel and electricity used for heat production.

For DH systems that produce heat in CHP plants, the CC approach for electricity assessment generally yields lower CO₂ emissions for DH production than for the NGCC approach. The type of fuel used is less important for the contribution to the global emissions when the CC approach is used than for when the NGCC approach is used. Thus a high α\text{system} value is more important to yield low levels of emissions when the CC approach is used, while a large share of biomass in the fuel mixes is more important when the NGCC approach is used. For the CC approach low levels of emissions can be reached even when large amounts of fossil fuels are used. The DH system in Malmö is an example of this.

The changes in CO₂ emissions for the heat demand reduction scenarios varies between the investigated DH systems. The types of fuel that are used, and how much different heat production plants are used influence to what extent the global CO₂ emissions are affected by heat demand reductions.

CO₂ emissions are generally reduced if heat demand reduction mainly leads to less heat being produced in fossil-fuelled heat-only boilers. If CHP production is reduced by demand reduction, the emissions decrease if the fuels used yield higher emissions than the credited emissions due to CHP electricity generation. This depends on the type of fuel used, the α value of the CHP plants, and the approach used for CO₂ assessment of electricity.

For systems with nearly 100% CHP production and extensive use of biomass, the contribution to global CO₂ emissions due to DH production is increased with a reduced heat demand regardless of the electricity assessment approach used. However, when emission reductions due to biomass savings are credited for and the NGCC approach is used CO₂ emissions are reduced with the reduced heat demand for all studied DH systems.

Large-scale implementation of HWC household appliances that use DH only marginally affects the heat demand and thus also only marginally affects the CO₂ emissions from the analysed Uppsala DH system. The small changes in emissions are, however, clearly dependent on the choice of electricity assessment approach due to the fact that the fossil-fuelled CHP plant in Uppsala is used to supply intermediate heat load and is therefore affected by marginal changes in heat demand.
8.4 Heat demand reduction sensitivity analysis for the Swedish DH sector

Figure 8.6 shows the total changes in fuel use and CO2 emissions for the Swedish DH sector as a whole based on the typical systems in appended paper V. In total, heat demand reductions mainly reduce the use of fossil fuels and biomass. Incineration of municipal waste and utilisation of IWH are only marginally affected (see diagram (a) in Figure 8.6). Electricity use for heat pumps is reduced to zero by a 50% heat demand reduction.

In diagram (b) in Figure 8.6, it is shown that if building energy efficiency is improved in all Swedish DH systems, it reduces the CO2 emissions for all analysed heat demand reduction levels when the NGCC approach is used for CO2 assessment of electricity (Section 6.3.1). With this approach Swedish DH yields a negative contribution to (i.e., reduces) global CO2 emissions for heat demand reduction levels above 15%. Use of the CC approach for electricity assessment makes Swedish DH yield negative CO2 emissions at current demand and all heat demand reduction levels with a maximum reduction of global CO2 emissions at 20% heat demand reduction. With more than 40% heat-demand reduction, Swedish DH would, however, reduce global CO2 emissions less than today.

![Figure 8.6. Heat demand change sensitivity analysis for the Swedish DH sector based on typical DH systems presented in paper V. Results are shown for annual fuel use (diagram a) and CO2 emissions (diagram b).](image-url)
9. Discussion

This chapter provides an overall discussion on methodology, input data, and analysed system effects from Swedish DH production due to building heat demand reductions.

9.1 Methodology and input data

The used cost-optimising DH models do not consider unpredictabilities that impact on DH systems in reality. Unforeseen production plant shutdowns due to malfunctioning production units, or unpredictable variations in fuel and electricity prices are factors that, among other things, influence heat and electricity production but are not considered in the model results.

The optimisation models allow shorter operation times than what might be realistic. A CHP unit, as the one in Uppsala, was, according to results presented in paper III, operated only for one month during a full year when heat demand in HWC household appliances was added to the heat demand in the 2030 scenario case. It would probably be more realistic that other production units would not be operated at their maximum output in order to prolong the operation time of the CHP unit above its minimum load level, even though this might theoretically not be cost-optimal. The feature of long-term operation strategy is also not included in the optimisation models used here.

The FMS model is a less detailed and more limited LP cost-optimisation model than MODEST. MODEST provides more flexibility in model structures with potentially higher numbers of components and energy flows, whereas the FMS is more flexible in the number of time-steps. However, the main advantage of the FMS tool is that it is implemented in conventional softwares (Matlab and Excel) that do not require the purchase of external optimisation software and do not have specific requirements on computer operation systems. The open source code of the FMS enables it to be modified and adapted by all users to fit their specific requirements.

Linear programming cost-optimising models assume that heat production plant merit-order is exclusively determined by heat production cost. The validity of this assumption can be questioned for heat utilised from waste incineration processes and utilisation of IWH. The exact costs for fuel, IWH and reception fees for municipal waste are often difficult to obtain from energy companies. Household waste is not a fuel available for purchase on a market in the same way as, for example, oil and the amount of waste to be used
for heat production depends on the regional waste production and contracted waste imports. Utilisation of IWH may be based on a contracted assignment from the DH company to receive surplus heat whenever it occurs. Commitments to treat waste and utilise IWH are probably occasionally reasons to avoid use of lower cost heat production options. However, the DH production costs for waste incineration and IWH can be adjusted to minimise the unrealistic occurrence of decreased or shut down waste incineration and IWH utilisation in model results.

An important issue when working with energy system modelling and scenario making is that the results strongly depend on assumptions made regarding future conditions for the analysed system and its surrounding systems. Future conditions, such as fuel and electricity prices, heat demand, and changes in DH and electricity production units are not known in advance. This requires that assumptions regarding future conditions are made with caution when reflecting over the impact the assumptions have on the modelling results.

The levels of future Swedish electricity prices are hard to predict. Short-term (diurnal) and long-term (seasonal) variations in electricity prices depend on several factors such as climate, prices of fuel, intermittence in renewable power generation, etc. It is reasonable to expect some seasonal differences due to the cold and dark Swedish climate in winter and diurnal variations due to higher electricity demands during the day-time. As the Nordic electricity network is increasingly integrated with the European network, electricity prices are also expected to adapt more to the European price level and larger diurnal variations.

The statistics used to define the typical DH systems described in Chapter 5 and paper V were obtained from the Swedish DH association. These statistics were used in their original form, which means that any errors due to incorrectly reported values from companies or due to incorrect assembly of data by the Swedish DH association have not been eliminated. Another aspect is that the used statistics contain fuel use and heat production data for 2011. There is a possibility that changes have been made in DH production since then, such as the replacement of DH production units.

The criteria used to define the typical systems were based on the type of fuel used and if the systems use CHP units or not. These criteria were used in order to avoid unrealistic competition among fuels and heat production units that are not commonly combined in real DH systems. However, if other aspects or characteristics in the DH sector are investigated, other criteria can be used to define typical DH systems, such as system size or utilisation of IWH.

It could be discussed if emissions from actual fuel, such as fossil fuel, should be accounted for in the same way as emissions from waste incineration. Waste incineration combined with DH production serves a double purpose, both as a favourable fuel for heat production and as a way to treat waste. Associating CO₂ emissions to the use of waste in DH production might incorrectly place the responsibility for emissions from waste incineration on the DH
companies. It should rather be considered a social responsibility to decrease the production of waste, and thus also the emissions that it causes.

9.2 System effects

Energy efficiency measures in existing buildings are crucial for reducing the Swedish use of primary energy. Therefore it is necessary for DH systems in general to adapt heat and electricity production to an energy system with less heat demand in buildings. Reduced demand for heat in district-heated buildings can, to some extent, be counteracted by the establishment of new residential, commercial and industrial heating demands. But, as is indicated from the results presented here, the potential future demand reductions are at least larger than potential additional heat demands in residential buildings (see Section 7.2 and appended paper II).

Heat demand reduction calculations due to energy-efficiency measures in buildings result in a more levelled demand over the year. An important issue concerning such efficiency measures is how they affect production of electricity in CHP units. Peak DH 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 fluctuating heat demand with reduced peaks could also reduce the number of peak-demand boiler start-ups and shut-downs.

To further contribute to the levelling of the annual heat demand profile, non outdoor temperature-dependent applications such as industrial processes and household appliances (for example washing machines, dryers and dish washers) can be considered. A combination of heat and electricity production with production of biofuels for vehicles could also be a possible way to prolong plant utilisation hours over the year and enable larger CHP production.

The results presented here focus on the impact of heat demand changes on the operation of DH systems as they function today. But the heat demand changes investigated here would take decades to realise and the results should be interpreted with that in mind. The results should therefore be interpreted as a worst case, where no changes are made on the heat production side to meet reduced future heat demand. The results show that even if no production side adaptations are made in Swedish DH systems, energy efficiency measures yield reduced global CO\textsubscript{2} emissions in most cases investigated here. A developed approach would be to assume changes of heat production as well. In the Uppsala DH system, for example, the peat-fuelled CHP unit and heat-only boiler are to be replaced by a smaller biomass fuelled CHP unit within a relatively short period of time. This will significantly change the system effects due to DH demand changes in Uppsala.
From a decision-making perspective it is important to consider the long-term impact of decisions concerning building 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 when making decisions concerning future buildings. Reduced heat demand in buildings will become a challenge for DH companies and a situation to which they will have to adapt. An example of such an adaptation is the development of technology for low temperature DH networks to minimise heat distribution losses, which otherwise risk becoming high in traditional DH networks if building heat demands are reduced. The concept of the 4th generation DH addresses the DH system characteristics necessary for adaptation to future conditions [26], such as distribution networks with less distribution loss and flexible CHP units that can be used for power system balancing.

The assumption that CHP generated electricity is considered to replace less efficient power plants with higher electricity production costs in the power system, rests on the condition that such plants in fact are operated within the system and influenced by CHP production. If, for example, large amounts of intermittent power generation (solar, wind, wave, etc.) are introduced into the system, this might result in a situation where occasionally cheap and renewable power generation constitutes the marginal power generation. In such a case the positive aspects of CHP electricity generation should be questioned.

The global system effects from heat demand reductions in Swedish DH systems are not solely dependent on the changes in building energy efficiency, they also depend on changes in European power generation. This means that it is difficult to assess more precisely the global system effects of heat demand reductions in Swedish district heated buildings. If emissions avoided due to CHP electricity are credited for and coal-condensing power plants are gradually replaced by NGCC power plants, it is reasonable to expect that the future contribution to global CO₂ emissions will be somewhere in between the calculated results for the CC and the NGCC approaches. And if global biomass use is increased in the future and biomass savings are credited for, the system effects of heat demand reductions will lead to lower contributions to global CO₂ emissions.

It is clear that assumptions regarding the present and the future features of the European and the global energy systems have a significant influence on the level of indirect CO₂ emissions caused by Swedish DH systems. The complexity of the dynamics of these features should therefore be considered and discussed when calculating CO₂ emissions.

In this study CO₂ emissions are calculated for DH production. However, it could be reasonable to apply a marginal perspective on DH use, for example when considering the CO₂ emissions yielded by connecting a single additional building to a DH system. This would increase the use of the heat production unit with the highest heat production cost when operated.
A situation where energy efficiency measures in buildings are not implemented in favour of heat and electricity production in DH systems might result in a non-flexible and latched local energy system, with an unnecessarily large energy demand for decades to come, during which the buildings are not refurbished again.

Europe is transforming a coal-based energy system to a system with an increasing use of natural gas and renewable energy sources. This reduces the possibility for Swedish DH production of constituting a carbon sink and the competition for biomass will probably increase from several sectors. Therefore reduced energy demand should generally be considered beneficial and be considered a way to decrease the use of primary resources, and the structure of DH production should be adapted to DH demand rather than the other way around.
10. Conclusions

This chapter summarises the conclusions drawn from the results presented in the summary of this thesis and relates them to the main objectives presented in Section 1.1.

10.1 The impact of changed heat use in MFRBs on the demand for DH

Heat demand reductions were calculated separately for the domestic hot water (DHW) demands and space heating (SH) demands in multi-family residential buildings (MFRBs). SH demand can generally be reduced to a larger extent than heat demand for preparation of DHW. The following conclusions were drawn from the heat demand reduction calculations

- Energy saving measures in district heated MFRBs reduce the total demand for DH and lead to a more levelled annual heat demand profile, because space heating demand reductions are larger for cold seasons than for warm.

- Large-scale implementation of DH use in hot-water-circuit (HWC) household appliances and DH connection of 20,000 new apartments in energy efficient MFRBs increases DH demand only a little in the analysed Uppsala DH system, but contributes to the levelling of the annual DH demand profile.

10.2 The effects of heat demand changes on fuel use, heat production and electricity generation in Swedish DH systems

Twelve DH systems with different DH production unit composition and different fuel use were modelled to investigate how heat demand reductions affect fuel use, DH production, and CHP electricity generation in Swedish DH systems. Scenarios where total heat demands were reduced by 17-20% were investigated and compared for the modelled DH systems. Heat demand reduction changes influence heat and electricity generation differently depending on
the DH systems’ composition of heat production units and the fuels used. The conclusions for the impact of heat demand reductions on fuel use, DH production and CHP electricity generation are

- Mainly peak and intermediate DH load is reduced by heat demand changes due to energy savings in MFRBs. Therefore the DH production that is used mainly is to supply these loads mainly reduced when the heat demand is reduced. Nine of the twelve studied DH systems use fossil-fuelled heat-only boilers for peak load supply, and intermediate load is in all systems supplied by biomass- or fossil-fuelled CHP plants, biomass-fuelled heat-only boilers, or in a few cases industrial waste heat (IWH). Use of fossil fuels and biomass are thus mainly reduced when heat demand is reduced. Incineration of municipal waste and utilisation of IWH are only marginally affected

- CHP electricity generation is affected differently by heat demand reductions depending on what heat load the CHP-produced heat supplies. CHP production is affected more if the CHP production is used to supply intermediate or peak DH load. Otherwise, if CHP production is used mainly for base load production, it is only marginally reduced by heat demand reductions. If heat can be wasted while CHP plants are operated the waste of heat is increases with a reduced heat demand.

- The $\alpha_{\text{system}}$ value constitutes the relation between generated CHP electricity and produced DH for a DH system and reflects the utilisation of the system for the production of CHP electricity. The changes of $\alpha_{\text{system}}$ values due to reduced DH demand depends on the share of CHP production in the heat production mix, CHP-plant $\alpha$ values, and the kind of heat load supplied by CHP plants. If CHP production is used for peak and intermediate heat load, but not base load, the $\alpha_{\text{system}}$ value is decreased when the heat demand is reduced. For DH systems with a share of CHP production close to 100%, the $\alpha_{\text{system}}$ value is only marginally affected by heat demand reductions. Furthermore, if CHP production is mainly used to supply base DH load, the $\alpha_{\text{system}}$ value is generally increased by heat demand reductions.

- When heat demand is reduced step-wise by 5,10,....50% in the entire Swedish DH sector, it is mainly the use of biomass and fossil fuels that is reduced. By a 50% heat demand reduction, fossil fuels are nearly eliminated from the Swedish DH fuel mix and biomass use is halved.
10.3 Changes in global CO\(_2\) emissions due to DH production when heat demand is changed

CO\(_2\) emissions due to DH production were calculated for reference cases and heat demand reduction scenarios by associating CO\(_2\) emission factors to the annual use of each fuel, as well as electricity use and production. Co-generated electricity in CHP units is considered to replace an equal amount of electricity that would have been generated in less efficient power plants elsewhere in the power system if it had not been produced in the CHP units. Two different approaches for CO\(_2\) assessment of electricity use and generation were used; a short-term approach where CHP electricity replaces electricity from coal-condensing (CC) power plants, and a long-term perspective where electricity from natural gas fired combined cycle (NGCC) power plants is replaced. The following was concluded from the CO\(_2\) emission calculations:

- The CO\(_2\) emissions due to DH production depend to a large extent on the approach used for CO\(_2\) assessment of electricity. The characteristics of DH production also influence the emissions significantly.

- For DH systems that produce heat in CHP plants, the CC approach for electricity assessment generally yields lower CO\(_2\) emissions that are less dependent on the fuel used for DH production than the NGCC approach. Thus a high \(\alpha_{\text{system}}\) value is more important in order to yield low levels of emissions when the CC approach is used, while a large share of biomass in the fuel mixes is more important when the NGCC approach is used.

- CO\(_2\) emissions are generally reduced if a heat demand reduction mainly leads to less heat being produced in fossil-fuelled, heat-only boilers. If CHP production is reduced by demand reduction, the emissions are reduced if the fuels that are used yield higher emissions than the emissions reduced elsewhere due to CHP electricity generation. This depends on the type of fuel used, the \(\alpha\) values of the CHP plants, and the approach used for CO\(_2\) assessment of electricity.

- For systems with nearly 100% CHP production and extensive use of biomass, the contribution to global CO\(_2\) emissions due to DH production is increased with a reduced heat demand regardless of the electricity assessment approach used, because less fossil power generation can be replaced.
• When emission reductions due to biomass savings are credited for, CO₂ emissions are reduced by heat-demand reductions for all studied DH systems that use biomass. This is because the saved biomass can be used in CHP plants elsewhere in the energy system to replace fossil fuels.

• Large-scale implementation of HWC household appliances that use DH only marginally affects the heat demand and thus also only marginally affects the CO₂ emissions due to the analysed Uppsala DH system. The small changes in emissions are however clearly dependent on the choice of electricity assessment approach due to the fossil fuelled CHP unit in Uppsala being used to supply intermediate heat load and therefore affected by marginal changes in heat demand.

• If DH demand is reduced step-wise by 5, 10, ..., 50% in all Swedish DH systems, the resulting CO₂ emissions become lower than today for all heat demand reduction levels when the NGCC approach is applied. Swedish DH would even reduce global CO₂ emissions for heat demand reduction levels above 15% when using the NGCC approach because the emissions avoided when CHP electricity replaces other power production are larger than the emissions from fuels used for DH production. The CC approach makes Swedish DH yield such negative CO₂ emissions at the reference demand level and at all heat demand reduction levels, with a maximum reduction of global CO₂ emissions at 20% heat demand reduction. By more than 40% heat-demand reduction, Swedish DH would, however, reduce global CO₂ emissions less than what is done today with the CC approach.

10.4 Overall conclusion
The overall conclusion of the results presented in the summary of this thesis is that the system effects from 17-20% heat demand reductions in Swedish DH systems depend largely on the DH systems’ composition of heat production units and fuels used, and on the approach used for electricity CO₂ assessment. Generally heat demand reductions tend to reduce the use of fossil fuels and biomass, and global CO₂ emissions are in most cases also reduced when considering that lower CHP production means increased other fossil fuelled electricity generation. This indicates that energy savings in MFRBs in most cases are likely to reduce contributions to global CO₂ emissions from Swedish DH production.
11. Further work

The results presented here are valid for DH systems as they function today. But as large-scale energy savings in buildings are not achieved over-night, there is the possibility of adapting DH production to lower heat demands. Further investigation is needed on how Swedish DH systems should be transformed to be better suited for a future energy system with generally more renewable fuels and renewable intermittent power generation, and probably higher fuel costs. This could be done by considering how, and to what extent, existing DH systems can be transformed into 4th generation DH systems [26].

The heat load reductions analysed in the appended papers of this thesis are calculated somewhat roughly. More detailed analyses are needed on how different energy efficiency measures affect the heat demand in different categories of buildings. In addition, the composition of building types might vary between different DH systems. The more complex equations used for heat demand reduction calculations in paper II (Equations 2 to 7) can be used for such analyses.

System effects other than global CO₂ emissions, such as primary energy use, need to be investigated with differences in DH production units between systems taken into consideration. In paper II in this thesis primary energy use is calculated for the Uppsala DH system; similar calculations for the other eleven investigated DH systems, as well as additional systems, would complement the picture.

DH production changes and system effects due to the implementation of hot-water-circuit (HWC) household appliances that use DH need to be investigated further, and for DH systems other than Uppsala. There is also the need to investigate the potential of different DH systems in order to further level annual DH demand profiles by using DH to replace electricity and fuels in applications such as industrial processes and absorption cooling machines, which to some extent have been investigated for individual DH systems and for some regions in [60].

The FMS tool can be further developed by implementing an energy storage feature that allows heat to be stored between time-steps. The FMS structure could also be improved by an extension that includes the possibility of using more than three different fuels, to include cooling and steam demands, and to use more complex energy-flow relations, for example, relate arbitrary energy flows to each other.

In general, further investigations are needed on how global energy resources are optimally utilised in order to reduce climate impact and primary energy
use. The European municipal waste should be treated as a necessary evil and waste production should be minimised, but the optimal locations of waste incineration needs to be investigated, from a European perspective, so that produced heat is utilised in the most effective way. Biomass should also be used in areas and for purposes where it has the best effects. For example, is it possible that biomass might do more good replacing fossil fuels in the transport sector, since other alternatives are few, despite the fact that biomass might be utilised with greater efficiency in a CHP plant? Or is it even more beneficial to combine CHP production with biofuel production, as has been investigated to some extent in [60]. Another example is if DH systems are located near a potential surplus of industrial waste heat (IWH), should they prioritise the utilisation of IWH and refrain from building a CHP plant that prevents IWH utilisation?

Adaptation of energy systems to future conditions requires knowledge, and there are several questions that need to be answered and issues that need to be investigated to gain that knowledge.
12. Svensk sammanfattning

För att förhindra den globala uppvärmningen, eller åtminstone minimera dess konsekvenser, måste medlemsstaterna i EU minska sin primärenergianvändning, släppa ut mindre koldioxid och öka användningen av förnybar energi. Europeiska byggnader har en stor potential för energibesparing och är således en viktig faktor för att reducera den europeiska energianvändningen.

Det har hävdats att energibesparingar i byggnader som värms med fjärrvärmor ökar de globala utsläppen av koldioxid (CO₂) som orsakas av svensk fjärrvärme produktion. Det skulle bero på att mindre elektricitet skulle produceras i kraftvärmeverk på grund av det lägre värmebehovet och den elen skulle behöva ersättas av importerad el från ineffektiva fossileldade europeiska kraftverk med höga CO₂-utsläpp.

I den här avhandlingen studeras den nuvarande svenska fjärrvärmeproduktionens lokala och globala systemeffekter vid förändrade värmebehov i form av ändringar i bränsleanvändning, värme- och kraftvärmeproduktion och koldioxidutsläpp. Tolv fjärrvärmesystem studeras med olika sammansättningar av anläggningar för värme produktion, kraftvärme och tillvaratagande av spillvärme. Åtta system är enskilda svenska fjärrvärmesystem och fyra system är typsystem som är definierade utifrån bränsle-, värme- och kraftvärme- produktionsstatistik för alla svenska fjärrvärmesystem. De fyra typsystemen representerar tillsammans hela den svenska fjärrvärmesektorn.

För att beräkna koldioxidutsläpp används flera olika metoder för att koldioxidvärdering använda. För att koldioxidvärdering använda, används och produceras i svenska fjärrvärmesystem antas indirekt påverka driften av den dyraste elproduktionen som sker i det europeiska kraftsystemet. I ett kortare, nutida, perspektiv kan denna elproduktion antas ske i köllecontainerraddningskraftverk med höga CO₂-utsläpp. I ett längre, framtida, perspektiv är det vanligt att anta att de har ersatts av naturgaseldade kombikondenskraftverk, som har ungefär färre CO₂-utsläpp per producerad enhet elektricitet som kolkraftverken.

Scenarier för minskat värmebehov för rumsuppvärmning och varmvatten i fjärrvärmevärmda flerbostadshus till följd av energieffektiviserings studeras. Dessutom studeras hur fjärrvärmebehandlings aktivitet i Uppsala fjärrvärmesystem påverkas av storskaliga konverterings av vitvaror till att använda fjärrvärme istället för el för uppvärmning av tvättmaskiner, torkumläglare och diskmaskiner samt för drift av värmeförräkningskylskåp. För Uppsalasystemet beräknas också hur värmebehandlings aktivitet påverkas av anslutning av 1000 nybyggda energieffektiva flerbostadshuslägenheter per år mellan 2010 och 2030.
Studierna utförs huvudsakligen med hjälp av kostnadsminimerande energisystemmodellering. Två olika modelleringssverktyg som båda använder optimeringsmetoden linjärprogrammering används. MODEST är en konventionell mjukvara utformad för bland annat fjärrvärmemodellering och optimering av fjärrvärmeproduktion. Ett enklare verktyg är FMS (fixed model structure), som utvecklats inom ramen för denna avhandling och som är anpassat för att modellera fjärrvämesystem med hjälp av relativt lite indata och FMS kan därmed användas för att på kort tid beskriva fjärrvärmeproduktion i flera fjärrvämesystem.

Resultaten som presenteras här visar att energibesparingar i fjärrvärmepuppvärmda byggnader minskar efterfrågan på fjärrvärme och ger mindre variationer i fjärrvärmehovet mellan årtiderna. Konvertering till fjärrvärmemedrivna vitvaror samt anslutning av nya byggnader förändrar Uppsalas fjärrvärmehov i relativt liten utsträckning men kan ändå ha en viss påverkan på värmekraftvärmeproduktionen och följdäckligen även på koldioxidutsläppen. Värmebehovsreduceringar leder främst till minskad användning av fossila bränslen och biobränsle för fjärrvärmeproduktion medan avfallsförbränning och utnyttjande av industriell spillvärme bara påverkas i liten utsträckning. Kraftvärmeproduktion minskar nämnvärt om andelen kraftvärme i fjärrvämesystemet är stor, eller om kraftvärme används för att täcka mellanlast eller topplast, som främst förekommer under vintern. \( \alpha_{\text{system}} \) värdet (som är förhållandet mellan årliga kraftvärmeproducerad el och totalt producerad fjärrvärme i systemet) ökar när värmebehovet minskar om kraftvären huvudsakligen förorsöker baslasten i systemet.

De beräknade \( \text{CO}_2 \)-utsläppen på grund av fjärrvärmeproduktion beror på vilken metod som används för koldioxidvärdering av el och utsläppen minskar generellt då värmebehovet minskar, utom då fjärrvärmen till stor del produceras i kraftvärmeverk och utsläppen från lokal bränsleanvändning minskar mindre än vad utsläppen från ineffektiva europeiska kraftverk ökar då mindre kraftvärmee-el produceras. Generellt minskar koldioxidutsläppen som orsakas av svenska fjärrvämesystem då värmebehovet reduceras om kraftvärmefråns cräms främst används för att förorsöka baslasten.

För hela den svenska fjärrvärmesektorn sammantaget gäller att ett reducerat värmebehov leder till att fjärrvärmeproduktionen orsakar lägre \( \text{CO}_2 \)-utsläpp oavsett vilket perspektiv som används för koldioxidvärdering av el. Dessutom visar resultaten att svensk fjärrvärmeproduktion utgör en kolsänka, dvs att de globala \( \text{CO}_2 \)-utsläppen skulle ha varit högre om fjärrvärme inte producerats i Sverige, oavsett om värmebehovsminskning sker eller inte, om el från kolkondenskraftverk antas trängas undan av kraftvärmeproducerad el. Om istället el från naturgas-kombikraftverk antas trängas upp medan värmebehovsminskningar över 15% till att svensk fjärrvärmeproduktion utgör en kolsänka.

Om det beaktas att det biobränsle som inte behövs för fjärrvärmeproduktion kan ersätta fossila bränslen någon annanstans i energisystemet innebär
minskat värmebehov även minskade CO2-utsläpp för alla de enskilda studerade fjärrvärmesystemen.
Acknowledgements

First I would like to thank my main supervisor, professor Ewa Wäckelgård, who gave me the opportunity to write this thesis and to learn about energy in buildings and district heating. I appreciate that you always take time for discussion, both concerning energy systems, and concerning other issues in life, especially life with four children. I also appreciate your patience when family-related issues have interfered with work.

Dag Henning, my co-supervisor and co-writer, I am grateful for all the phone calls you have answered on week nights, week-ends, during vacations, and even when you are attending wedding dinners (!!!). You taught me most of what I know about energy, district heating, and energy system modelling. I admire your patience with all my questions. Your contributions to this thesis have been most important and I hope our collaboration will continue.

Joakim Widén, my on-site co-supervisor and former PhD-student colleague, I apologise for all the monologues that you have had to listen to, while I ventilated my mind. But sometimes I let you talk as well, right? Your skills as a researcher, course administrator, and scientific writer amaze me. Your contribution to this thesis as co-supervisor, colleague and co-writer are most appreciated.

Thanks to Lars Fälting and Anders Forssell for interesting collaboration this far, and hopefully there is more to come.

I thank Anna Karlsson, Andreas Larsson and Jan Zetterberg at Vattenfall Heat Uppsala for providing me with data from the district heating system in Uppsala.

Thanks to Dick Magnusson for helping me with Figure 5.1.

I would like to thank all the rest of my colleagues at the Division of Solid State Physics for providing a good work atmosphere, and nice coffee breaks. I especially thank the members of the BEESG group; Annica, Joakim W, Joakim M, David, Rasmus, and Ewa.

Everyone involved in the Energy Systems Programme deserves to be mentioned here and especially all my fellow PhD students, many whom today are PhDs. Thank you for inspiring discussions during meetings and courses in the first couple of years of this project.

Thanks to Arne Roos and Roberta Aplin Roos for helping me with language corrections and valuable comments on the thesis content. I appreciate that you were patient with me even though I was late with the language-check request, and that the final couple of weeks writing the thesis were a bit chaotic.
Mats Gustafsson at the Department of Medical Sciences, Cancer Pharmacology and Computational Medicine, thank you for initially getting me interested in research. I am most grateful that I had such an inspiring supervisor while working on my masters thesis.

Outside the walls that are surrounding the area of energy systems research I would like to say hi to my parents and to my brother and sister and their families, thanks for all the years of support. All my valuable friends and their families, you know who you are, and without you life would be dull.

Finally, and most importantly, I would like to thank my wife Sofia; you are absolutely amazing. I am impressed with what you have achieved the last couple of years and what we achieve as a family each day. I love you!

I am also grateful to get to share house and life with my four children Noel, Vilhelm, Agnes, and Emma. I love you all, for who you are, for putting things into perspective, and for constantly reminding me of the unpredictability of life.
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