HEAT DEMAND PROFILES OF BUILDINGS' ENERGY CONSERVATION MEASURES AND THEIR IMPACT ON RENEWABLE AND RESOURCE EFFICIENT DISTRICT HEATING SYSTEMS

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School of Business, Society and Engineering
To my family
Acknowledgements

I would like to thank my supervisors Prof. Erik Dahlquist, Dr. Fredrik Wallin, Prof. Björn Karlsson and Dr. Jan Akander for their guidance and support in my academic struggles. My company mentors Jan Helgesson (Eskilstuna Kommunfastigheter) and Ulf Björklund (Eskilstuna Strängnäs Energy and Environment) for introductions and guidance in company activities. An extra thanks to Jan Helgesson, my boss at Eskilstuna Kommunfastigheter, for his support and great patience with my research work. My PhD project steering group members Magnus Widing, Kristina Birath, Lotta Niva and Riikka Vilkuna for helping me understand how Eskilstuna City’s and its companies are working with energy and environmental issues. My colleagues at Mälardalen University, Reesbe research school and Eskilstuna Kommunfasigheter for interesting discussions about research and other more or less urgent topics. My family, Jessika and Lovis, for making life great.

This thesis is based on work conducted within the industrial post-graduate school Reesbe – Resource-Efficient Energy Systems in the Built Environment. The projects in Reesbe are aimed at key issues in the interface between the business responsibilities of different actors in order to find common solutions for improving energy efficiency that are resource-efficient in terms of primary energy and low environmental impact.

The research groups that participate are Energy Systems at the University of Gävle, Energy and Environmental Technology at the Mälardalen University, and Energy and Environmental Technology at the Dalarna University. Reesbe is an effort in close co-operation with the industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).

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Summary

Increased energy performance of buildings is seen as an important measure towards mitigating climate change, increasing resource utilisation efficiency and energy supply security. Whether to improve the supply-side, the demand-side or both is an open issue. This conflict is even more apparent in countries such as Sweden with a high penetration of district heating (DH). Many Swedish DH systems utilise a high share of secondary energy resources such as forest industry residuals, waste material incineration and waste heat, as well as resource efficient cogeneration of electricity in combined heat and power (CHP) plants. The effect of implementing ECMs on the DH system’s heat and electricity production under different electricity revenue scenarios is computed and evaluated in terms of resource efficiency and CO2 emissions.

These complex relationships are investigated via a case study on the Eskilstuna DH system, a renewable energy supply system with a relatively high share of cogenerated electricity. Heat demand profiles of ECMs are determined by building energy simulation, using recently deep energy retrofitted multifamily buildings of the “Million Programme”-era in Eskilstuna as model basis. How implementing ECMs impact on the DH system’s heat and electricity production under different electricity revenue scenarios has been computed and evaluated in terms of resource efficiency and CO2 emissions.

The results show that different ECMs impact differently on the DH system. Measures such as improved insulation level of the building’s envelope, which decrease the heat demand’s dependence on outdoor temperature, increase the amount of cogenerated electricity. Measures such as thermal solar panels, which save heat during summer, have a negative effect on the absolute amount of cogenerated electricity. Revenues from cogenerated electricity influence the amount of cost-effectively produced electricity much more than the impact from ECMs. Environmental benefits of ECMs are relatively small in low CO2 emitting and low PE content DH systems with electricity cogeneration. The consequences can even be negative if ECMs lead to increased electricity production by fossil fuel condensing plants. However, all the studied ECMs increase the relative amount of cogenerated electricity, i.e. the ratio of the amount of cogenerated electricity to the heat load. This implies that all the studied ECMs increase the overall efficiency of the Eskilstuna DH system.
Sammanfattning

Att förbättra byggnaders energiprestanda ses som en viktig del i arbetet att minska växthusgasutsläppen, öka resurseffektiviteten och minska energiberoendet. Är det mera fördelaktigt att minska byggnadernas energiförbrukning eller ska fokus ligga på att förbättra energisystemet? Denna frågeställning är skärsskilt angelägen i länder som Sverige med en hög andel av fjärrvärme. Den Svenska fjärrvärmesektorn försörjs redan idag till en stor del av sekundära och förnybara energiresurser såsom restprodukter från skogsindustrin, avfallsförbränning och industriellspillvärme. Även samproduktion av värme och el i kraftvärmeverk är vanligt förekommande. Energieffektivisering i byggnadsbeståndet påverkar driften av fjärrvärmesystemet. Om samproduktion av el minskar på grund av energieffektivisering, och denna el värderas högre än bränslebesparing, så skulle konsekvenserna vara negativa.

I denna avhandling studeras dessa komplexa förhållanden genom en fallstudie av Eskilstunas fjärrvärmesystem, ett biobränsle baserat energiförsörjningssystem med relativt hög andel kraftvärme. Säsongprofiler för energieffektiviseringsåtgärder har bestämts med hjälp att energisimulering baserade på nyligen grundrenoverade flerfamiljshus av miljonprogramstyp, belägna i Eskilstuna. Hur energieffektiviseringsåtgärder påverkar fjärrvärmesystemet värmee- och elproduktion under olika elintäktsscenarier har beräknats och bedömts i avseende resurseffektivitet och koldioxidutsläpp.

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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.


II. Lundström L. and Song J. Seasonal Dependent Assessment of Energy Conservation within District Heating Areas, Stockholm: Svensk Fjärrvärme; 2014


My contributions

• Paper I and III – all modelling, calculations, visualisation and most of the writing
• Paper II – all modelling and calculations except the parts concerning price models, and half of the writing.
List of papers not included


II. Dahlquist E., Vassileva I., Campillo J. and Lundström L. Energy efficiency improvements by renovation actions: in Lagersberg and Råbergstorp, Stoke on Trent and Allingsås. Mälardalen University, Forskningsrapport 2016:1


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Nomenclature
DH District heating
HO Heat only (boiler)
CHP Combined heat and power
FGC Flue gas condensing
ECM Energy conservation measure
HDD Heating degree days
TMY Typical meteorological year
SEK Swedish currency
SD Standard deviation
PE Primary energy
CO2 Carbon dioxide
PV Photovoltaic
α Electricity-to-heat output ratio for a CHP plant
α-system Electricity-to-heat output ratio for a whole DH system

Million Programme
Buildings built during 1965–1975, forming a large part of
the Swedish current building stock
Nomenclature

<table>
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<td>HO</td>
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<td>CHP</td>
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<td>FGC</td>
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Introduction

Increased energy performance of the building stock of the European Union is seen as an important measure towards mitigating climate change, increasing resource utilisation efficiency and energy supply security [1], [2]. Whether to improve the supply-side, the demand-side or both is an open issue. This conflict is even more apparent in countries such as Sweden that have a high penetration of district heating (DH). Many Swedish DH systems have a high share of secondary energy resources such as forest industry residuals, waste material incineration and waste heat, as well as resource efficient cogeneration of electricity in combined heat and power (CHP) plants.

Implementing an energy conservation measure (ECM) in a DH connected building stock will affect the operation of the whole DH system. If there are CHP plants and the cogeneration of electricity decreases due to an ECM, and this electricity is valued higher than the fuel savings, the ECM would have negative consequences. These complex relationships are investigated here via a case study on the Eskilstuna DH system, a renewable energy supply system with a relatively high share of cogenerated electricity.

1.1 Previous research

Gustavsson's articles from 1994 [3], [4] form a comprehensive study of demand-side energy conservation within Swedish DH systems and deal with issues that are still of concern today. It was estimated that there was a 30-60% energy conservation potential (considering marginal operating costs and avoided future investments in DH production); that energy conservation would alter the shape of the heat load duration curve in a favourable way; and that increased share of biomass fuels and cogeneration of heat and electricity would decrease fossil CO2 emission rates.

In more recent papers [5]–[13] climate change mitigation, demand-side ECMs and their impact on CHP plant operation have come into focus. Difs et al. [5] studied demand-side ECMs in the DH system of Linköping, Sweden, and their different impacts, considering local direct impact (from combustion) and global indirect impact (the consequence of cogenerated electricity being displaced by an assumed standalone and fossil based electricity production). They showed that even if ECMs reduce direct CO2 emissions, total (direct and indirect) CO2 emission impact of some ECMs could be close to zero.
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Gustavsson et al. [6] and Truong et al. [7] investigated building ECMs and how these would have an impact on primary energy usage under different DH production configurations, considering the interactions between energy demand of the buildings and CHP plant operation. They demonstrated that electricity saving measures in buildings connected to DH systems with a high share of CHP production yield high primary energy savings, mostly due to the electricity saving itself, but also partly due to increased cogeneration of electricity as saved electricity in buildings gives rise to new heat demand. Heat recovery ventilation measures had a less favourable impact, partly due to increased electricity demand at the building level.

DH systems differ in composition of production units as well as the fuel mix (see Figure 6), making it problematic to generalise results from case studies. Åberg [8] conducted a study where the Swedish DH sector was grouped into four typical systems. The results show a general reduction of total CO\textsubscript{2} emissions in the Swedish DH sector due to demand-side ECMs, but also that the reduction potential depends on the configuration of the DH system.

Harrestrup and Svendsen [9] showed in a Danish study that ECMs that decrease the peak load could enable lower supply temperatures in the DH system, which increases possibilities for inclusion of renewable energy sources such as geothermal. The same authors [10] studied the DH system of Copenhagen, where they concluded that in order to reach Danish energy targets, it would cost roughly the same to increase demand-side efficiency as it would to mitigate the supply side to renewable production. It was argued that rapid implementation of demand-side ECMs could be a better option, as this could avoid a future situation where there is an excess of renewable production capacity.

Klobut et al. [11] stated that the Finnish specific energy consumption of buildings heated by DH has decreased by 50\% over a 35 year period, and this trend is expected to continue in light of energy policies issued by the EU and its member states. The authors also concluded that today’s DH sector might not be competitive when considering a future low density heat market, especially if the sector does not increase its rate of development. Magnusson [14] argues that Sweden’s old and established DH sector is heading towards a phase of stagnation, or even a phase of declining heat loads. This is due to increased energy performance in both new and retrofitted buildings; market saturation in the key sector, multi-dwelling buildings; and competition from other heating systems.

Jennings [15] states that from a UK perspective “There is a primary conflict when considering the impact of an energy system retrofit decision in buildings: whether to improve the efficiency of supply-side technologies, or whether to invest in demand-side technologies with the intention of reducing primary energy requirements, and maintaining the embedded value of the incumbent supply-side technologies”. As pointed out by Gustavsson [3], [4],
this conflict between supply and demand sides may be more difficult to manage for DH systems compared to other types of supply-side technologies due to capital intensive investments and limited possibilities of alternative use. Nässén and Holmberg [12] modelled how the potential trade-offs between supply-side and demand-side technologies, in Sweden, depend on climate policy and energy prices. In a scenario where traditional condensing power dominates together with high CO₂ emission allowances prices, the results show high profitability for CHP plants and therefore little incentive to reduce heat demand. In contrast, a scenario where electricity production alternatives with low CO₂ emissions are available would promote ECMs within DH networks.

1.2 Research questions

None of the reviewed articles studies the effect of demand-side ECMs in fully renewable DH systems with high share of cogeneration of electricity. This thesis fills this knowledge gap by investigates such DH-system, using Eskilstuna city as a case study:

**Q1.** What are the differences in impacts of different ECMs on the DH operation?

**Q2.** What are the benefits of ECMs in buildings connected to renewable and resource efficient DH systems?

1.3 Objectives

The objectives are as follows:

- Determine heat demand profiles of ECMs by simulation of buildings energy demand. By using recently deep energy retrofitted multifamily buildings of the “Million Programme”-era in Eskilstuna as model basis;

- Create a model of the Eskilstuna DH system investigating:
  - the DH system interaction with the buildings’ heat demand and ECMs;
  - the interaction between heat load and system temperatures;
  - the production dependence on weather conditions;
  - the production dependence on electricity revenues
  - Estimate ECMs’ impact on heat and electricity production under different electricity revenue scenarios and evaluate the results in terms of resource efficiency and CO₂ emissions
1.4 Scope and delimitation

The developed building energy model is based on existing multifamily build-

ings of the “Million Programme”-era located in the mid-Sweden climate area.

Approximately 50% of the Eskilstuna DH system’s heat demand comes from

multifamily buildings. Roughly 75% of Swedish multifamily buildings were

built before the 1980s [16], and a major proportion of these can be classified

as “Million Programme”-era buildings. The modelled building type and its

derived ECM profiles would therefore be expected to represent a large pro-

portion of future DH load reductions. Many of the studied ECMs would have

similar heat demand profiles if implemented on other types of buildings in

similar climatic conditions.

The study on impacts in the DH system was based on a model of the Eskils-

tuna DH system, which uses almost 100% renewable fuel sources and has

electricity cogeneration. The results are therefore not easily generalisable to

other current DH systems, but in the future, more DH systems are likely to

have similar characteristics. Eskilstuna is currently in a situation many cities

are expected to be in in the future.

A heat storage tank exists in the real DH system, which it is not included

in the model. The heat storage is mainly used to level out diurnal variations.
By using daily average values, it is assumed that the function of the heat stor-
age is reasonable well modelled. The operational cost of the DH system is

calculated but only for the purpose of optimising the order of operation of the

plants. Investment cost for ECMs is discussed in the context of feasibility of

the technical energy conservation potentials. But no investment cost calcula-
tions are conducted on either the building nor on the DH system side.

1.5 Thesis outline

The main contributions of this thesis consist of the following, corresponding
to the appended papers: Paper I investigates different commonly used methods
for assessing and allocating CO2 emission rate and presents the results for the
100 largest Swedish DH networks. Paper II constitutes the groundwork on
which paper III builds. Papers II & III describe a method developed for cor-
recting DH heat loads to a typical meteorological year (TMY), a DH system
optimisation model and heat demand profiles of ECMs in multifamily dwell-
ings; and studies the marginal impact on the DH system and performs CO2
and primary energy evaluation. This thesis contains material that has not been
published in the attached papers: Sections “3.2.2 Spreadsheet calculation
model” and “3.3 The electricity price model” describes new methods that are
not used in the papers; Sections “4.1 Potential of energy conservation
measures”, “4.3 Impact on DH system temperatures”, “4.4 Electricity revenue
scenarios” present results that are not part of the papers.
2 Background

This chapter presents the background to the research presented in this thesis. Section 2.1 presents energy use in buildings in the form of buildings’ energy balance, and describes energy conservation measures. Section 2.3 briefly presents DH systems. Section 2.4 walks through energy use assessment approaches. Section 2.5 describes the case study on Eskilstuna City.

2.1 Energy use in buildings

Understanding building’s energy balances is crucial to understanding DH systems’ operation strategies and long-term development, and gives insights into existing energy conservation potentials and how these can affect DH systems. Thermodynamic laws state that energy is always conserved. When energy is “consumed” in economic terms, it actually implies it has changed from higher valued to lower valued energy (i.e. the quality of energy is reduced). However, energy can cross a certain defined system boundary, resulting in “energy losses” for the specific system. A building’s energy balance is the relationship between energy supply and energy losses (energy leaving the building maybe in a changed form).

![Image](image.png)

*Figure 1. A building’s energy balance and system boundary.*
Figure 1 shows a building’s energy balance with the system boundary set as the building site. The building has requirements that need to be satisfied to maintain a good indoor environment. Space heating and cooling are supplied to keep the temperature within comfortable limits, for example between 20-25°C during the heating season and < 25°C during the cooling season. A certain exchange rate of new outdoor air is required to maintain fresh indoor air. The outdoor air may need to be heated, cooled and/or (de)-humidified to maintain indoor comfort. Hot water is needed for showering, dish washing, etc. Electricity is needed for lighting and appliances and for the building service systems. Most electricity used for household appliances ends up as heat, either as a gain or as load. Electricity dissipated as heat, e.g. from an exhaust fan motor or outdoor lighting, will not add to the heat gain/load, and will be lost as heat to the environment. Choice of window placement and glazing properties influence the amount of passive heat gain/load from insulation. On-site energy collectors/converters such as photovoltaic (PV) panels, thermal solar panels, wind turbines or heat sources/sinks of heat pump systems can be used to alter the need for supplied energy to the building. Surplus from on-site generated energy can also be exported, most commonly electricity from PV panels.

Figure 2. The studied multifamily building’s energy balance as a smoothed duration plot. (Y-axis shows power per square meter of floor and x-axis show duration in days.)
An energy balance of a typical multifamily building of the Swedish “Million Programme”-era which has not been renovated is shown in Figure 2 (see Section 3.3 for more details about the buildings). The positive side of the y-axis shows the energy supply streams, and the negative side of the y-axis shows the leaving energy streams (the losses).

Space heating, domestic hot water supply and distribution form the heat demand of the building – which constitutes the available heat market for DH suppliers. The outdoor temperature at which the building does not need any more space heating is referred to as the building’s balance temperature. Heat gain from solar, occupants and electricity decreases the heat demand. Heat storage in internal mass (not shown in the figure) also contributes to decreasing heat demand. Heat demand can be decreased further by reducing domestic hot water consumption and distribution losses; improved insulation of the envelope; heat recovery ventilation; increasing heat gains from electricity or insulation through windows or by better control schemes for less overheating. The building’s heat demand can be decreased more actively by on-site energy collectors such as thermal solar panels or ambient air heat exchangers. Heat pumps are designed to move heat opposite to the direction of spontaneous heat flow by absorbing heat from a colder space and releasing it to a warmer one. In order to achieve this heat transfer, a certain amount of higher quality energy (usually electricity) is consumed. In the context of retrofitting multifamily buildings, exhaust air from the ventilation system is the most likely candidate as a heat source for the heat pump. Boreholes, ambient air, lakes and rivers can also be used as heat sources.

2.2 Energy conservation measures

The building sector in the EU has been identified as having a large energy saving potential. The energy performance of buildings directive (2010/31/EU) requires that all new buildings must be nearly zero energy buildings by 2020 and that member countries shall set minimum energy performance requirements for new buildings as well as for deep renovation of buildings including replacement or retrofit of building elements. The specific energy consumption of buildings heated by DH has fallen in recent decades [11], and this trend can be expected to continue in light of energy policies and visions by the EU and its member states. The energy balance figure of a multifamily building ( ) in the previous section provides an overview of where there is technical potential for energy conservation. If an ECM is to take place, the property owner has to believe that it is profitable. Therefore, cost-effective (from the property owner’s perspective) energy saving potentials are of main interest as these will form the largest part of future energy savings. Based on modelling results from [17], Figure 3 shows estimates of the energy saving potentials for the Swedish residential sector. Improving the insulation level of the building envelope is
estimated to not be cost-effective, while reducing indoor temperature is estimated to have quite a large cost-effective energy saving potential.

![Figure 3. Estimate of energy saving potentials for the Swedish residential sector. (Grey bars denote the technically possible potential; and dark bars the amount of these that are cost-effective. Data source is modelling results by É. Mata et al [17].)](image)

2.3 District heating

District heating is a technical system with centralised heat production and a network of pipelines using hot water as an energy carrier to distribute heat to end users. The product can also be cooling, in which case chilled water is distributed. A driving force for DH is its ability to provide heat in urban areas from centralised production units in a more resource efficient way than would be the case with separate heat production units at each site. DH makes it possible to utilise lower valued resources such as industrial surplus heat, bulky residual biomass and waste materials, thereby contributing to improved total energy system efficiency by avoiding the use of high exergy fuels and by offering distribution possibilities for surplus heat. Resource utilisation is further improved by cogeneration of heat and electricity at CHP plants. In a CHP plant, electricity and heat/steam are generated simultaneously in an integrated
system from the same input fuel supply, thus improving the resource utilisation rate compared to separate heat and electricity production.

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Figure 4 illustrates the energy balance and system boundaries of a DH connected building stock. Operation of the buildings typically requires heat, cooling, and electricity. Some is locally generated on the building site, e.g. passive solar heat gains through windows or actively through PV and thermal solar panels. In some cases, on-site production can be exported to nearby buildings. Heating and cooling brought from the surroundings by a heat pump is also classifiable as on-site resources. The ‘Nearby’ in Figure 4 denotes the urban area connected to the same DH network. This level also denotes the level at which the DH system operates. Heat, cooling, electricity and other products are produced in centralised plants. The heat can be a by-product of a nearby industrial process, i.e. industrial waste heat.

Most urban areas depend on import (the ‘Distant’ in the figure) of fuel and electricity. Fuels are imported from both near and far. In the case of bulky biomass, these are usually relatively local but may also be imported from other countries depending on logistical possibilities and prices. In Sweden, all fossil fuels are imported from other countries, while Sweden produces roughly the same amount of electricity as it consumes. The electricity production and consumption in the Nordic countries is integrated, and electricity supplied to a Swedish urban area can, for example, be defined as a mix of Nordic electricity production. A CHP plant in the DH system of an urban area will increase the amount of needed fuels but decrease the need for electricity. Energy conservation measures in the building stock will affect the DH system’s heat load and thus the fuels and electricity flows through the system borders.
DH systems exist in most countries, but predominate in Nordic countries as well as countries of the former Soviet Union. In most of these countries, DH has a heat market share of over 40% of the building stock [18]. Today China shows the fastest DH sector growth and there is also potential for DH sector growth in many Central and Western European countries [19], [20]. Many DH systems of the Nordic countries have reached saturation (stagnating or declining heat loads) and are addressing new issues when heat demand savings can no longer be met by extending the DH network [14]. As shown in Figure 5, today’s Swedish DH systems have: to a large extent mitigated from fossil fuels; increased the share of CHP production; and slowed its expansion.

2.4 Energy quality and environmental impact assessment

Here energy usage assessment is grouped into four principal approaches:

- Primary energy
- Climate change impact
- Non climate change related environmental impact
- Energy quality
Primary energy (PE) refers to energy resources in a form that has not been subject to any conversion or transformation. Examples of primary energy resources are unrefined fuels, uranium, wind energy and solar radiation. A PE-factor measures resource efficiency and is defined as the amount (heat content equivalents) of PE needed to deliver one unit of energy useful for human society, so called secondary energy or energy carriers. Examples of energy carriers are electricity, refined oil and water distributing heat or cooling in a DH network. PE-factors can also include a life cycle analysis part, where energy sources such as forest residuals are given low PE content. This approach is justified through the claim that these resources would otherwise remain unexploited in the forest and thereby be wasted. Additionally, resources such as solar or wind energy are often given a low PE-factor as these resources can be considered to be practically unlimited.

Figure 6. CO₂ emission factors for district heating for the 100 largest Swedish district heating networks. (X-axis shows electricity-to-heat output ratio (α-system). Size of bubbles indicates amount of supplied heat. (a) Emissions are allocated by the efficiency method and (b & c) includes both direct and indirect emissions. Eskilstuna district heating system is marked in red.)

Impact on climate change is measured as emitted CO₂ equivalents in relation to the amount of supplied energy. A related metric is the share of fossil fuels, which is measured as energy input in the form of coal, fossil oil and natural gas in relation to energy delivered. Burning biomass for energy purposes is commonly assumed to be CO₂ neutral, based on the premise that as long as the total biomass is not decreasing, the same amount as the released carbon is captured by biomass growth. Figure 6 shows results from paper I where CO₂ emission factors for district heating are calculated by different commonly used methods, described as follows. The ‘efficiency method’ (subfigure Figure 6a) takes into account that more fuel would be consumed if the electricity and heat were produced separately, and thereby allocates more of the fuels/emissions
to the cogenerated electricity than would be the case with energy content allocation [21]. Subfigures b & c consider indirect CO2 emission by assuming that the cogenerated electricity of the DH network is replacing grid electricity production with CO2 emission factors of 100 and 800 kg/MWh. These values roughly correspond to the average Nordic electricity mix and an assumed marginal production based on coal condensing plants respectively.

Energy quality refers to how useful a unit of energy is to human society, i.e. the ability to produce goods and services [22]. Energy is measured by the heat content because all forms of energy can be completely converted to heat in an easy and well-defined way. However, this metric does not account for quality differences between energy carriers; a unit of electricity has the same value as a unit of heat. This is not entirely fair since electricity can be used for tasks that heat cannot, and can also perform tasks more effectively. Exergy is a concept that is used to express energy quality, and is defined as the maximum useful work that can be done by a system as it approaches thermodynamic equilibrium with its surroundings [23]. Electricity is 100% recoverable as work and therefore has exergy to energy ratio of 1 [24]. The exergy to energy ratio of heat is given by the Carnot maximum thermal efficiency formula:

$$\eta_C = 1 - \frac{T_C}{T_H},$$

where temperatures are given in Kelvin, $T_H$ denotes a hot reservoir and $T_C$ denotes a cold reservoir. District heating with a 50°C temperature difference between the supply and return pipes has an exergy to energy ratio of about 0.14, indicating that the exergy content of a unit of electricity is about 7 times higher than in a unit of district heating. The weakness of the exergy concept is that it does not vary with energy density, cleanness, conversion efficiency, etc., and hence does not necessarily reflect qualities of energy forms that determine their economic usefulness or environmental impact. Karlsson et al [24] suggest that practical conversion efficiencies should be considered when determining quality differences between energy carriers.

A heat pump with a thermodynamic efficiency ($\eta_{TD}$) of 50%, $T_H = 75^\circ C$ and $T_C = 25^\circ C$ has a coefficient of performance of $\text{COP}_{HP} = \eta_{TD} * \frac{T_H}{(T_H - T_C)} = 3.5$. This implies that a unit of electricity can provide roughly 3.5 times more useful heating than a unit of district heating, and therefore can be seen as having a 3.5 times higher “practical heating value”.

### 2.5 Case study on Eskilstuna city

Eskilstuna municipality is situated in mid-Sweden and has a population of 100,000 people. Most buildings in the Eskilstuna-Torshälla urban area (roughly 70,000 people) are connected to the DH network. In 2012, DH end consumption was distributed as follows: 47% to multifamily buildings, 15% to single-family houses, 9% to industry and 25% to offices and public spaces.

The DH system produces about 770 GWh of heat annually and the daily mean peak heat load is about 220 MW at an outdoor temperature of -14°C.
(long-term average of the heating season’s three coldest days). The CHP plant can cogenerate about 200 GWh of electricity annually, and is almost 100% renewable, as it uses biomass fuel and bio-oil. Figure 7 shows the order of operation of plants and the heat load duration for a typical meteorological year. Figure 6 show Eskilstuna’s CO₂ emission rate and electricity-to-heat output ratio compared to other Swedish DH systems.

![Duration plot of the studied Eskilstuna district heating system.](image)

*Figure 7. Duration plot of the studied Eskilstuna district heating system. (Heat load is for a typical meteorological year.*)*
3 Methodology and description of models and methods

The building energy model and energy conservation measures (ECMs) described in Section 3.1 are modelled and simulated with IDA ICE, a whole-year detailed and dynamic multi-zone simulation tool for studying energy consumption as well as the thermal indoor climate. Paper II and paper III use Matlab Optimization Toolbox for modelling the Eskilstuna DH system and computing the production mix optimisation (Section 3.2.1). In this thesis, the DH system is modelled separately with a spreadsheet tool called LAVA2 (Section 3.2.2). This move was motivated by the freely availability and customisability of LAVA2. It can be easily customised and has the capability to calculate the system temperature impact. Statistical modelling using the R programming language is used for the electricity price model (Section 3.3) and the weather correction method (Section 3.4). Visualisation of results is done using the R package ggplot2 by Wickham [25], a tool that builds on the “Grammar of Graphics” concept for abstracting graphics to make thinking, reasoning and communicating graphics easier. System analysis is conducted to study the impact of ECMs in buildings on the DH system. The impact is evaluated in terms of primary energy efficiency and CO2 emission rates. Rather than focusing on individual parts (e.g. ECM in a building), system analysis focuses on the whole and the internal relations between system parts.
3.1 Building energy model

Building energy modelling is the procedure of creating a virtual replica of a building. Energy modelling can for example be used to demonstrate compliance with regulations; to predict energy consumption of a proposed building design; for life cycle cost analyses by comparing different building design alternatives to determine which is most cost-effective; or for energy retrofit analysis by predicting savings associated to proposed ECMs.

An energy model comprises of many sub-models describing building component parts such as walls, windows, equipment, heat supply system, etc. These sub-models consist of differential equations describing heat and mass transfer modes, parameters that govern these processes (e.g. thermal conductivity) and of interfaces describing interactions with other sub-models. A simulation is performed by taking the model through weather conditions of a particular period, e.g. a typical meteorological year.

Figure 9. The existing multifamily buildings in Lagersberg, Eskilstuna. (The red circle marks buildings that are part of the Lagersberg renovation project. Red arrows show the two buildings used as basis for the energy model. Photo: Eskilstuna Kommunfastighet.)

The building energy model is described and applied in paper III. The geometrical model is based on two existing multifamily residential buildings in the Lagersberg district in Eskilstuna, Sweden (see Figure 9). The buildings are typical of the early Swedish “Million Homes Programme”-era of the 60s and 70s. They share a DH substation, are 4 floors high (the ground floor has common spaces such as storage rooms and garages), consist of 6900 m² heated floor area and have external walls of aerated concrete. The buildings are part of a larger district renovation project that consists of 23 similar buildings. They have recently been renovated with the goal of reducing the bought energy by half. There are two technical reports [26], [27] available with detailed descriptions of the buildings, the renovation process and outcome.
The simulation is performed with the IDA ICE 4.6 software. The energy model’s specific energy consumption is based on all 23 buildings of the Lagersberg district renovation project. The baseline model’s specific electricity consumption is as follows: 26 kWh/m²,y household electricity and 19 kWh/m²,y facility electricity. District heating specific consumption is 30 kWh/m²,y for domestic hot water, 8 kWh/m²,y for heat losses (distribution and hot water recirculation) and 100 kWh/m²,y for space heating. The model’s ground area is 1810 m², envelope area is 7360 m², envelope area per volume is 0.38 m²/m³, window/envelope ratio is 13%, the average U-value is 0.87 W/K,m² and ventilation consists of mechanical exhaust air at 0.39 l/s,m². The original buildings had a poorly performing exhaust and return ventilation system with heat recovery which is not included in the baseline model.

Eight different ECMs (Table 1) are modelled and simulated – all of which, except for the exhaust air heat pump and ‘Household electricity’, have been applied at the Lagersberg renovation project.

| Table 1. The eight ECMs that are modelled. |
|-------------------|----------------------------------|
| ECM               | Modelled as                               |
| Building envelope | 5 cm additional insulation on façades, 10 cm extra on attic, additional insulated glass units in windows. A total U-value decrease of 32% |
| Heat recovery ventilation | Heat recovery efficiency set to 80%, frost protection set point at 0°C, supply air flow at 0.35 l/s,m² floor area, exhaust air flow set 5% higher than supply air flow, specific fan power at 1.25 kW/m³,s for both fans (doubled electricity consumption compared to baseline model) |
| Household electricity | 20% annual increase of household electricity consumption, distributed accordingly to the historical consumption pattern. Increased electricity consumption leads to decreased heat demand |
| Indoor temperature | 1°C lower indoor temperature. Motivated by the effect of a better control scheme resulting in a more even indoor temperature in different parts of the building, therefore allowing for an overall lower indoor temperature |
| Domestic hot water | A 20% uniformly distributed yearly decrease, appearing as a straight line when average daily domestic hot water savings is plotted against time as diurnal variations are evened out |
| Exhaust air heat pump | Supplies heat for both space heating and domestic hot water, dimensioned to take 1/3 of the exhaust air flow and connected to a 1 m³ stratification tank |
| Operational optimisation | Difference between an ideal controller and a more realistic one which does not adapt as quickly to passive heat gains or rapid temperature changes |
| Thermal solar | Delivers heat for both space heating and domestic hot water, dimensioned to match domestic hot water consumption during the summer season |
3.2 District heating models

3.2.1 Cost optimisation model

Optimisation refers to a branch of applied mathematics concerned with the minimisation or maximisation of an objective function, usually under certain constraints. Often used as tool to resolve how to allocate scarce resources optimally, but can be used for any problem that can be stated with an objective function. Cost optimisation is used to determine the DH production mix. The production cost of a DH system with CHP units can be described by the cost function

\[ y = \sum_{i}^{n} (x_i \times Cost_i + x_i \times \alpha_i \times (Cost_i - Income_i)), \]  

where \( y \) is the total cost, \( x_i \) is the amount of district heating produced for unit \( i \), \( Cost_i \) is the production cost per unit thermal output (includes fuel cost, environmental taxes, maintenance cost and plant efficiency), \( \alpha_i \) is the ratio of electricity produced per unit produced heat and \( Income_i \) includes revenues from selling electricity. Constraints are \( \sum x_i = \text{total heat load}; \ x \in [0, ub] \), where \( ub \) is the upper bounds vector (maximum capacity for each unit); \( x_j \leq \alpha_i \times x_i \) where \( i \) is a CHP plant and \( j \) is the turbine bypass of that CHP plant; \( x_j \leq ub_j/ub_i \), where \( i \) is a CHP plant and \( j \) is the flue gas condenser of that CHP plant. The cost function can then be minimised by using an optimisation algorithm, paper III uses the constrained nonlinear programming solver \( fmincon \), available in the Matlab Optimization Toolbox. Table 2 presents the parameters used in paper III.

<table>
<thead>
<tr>
<th>Unit</th>
<th>CHP</th>
<th>FGC*</th>
<th>Bypass turbine</th>
<th>Biomass HO</th>
<th>Oil HO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production cost (SEK/MWh)</td>
<td>250</td>
<td>0</td>
<td>250</td>
<td>220</td>
<td>750</td>
</tr>
<tr>
<td>Capacity (MW)</td>
<td>72</td>
<td>24</td>
<td>38</td>
<td>70</td>
<td>No limit</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
<td>1.02</td>
<td>0.8</td>
</tr>
<tr>
<td>( \alpha )-value</td>
<td>0.53</td>
<td>-</td>
<td>-1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Flue gas condensing

3.2.2 Spreadsheet calculation model

The calculation model called LAVA2 [28], [29] was developed by Selinder and Walletun on behalf of the Swedish District Heating Association. This is an Excel spreadsheet based calculation tool, originally designed to estimate cost savings of changed supply and return temperatures in existing DH systems. The run order of the plant is achieved by cost minimisation through a series of if-else statements and lookup tables, and the tool can be classified as an optimisation tool. The LAVA2 tool is used as a basis and enhanced with a new heat load model, turbine bypass possibility, electricity price generator,
ECM profiles and a new run order calculation. The calculation is conducted with daily values and 365 spreadsheet rows for a year. The current (“before”) state of the DH system is determined and a new “after” state results after ECM has been applied. The characteristic of the ECM saving is determined by analysing the difference between the before and after states.

![Figure 10. Calculation process scheme.](image)

(The highlighted parts are performed in the spreadsheet calculation model.)

Heat loss in the distribution network (2) and electricity for pumping work (3), are calculated as in the original LAVA2 tool.

\[
Q_L = \frac{Q_{YL}}{T_{YD}} \times \left( (T_S + T_R)/2 - T_M \right), \tag{2}
\]

- \(Q_L\) = heat loss, MW
- \(Q_{YL}\) = yearly mean heat loss, MW
- \(T_S\) = supply temperature, °C
- \(T_R\) = return temperature, °C
- \(T_M\) = yearly mean outdoor temperature, °C
- \(T_{YD}\) = yearly mean difference of \((T_S + T_R)/2 - T_M\), °C

\[
E = \frac{\dot{V}^{3.5} \times \Delta P / (\dot{V}_M)^{2.5}}{\eta} \tag{3}
\]

- \(E\) = electricity used for pumping, MW
- \(\eta\) = efficiency of pumps
- \(\dot{V}\) = actual flow, m³/s
- \(\dot{V}_M\) = mean flow, m³/s
- \(\Delta P\) = mean pressure drop, MPa

A flue gas condenser (FGC) recovers part of the latent heat of water vapour in the flue gases by cooling the flue gases with the return from the DH network.
This means that the lower the return temperature, the more energy can be extracted from the flue gas and transferred to the DH network. Other parameters affecting the efficiency of the FGC are the type of fuel used (fuel hydrogen and moisture content), flue gas temperature and the equipment used. The empirical model of the original LAVA tool is used to model the FGC performance as a function of the return temperature. Figure 11 shows the performance curves of the FGC in the Eskilstuna DH system, tuned to fit measured data.

![Figure 11. Increase in boiler output as a function of return temperature.](image)

Supply and return temperatures (Figure 10f) are determined by an empirical 4th order polynomial function of the heat load, see Figure 12.

![Figure 12. Points showing daily mean supply and return temperatures of the Eskilstuna district heating system, for the years 2012 to 2014. (Lines show temperature as a 4th order polynomial function of the heat load.](image)
The $\alpha$-value of the CHP is modelled as linearly correlated to the supply temperature. From measured data it can be determined that $\alpha$-value = 0.55 at supply temperature of 80 °C and $\alpha$-value = 0.53 at 110 °C. When a CHP plant runs on part load, the electricity production is affected negatively. To model this, a Weibull cumulative distribution function (4) is used and fitted to measured data as shown in Figure 13.

$$\alpha = \alpha_N * (1 - \exp(-(Q_H/\lambda)^k))$$  \hspace{1cm} (4)

$\alpha_N$ = nominal $\alpha$-value

$Q_H$ = heat output, MW

$\lambda$ = scale tuning parameter

$k$ = shape tuning parameter

Figure 13. Part load affects the $\alpha$-value negatively, and is modelled with a Weibull distribution function. Measured hourly values from 2012–2014.

The order of operation (Figure 10h) of the plants is decided by minimising production cost at nominal output levels. The production cost for the heat only plants is simply the fuel and tax cost divided by boiler efficiency plus maintenance cost, represented by the first part of Equation (1) in Section 3.2.1. For a CHP plant the production cost also depends on revenue from electricity, represented by the second part of Equation (1). The turbine bypass is treated as a separate heat producing unit and its production cost is set to equal the electricity revenues.

ECM profiles (Figure 10c) are imported into the spreadsheet and scaled to the desired amount of change in yearly heat load. The DH heat load and electricity prices for a typical meteorological year, (d) & (e) in Figure 10, are also imported. Figure 7 shows an example of a 70/30 % mixture of improved build-
ing envelope and domestic hot water ECM. As the supply and return temperatures of the DH system are modelled as being coupled to the heat load, FGC, heat loss and electricity production, the impact from the ECM on temperature levels can be evaluated.

3.3 The electricity price model

The electricity price is modelled as

\[ X \sim N(\bar{x}, s), \]  

where \( N \) denotes a normal (Gaussian) distribution generator with a standard deviation (SD) of \( s \) and the mean set by \( \bar{x} \). The mean \( \bar{x} \) is modelled as \( f(T, m) \), a function of the outdoor temperature \( T \) and a defined yearly mean price \( m \). The correlation to outdoor temperature is modelled with a generalized additive model (GAM) [30] using historical data from 2006-2015 for the training and typical meteorological year data for the predictions. There are many more factors affecting electricity prices, such as wind, water level in hydropower reservoirs and nuclear power availability factors. However, outdoor temperature strongly drives the DH system’s heat loads and is therefore the most relevant parameter to include in a DH context. Based on historical data, daily mean electricity prices are quite well described by a Gaussian distribution, as seen in Figure 14. The high price side has a slight long tail, and these few extreme cases will be lost in a model using a Gaussian distribution.

![Figure 14. Smoothed density estimates of Nord Pool electricity spot prices, for the whole period and as yearly distributions.](image-url)
3.4 Heat load for a typical meteorological year

A method for weather correcting DH heat loads is developed (first described in Paper III), utilising segmented multivariable linear regressions with typical meteorological year (TMY) data to enable the DH model and the buildings model to work with the same TMY dataset. Multiple linear regression of the form

\[ Y = \beta_0 + \beta_1 \cdot x_1 + \cdots + \beta_p \cdot x_p + \epsilon \]

is used, where \( Y \) denotes the response variable (the heat load), \( \beta_0 \) denotes the intercept, \( x_1, \ldots, x_p \) are explanatory variables (the climate parameters) with coefficients \( \beta_1, \ldots, \beta_p \) and \( \epsilon \) representing the unexplained part. Figure 15 illustrates how historical heat loads and historical weather data (a and b) are segmented (c) by the use of heating degree days (HDD). The regression coefficients are determined (g) through linear regression (d) and segmentation by TMY data (e and f), and used to calculate the TMY heat load (h). HDD is used to find change points for the segmentation and is calculated as the mean difference between a balance temperature of 17°C (roughly where heating needs to begin) and the hourly outdoor temperature for each hour per day: \( HDD = \sum_{h=1}^{24} (T_b - T_o)^+ \), where the + symbol indicates that negative values are not accounted for.

![Figure 15. Deriving the heat load for a typical meteorological year.](image)

3.5 Weather data

The typical meteorological year weather data by the Swedish Meteorological and Hydrological Institute (SMHI) for Eskilstuna were acquired from [31] and are described in [32]. A TMY consists of real observations but with each month originating from a different calendar year. These are selected by comparing the frequency distributions of daily climatic variables during a single month of a candidate year with the corresponding distributions for the same calendar month from a 30 year period. Historical weather data were acquired from the SMHI’s metrological weather station in Eskilstuna; modelled solar irradiation data were obtained from the SMHI STRÅNG project [33].
3.6 Heat demand profiles of ECMs

Heat demand profiles for the studied ECMs are acquired by calculating the daily average difference between the district heating demand (space heating and domestic hot water and losses) of the baseline model and a model where the ECM has been applied, resulting in vectors of 365 daily mean values. These daily values are rescaled to the same annual sum. Each of these 365 values has a corresponding set of weather variables in the TMY weather dataset and the TMY heat load of the DH system.
4 Results

This chapter presents and briefly discusses the findings from the simulation and analysis work. Section 4.1 presents the energy saving potential of the studied energy conservation measures (ECMs), using the heat balance of the building energy model (described in Section 3.1). Section 4.2 presents and discusses the heat demand profiles of the studied ECMs, which are derived in papers II & III. Section 4.3 presents results that show how much of the savings can be attributed to decreased DH system temperatures. Section 4.4 presents three electricity revenue scenarios for Swedish bio-based electricity cogeneration. The level of electricity revenues influences the order of operation of the plants. Section 0 ties the pieces together and presents the result of the energy system analysis when the ECMs (Section 4.2) are implemented under the three electricity revenue scenarios (4.4).

The results presented in Section 0 and in papers II & III differ as the results in the papers are based on the DH model described in Section 3.2.1 and use less comprehensive electricity revenue assumptions. The results in this thesis are based on the model described in Section 3.2.2. The CO₂ and primary energy evaluations are only presented in the papers.

4.1 Potential of energy conservation measures

How much an ECM can potentially save depends on whether the constraint is due to technical, practical or economic limitations. A building’s heat balance gives a good picture of the existing technical heat demand saving potentials for different ECMs.
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Figure 16 shows the heat balance of the studied typical Swedish “Million Programme”-era building that is due for renovation, and is representative for a large part of the existing heat demand in Swedish DH systems. Of the distribution losses, 35% occur on the building side of the substation and can be assumed to consist mostly of domestic hot water recirculation losses (metered as the consumption during warm summer nights in the Lagersberg district). The remaining 75% of the losses occur on the DH distribution side and are an allocation estimate based on the total distribution losses of the DH network. The ‘Space heating’, ‘Domestic hot water supply’ and 35% of the ‘Distribution’ form the part of the heat that is brought to the building – i.e. the building’s heat demand. The heat gains from electricity consumption, solar and occupants reduce the building’s heat demand, as does heat stored and discharged from the building’s internal mass. The DH system’s heat load consists of the building’s heat demand and distribution losses in the DH network. The actual end usage is shown under the zero line. ‘Envelope transmission’ consists of roughly 50/40/10 % of heat losses through windows, external walls & roof and ground floor respectively.

From Figure 16 it seems that improving the insulation level of the envelope has the largest potential for heat demand saving. However, this technical potential is limited by cost and feasibility, which vary depending on the building.
(see Section 2.2). In the studied renovation case the following measures where taken: 5 cm additional insulation on façades, 10 cm extra in the attic, additional insulated glass units on windows. This decreases the envelope transmissions losses by 35%, which is equivalent to approximately 23% heat demand reduction. It is possible to increase the insulation level further but this will introduce additional costs, e.g. the window frame would need to be adjusted outwards if the façade thickness grows too much.

Efficient heat recovery ventilation systems can reduce the losses due to ventilation and infiltration by up to 90%, but a reduction of 70-80% is more realistic for older buildings where it can be difficult to collect all the exhaust air and get well-sealed ducts. A heat recovery system with an efficiency of 80% reduces the heat demand by roughly 28% for the studied building.

As seen in the figure, heat gain from electricity consumption reduces heat demand. Most household electricity consumption can be assumed to end up as heat gain (exceptions are for example warm water discharge from dishwashers and washing machines). For facility electricity this depends on the location of the equipment, for example dissipated heat from an exhaust fan motor or outdoor lighting will not end up as useful heat gain. Saving 1 kWh/y of household electricity in a non-renovated building of the “Million Programme”-era will increase the heat demand by roughly 0.7 kWh/y (while increasing electricity consumption has the opposite effect). For a building of higher energy standard and thus lower heating balance temperature, this value would be smaller.

Two operational optimisation schemes that affect the heat demand are studied here. The first is modelled as simple lowering of the indoor temperature. The motivation for this is that improving the control scheme results in a more even indoor temperature in the entire building, therefore allowing for a lower overall indoor temperature. The simulation results in heat demand reduction of 6% per °C decrease in indoor temperature level. The second control scheme is modelled as the difference between an ideal space heating controller and a more realistic one which does not adapt as quickly to passive heat gains or rapid temperature changes. Simulation results in a heat demand saving potential of 3-5%, mostly due to less overheating due to solar heat through windows. However, the potential varies depending on the technical status of the building. If the building has a poor control system, poorly balanced radiators, uneven temperatures or overheating due to solar heat gains then operational optimisation could save a large amount of energy for a relatively low cost. As these kinds of measures have relatively low investment costs they can be expected to account for a substantial share of future heat demand savings, even though their technical potentials are not as large as can be inferred from Figure 16.

In the studied renovation project, domestic hot water savings were achieved by installing water-efficient showerheads and taps and by individual metering
and charges for domestic hot water. This gave a measured 4% yearly reduction on the heat demand, roughly half the expected result.

Exhaust air heat pumps are limited by the amount of energy that can be collected by decreasing the exhaust air temperature to a specific lowest temperature (usually above 0°C to avoid freezing). An exhaust air heat pump requires electricity to operate, and thus the achieved heat savings come at a cost of higher electricity consumption. Here the exhaust air heat pump is modelled to supply heat for both space heating and domestic hot water, dimensioned to take 1/3 of the exhaust air flow and connected to a 1 m³ stratification tank. This gives a 25% reduction in the yearly heat demand. The air flow of the exhaust air heat pumps is limited to 1/3 of the exhaust air because in the studied buildings roughly 2/3 of the exhaust air outtakes were far from a DH substation. The potential savings are greater for buildings with fewer exhaust air outlets, e.g. for taller building.

The thermal solar system is dimensioned for the domestic hot water consumption during the summer season, and is connected to supply heat for both space heating and domestic hot water. This system results in a heat demand reduction potential of roughly 10%.

4.2 Heat demand profiles

For better comparability, all profiles are scaled to the yearly sum of 1 MWh (Figure 17). The y-axis shows the change in heat demand as daily mean power. The x-axis shows either the duration (subfigure a), with days arranged in ascending order according to the heat load of the DH system, or the correlated outdoor temperature (subfigure b). In order to obtain a clearer view smoothed trend lines are used, rather than the actual data points. The colour of the background indicates the marginal production of the DH system. As the y-axis has a unit of power and the x-axis in subfigure (a) has a unit of time, the area under the profile lines represents energy. The profiles therefore express when energy is consumed, how it is produced, the correlation with outdoor temperature, and how peak demand is affected.
The baseline heat demand of the building model matches the heat load of the whole DH system very well, as shown in Figure 17. This suggests that the baseline model should be representative of existing heat demands in many similar DH systems. At outdoor temperatures under the balance temperature, the heat demand correlates (Figure 17b) almost linearly with the outdoor temperature. It is clear from the duration plot (Figure 17a) that there are few days with very low temperature and the peak demand is relatively small, suggesting that this is more of a capacity issue than an energy issue.

Figure 18 shows the heat demand profiles of two ECMs that are dependent on the outdoor temperature. ‘Building envelope’ encompasses measures that affect heat transfer through the building envelope such as additional insulation and improved glazing of windows. For outdoor temperatures lower than the
Figure 17. Profiles of the heat demand of the baseline-building model and the heat load for the whole district heating system. The baseline heat demand of the building model matches the heat load of the whole DH system very well, as shown in Figure 17. This suggests that the baseline model should be representative of existing heat demands in many similar DH systems. At outdoor temperatures under the balance temperature, the heat demand correlates (Figure 17b) almost linearly with the outdoor temperature. It is clear from the duration plot (Figure 17a) that there are few days with very low temperature and the peak demand is relatively small, suggesting that this is more of a capacity issue than an energy issue.

Figure 18. Heat demand profiles of outdoor temperature dependent energy conservation measures, both as a duration plot and as the load correlated to the outdoor temperature.

Figure 18 shows the heat demand profiles of two ECMs that are dependent on the outdoor temperature. ‘Building envelope’ encompasses measures that affect heat transfer through the building envelope such as additional insulation and improved glazing of windows. For outdoor temperatures lower than the balance temperature (roughly 16°C in this case), this measure shows a linear correlation. Most heat recovery ventilation systems need some kind of freezing protection mechanism that acts below a specific outdoor temperature, and will therefore have heat demand profiles that level off in the low region of the temperature correlation plot. Systems that also recover the latent heat in the exhaust air (e.g. rotary enthalpy wheels) would have a profile similar to that of the ‘Building envelope’. From Figure 18a it can be seen that the differences between these two measures are small from an energy point of view. However, the ‘Building envelope’ measure decreases (compared to the amount of saved heat demand) the peak load by roughly 30% more than ‘Heat recovery ventilation’.

Figure 19. Heat demand profiles of three energy conservation measures, both as a duration plot and as the load correlated to the outdoor temperature.

Changes in heat gains from household electricity and changed indoor temperature levels have almost identical heat demand profiles, as shown in Figure 19. The building’s balance temperature will set the point below which the measures start to have an effect, and this point will move leftwards in the outdoor temperature correlation plot as the building becomes more energy efficient. The ‘Operational optimisation’ is most effective when outdoor temperature are around 5-15°C. This is mostly due to increased solar gains in this temperature range; at higher outdoor temperatures there is no longer any need for space heating and the savings drop towards zero.
Studies [18] have shown that there is a seasonal variation in domestic hot water, with higher consumption during winter, which can be explained by higher occupancy rate and colder incoming tap water (which can be expected to correlate with the ground temperature). Seasonal as well as diurnal variations are omitted from the model for domestic hot water affecting measures, which explains the straight line for the heat demand profile in Figure 20. The exhaust air heat pump measure generates a slightly higher saving at warmer outdoor temperatures, which is due to increased energy in the exhaust air at this point (warmer and more humid indoor air) as well as lower temperatures for the space heating system. An exhaust air heat pump providing heat only for space heating would have a profile looking like something between the ‘Indoor temperature’ and ‘Operational optimisation’ profiles.

4.3 Impact on DH system temperatures

In the DH model, described in Section 3.2.2, system temperatures are modelled as correlated to the heat load. The model can therefore be used to study how system temperatures can be expected to change if the heat load changes due to ECMs, assuming everything else is kept fixed and the DH system is operated in same manner as before. In order to get an impact that is large enough to visualise, the yearly heat load is modelled to decrease by 10%.
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As shown in Figure 21, DH system temperatures are affected differently depending on which ECM profile is used to model the decrease in heat load. For both studied ECMs, the supply temperature level decreases, but ‘Building envelope’ results in a more significant decrease. The return temperature decreases for both ECMs at colder outdoor temperature when the heat load is dominated by space heating needs. However, at outdoor temperatures higher than around 5°C, the model shows an increase in return temperature levels. This can be explained by the increasing share demand for domestic hot water and particularly domestic hot water recirculation, a system present in most buildings that circulates hot water so that distant faucets receive hot water promptly when turned on. Space heating during the low demand season cools the return temperature more than heat demand for hot water recirculation systems. Thus further decreased heat load can be expected to give increased return temperature levels during the low demand season.
Table 3. Impact on the modelled Eskilstuna district heating system from a 10 % heat load decreases, with system temperatures fixed and as coupled to the heat load.

<table>
<thead>
<tr>
<th>ECM profile: 'Building envelope'</th>
<th>Heat, boilers</th>
<th>Heat, FGCs</th>
<th>Electricity, cogeneration</th>
<th>Heat, losses network</th>
</tr>
</thead>
<tbody>
<tr>
<td>System temperatures fixed, MWh/y</td>
<td>-64 285</td>
<td>-10 723</td>
<td>4 039</td>
<td>0</td>
</tr>
<tr>
<td>System temperatures coupled to the heat load, MWh/y</td>
<td>-65 534</td>
<td>-9 775</td>
<td>4 686</td>
<td>-1 294</td>
</tr>
<tr>
<td>Difference, MWh/y</td>
<td>-1 249</td>
<td>948</td>
<td>647</td>
<td>-1 294</td>
</tr>
<tr>
<td>Difference, %/y</td>
<td>-2%</td>
<td>9%</td>
<td>16%</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ECM profile: 'Domestic hot water'</th>
<th>Heat, boilers</th>
<th>Heat, FGC</th>
<th>Electricity, cogeneration</th>
<th>Heat, losses network</th>
</tr>
</thead>
<tbody>
<tr>
<td>System temperatures fixed, MWh/y</td>
<td>-62 760</td>
<td>-12 578</td>
<td>-5 460</td>
<td>0</td>
</tr>
<tr>
<td>System temperatures coupled to the heat load, MWh/y</td>
<td>-63 041</td>
<td>-12 504</td>
<td>-5 329</td>
<td>-122</td>
</tr>
<tr>
<td>Difference, MWh/y</td>
<td>-281</td>
<td>74</td>
<td>132</td>
<td>-122</td>
</tr>
<tr>
<td>Difference, %/y</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
<td>-</td>
</tr>
</tbody>
</table>

Energy savings that can be attributed to changes in system temperatures are quite small in relation to savings due to the ECMS themselves. Table 3 shows the impact on the DH system model when it is altered by subtracting two different ECM profiles from the current heat load so that it decreases by 10%/y. The model is run twice, first accounting only for the ECM itself and a second time also including the impact of changes in system temperatures (by coupling the system temperatures to the heat load). The difference is attributed to the impact from the changed system temperatures. For ECMS such as ‘Building envelope’, the lower system temperatures result in an additional decrease in fuel savings by about 2% (due to more heat from FGC and lower distribution losses in the network) and an additional increased electricity cogeneration of 16%. For ECMS with characteristics similar to ‘Domestic hot water’, the yearly contribution from lower system temperatures is roughly zero – the disadvantage of increased return temperature at base loads roughly equals the benefits obtained at peak loads.

4.4 Electricity revenue scenarios

Three electricity revenue scenarios are shown in Figure 22. The ‘Low’ revenue scenario is an estimate for the next few years, where the mean price is set to 200 SEK/MWh (the current market expectation for the next years [34]) and
Table 3. Impact on the modelled Eskilstuna district heating system from a 10% heat load decreases, with system temperatures fixed and as coupled to the heat load.

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<tbody>
<tr>
<td>System temperatures fixed, MWh/y</td>
<td>-64</td>
<td>-285</td>
<td>-10</td>
<td>723</td>
</tr>
<tr>
<td>System temperatures coupled to the heat load, MWh/y</td>
<td>-65</td>
<td>534</td>
<td>-9</td>
<td>775</td>
</tr>
<tr>
<td>Difference, MWh/y</td>
<td>-1249</td>
<td>948</td>
<td>647</td>
<td>-1294</td>
</tr>
<tr>
<td>Difference, %/y</td>
<td>-2%</td>
<td>9%</td>
<td>16%</td>
<td>-</td>
</tr>
</tbody>
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Three electricity revenue scenarios are shown in Figure 22. The 'Low' revenue scenario is an estimate for the next few years, where the mean price is set to 200 SEK/MWh (the current market expectation for the next years [34]) and SD is set to 50 SEK/MWh (based on yearly SDs for the years 2013-2015, excluding variation correlated to the outdoor temperature). The ‘Mid’ revenue scenario uses a mean price of 270 SEK/MWh and a SD of 70 SEK/MWh. The ‘High’ revenue scenario is based on historical revenues and includes a Swedish electricity certificate worth 250 SEK/MWh, mean electricity price of 350 SEK/MWh and a SD of 120 SEK/MWh. At peak load and electricity revenues lower than the break-even (yellow ribbon in the figure), it is more cost-effective to produce heat by bypassing the turbine than using oil boilers. At base and mid load, the electricity revenues need to be higher than the blue ribbon or it is no longer cost-effective to cogenerate electricity.

![Figure 22. Daily mean electricity revenues as function of outdoor temperature and a Gaussian random number generator.](image)

Grey and orange ribbons show the used first and second standard deviations respectively. Yellow and blue ribbons show break-even lines, under which it is more cost-effective to bypass the turbine than to start up the next heat production unit.)
As seen in the Figure 22-I, using the mean value for the revenue would most of the time fall below the break-even line thus resulting in a very different estimate of the amount of electricity production than would be the case if the mean revenues were just slightly higher. Using a Gaussian distribution approach avoids sharp break-even lines. The break-even lines used are constant for the three scenarios and based on current production costs. Fuel prices do not vary much with season, but have long-term trends that tend to resemble the long-term trend of electricity prices. It is the difference between electricity revenues and the production cost of heat (mostly dependent on fuel costs and taxes) that is relevant here as the aim is to estimate the amount of cost-effectively cogenerated electricity. Government taxes and subsidies also play a crucial part. Current Swedish taxes are included in the production costs; and in scenario III, a Swedish electricity certificate worth 250 SEK/MWh is added to the electricity revenues. The CHP plant in Eskilstuna has used all of its electricity certificates rights, and scenario I & II appear more realistic for near future development.

### 4.5 Impact on the energy system

This section presents results of the impact on DH production, electricity cogeneration and consumption when implementing ECMs in buildings within the DH network. The DH system production mix depends on the heat load (which in turn is strongly dependent on weather conditions), electricity revenues and fuel prices. Varying weather conditions are taken into account by using typical meteorological year correction for the heat load (see Section 3.4). The effect of fluctuating electricity revenues is taken into account by using three scenarios: low, mid and high electricity revenue scenarios (see Sections 3.3 and 4.4).

Figure 23 shows the resulting impact on the system of eight different ECM profiles. The profiles shown in Figure 23a are the same heat demand duration profiles presented and described in Section 4.2. Figure 23b shows the impact of these eight ECM profiles under three different electricity revenue scenarios. The wider bars show which heat production unit is affected, while the thinner bars show how the electricity production/consumption balance is affected. Measures with heat demand profiles similar to ‘Building envelope’ lead to increased cogeneration of electricity under all three studied electricity revenue scenarios. This increased cogeneration is mostly due to decreased need for bypassing of the turbine.
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Figure 23. System impact of energy conservation measures, scaled to 1 MWh of change in annual heat demand.
(Negative values indicate a decrease/saving, positive values indicate an increase, (a) miniatures of the heat demand duration profiles (see Section 4.2), (b) wider bars show impact on heat producing units and the two narrow bars show the impact on the electricity cogeneration and electricity consumption.)

The increased electricity consumption of the ‘Heat recovery ventilation’ measure is roughly matched by the increased electricity cogeneration. The ‘Household electricity’ measure is modelled as an increase in electricity usage in order to get a heat demand reduction (for easier comparability in the figure). If the electricity usage instead decreases, the heat demand would increase. For example, a saving 1.4 MWh of household electricity in the model leads to an
increased heat demand of 1.0 MWh, which in turn leads to a slight increase or decrease of cogenerated electricity (depending on the electricity revenue scenario). The ‘Exhaust air heat pump’ leads to decreased cogeneration of electricity except in the low electricity revenue scenario where the effect is neutral. In the low electricity revenue scenario, cogeneration is affected negatively only for the ‘Thermal solar’ profile. In the mid-revenue scenario, all but the two first ECM profiles affect the cogeneration negatively. The price difference between the low and mid-revenue scenarios is moderate but they give quite different results as they are near the break-even line for when it is no longer cost-effective to produce electricity at the CHP plant.

Figure 24. Amount of yearly cogenerated electricity (y-axis) for heat loads (x-axis) altered by energy conservation measure profiles (line type) and for four electricity revenue scenarios (line colour). (The pink bar shows the current weather corrected heat load of the Eskilstuna district heating system.)

Figure 24 shows estimates of the amount of yearly cogenerated electricity. The red bar shows the current heat load of the Eskilstuna DH system for a typical meteorological year. The current heat load is altered by adding/subtracting ECM profiles so that the amount of electricity cogeneration is estimated for heat loads ranging from 630 to 790 GWh/y. The electricity revenue scenario corresponds to cost-effective electricity cogeneration in the three scenarios presented in Section 4.4, i.e. the turbine is bypassed when electricity revenues are too low. The ‘Max’ scenario corresponds to a scenario where
electricity cogeneration is maximised, i.e. the turbine is always used when there is a heat load (except for a revision period during the summer). It is clear that the electricity revenues have the strongest influence on the amount of electricity cogeneration. ECM profiles of the ‘Building envelope’ type either increase or have little effect on the amount of cogenerated electricity. ‘Thermal solar’ decreases the amount of cogenerated electricity under all electricity revenue scenarios (implementing ‘Thermal solar’ at this large scale is not a very realistic scenario; it is included only for comparison). ‘Domestic hot water’ decreases the amount of cogenerated electricity in the mid and high electricity revenue scenarios. The amount of cogenerated electricity relative to the heat load (i.e. the $\alpha$-system value) increases in all scenarios.
5 Discussion

The Eskilstuna DH system is almost 100% renewable fuelled (forest residuals and bio-oil) and has a relatively high share of electricity cogeneration. Hence, it is a highly resource efficient and low fossil CO₂ emitting energy supply system. The results of this study are therefore not easily generalisable to other current DH systems. Nevertheless, this is an interesting case as it highlights the impending problem of diminishing environmental benefits of ECMs on the demand-side. In future, more DH systems, at least in Nordic the Nordic countries, are likely to attain similar characteristics as DH production becomes more renewable and less primary energy intensive.

The results show that the impact of ECMs on the DH system varies for individual ECMs. Measures such as improved insulation of building envelope that decrease the heat demand dependence on outdoor temperature (thereby leading to a more even heat load curve) increase the amount of cogenerated electricity. Measures such as thermal solar panels, which save heat during summer, affect the absolute amount of cogenerated electricity negatively. The revenues from cogenerated electricity are the most influential parameters influencing the amount of cost-effectively produced electricity, and are much more influential than the impacts from ECMs. All ECMs increase the relative amount (the ratio between amount of cogenerated electricity and the heat load) of cogenerated electricity. This implies that ECMs increase the efficiency of the Eskilstuna DH system when efficiency is measured by, for example, energy efficiency or any evaluation system that values electricity higher than heat. However, if ECMs lead to increased import of electricity to Eskilstuna city, and this imported electricity is produced inefficiently, then the city’s whole energy supply system may be less efficient than before.

As described in Section 2.4 there are many means of assessing energy and the environmental impact of energy use. Paper II & III show results of assessment of environmental impact of each ECM in terms of primary energy (PE) and CO₂ emissions. These are strongly influenced by the choice of assessment perspective (an issue examined in paper I). For CO₂ the relatively subjective choice of origin of replaced grid electricity, e.g. Nordic mix or marginal production, has the strongest influence. While for PE assessment, the PE-factor of the biomass has the strongest influence. The environmental benefits of EMCs, measured in CO₂ emissions and PE consumption, are quite small (and can even be negative for some ECMs and assessment scenarios) in DH systems like Eskilstuna, which has an exceptionally high share of renewable fuels
and relatively high share of electricity cogeneration. In the short-term perspective, biomass residuals from the forest industry can be assigned with little or no PE content. From the perspective of human energy demands these resources would otherwise be wasted if not utilised in e.g. DH systems. On the other hand, if fossil fuels and perhaps nuclear power are to be replaced by renewable energy to a large extent – then all biomass resources should be attributed a PE value as they are limited resources and far from sufficient to replace the fossil and uranium based energy supply on their own.

For the studied DH system type, peak heat load is provided by bypassing the turbine, as electricity revenues are seldom high enough for it to be cost-effective to use (fossil or bio) oil boilers. This is partly due to the Swedish fossil fuel taxing system where DH companies pay high taxes when fossil fuels are used in heat only boilers, while CHP plants pay considerably less. Nordic electricity production also has its peak load at low outdoor temperatures, and on these occasions the marginal production is mostly provided by fossil fuel based condensing power. For instance, a rough calculation shows: a) the turbine is bypassed to provide 10 MW heat; b) the cogenerated electricity production is thus decreased by 10 MW; c) this 10 MW of electricity needs to be produced elsewhere, most likely by condensing power. Producing 10 MW by condensing power requires approximately 25 MW of fuel. Thus using heat only boilers instead of bypassing the turbine would be roughly 2.5 times more resource efficient.

Swedish electricity certificates are based on the amount of electricity produced, and their value does not vary with season or the electricity grid load. Thus, it will be cost-effective from the plant owner’s perspective to run biomass based CHP plant turbines (with electricity certificate rights) during the low load season even if the revenue from the electricity spot price is very low. On occasions with very low electricity spot prices, the marginal production in the Nordic electricity grid mainly originates from intermittent renewable energy sources such as hydro, wind and solar power, and hydropower production that cannot be completely shut down. On these occasions, bio-based CHP electricity competes with other renewable production. This is not desirable, as economic incentives for bio-CHP based electricity production should steer towards increased production during periods of high demand.

A scenario of increased electrification of buildings’ heating demand, higher share of intermittent power production (i.e. wind and solar) and perhaps changes in incentivisation from tax and subsidies would most likely lead to higher electricity revenues at low outdoor temperatures. In such a scenario it may be feasible to invest in CHP plants covering DH mid and peak heat loads that are currently covered by heat only boilers. Levelling out the heat load in this way also reduces the heat demand dependence on outdoor temperature. A scenario like this could also reduce the current practice of bypassing the CHP turbines at peak heating load, implying that electricity cogeneration would be more negatively affected by ECMs than in the presented results.
According to the literature review (Section 2.2, results by É. Mata et al.), improving the insulation level of the building envelope is not very cost-effective while reducing indoor temperature is estimated to have quite a large cost-effective energy saving potential. These estimates for energy savings potential for decreased indoor temperature seem to be optimistic in comparison to the results in Section 4.1. The studied renovation case of Lagersberg (Section 3.1) is an example where additional insulation of façades can be cost-effective. The aerated concrete façades were in need of new plastering, and the additional insulation doubled as a base for the new plaster. The cost of scaffolding and plastering would have been incurred anyway and was therefore not fully allocated to the ECM cost. A major part of the (near to mid) future energy savings mix can be expected to comprise of operational optimisation measures such as lower indoor temperatures. Unfortunately, according to the results of this thesis, such measures tend to reduce heat demand at times when this not favourable for the operation of the DH system.

The energy system modelling and construction of scenarios are strongly influenced by assumptions made regarding future conditions – conditions that are not knowable in advance, such as future fuel and electricity prices, subsidies and taxes, technological advancement on both supply and demand sides. The only sure thing is that the results presented in this paper will not be exactly the same as the real outcome. The electricity revenue scenarios in Sections 3.3 and 4.4 and the different CO₂ and PE factors in paper III provide means of dealing with these kinds of uncertainties. The use of a Gaussian distribution for the electricity revenue scenarios makes the break-even lines less sharp, thereby making the model less sensitive to assumptions regarding revenues and costs. Implementing ECMs in the building stock is an ongoing effort that will take decades to realise. The results should be interpreted with this in mind, and the DH system will have time to adapt to changes even though the investment cycles in DH systems are slow.

The weather normalisation method presented in paper III proves useful for getting the heat load of the DH model and the building energy model to work with the same weather dataset. The method could also be used to predict future heat loads accounting for climate warming by using climate files similar to those derived for Finland [35]. In paper [36] Finnish heating demand is predicted to decrease by about 3% per decade due to global warming.
6 Conclusions

The conclusions of this thesis are presented in relation to the research questions (stated in Section 1.2).

What are the differences in impact of different ECMs on the DH operation?
Various ECMs in the building stock will impact differently. Measures that decrease the heat demand’s dependence on outdoor temperature, such as improved insulation level of the building’s envelope, will increase the amount of cogenerated electricity. In contrast, measures such as thermal solar panels, which save heat during summer, affect the absolute amount of cogenerated electricity negatively.

The revenues from cogenerated electricity are the most influential factors on the amount of cost-effectively produced electricity, and are much more influential than the impact from ECMs.

What are the benefits of ECMs in buildings connected to renewable and resource efficient DH systems?
All studied ECMs increase the relative amount (the ratio between amount of cogenerated electricity and the heat load) of cogenerated electricity. This implies that the overall efficiency of DH systems is increased.

Environmental benefits of ECMs are quite small in low CO$_2$ emitting and low PE content DH systems with electricity cogeneration. The consequences can even be negative if ECMs lead to increased electricity production by fossil fuel condensing plants. Environmental assessments are highly dependent on the choice of assessment perspectives: for CO$_2$ emission, the relatively subjective choice of origin of replaced grid electricity, e.g. Nordic mix or marginal production in fossil fuel condensing plants. In PE terms, it depends on whether the PE content of forest residuals is considered or not.

Reduced heat loads lead to decreased system temperatures in the existing DH network for most studied ECMs. The benefit is quite small compared to the heat saving itself but contributes to a more efficient energy supply system. The practise of bypassing the turbine at peak heat load is less resource efficient than using heat only boilers.
7 Future work

This licentiate thesis studies the interaction between the buildings’ heat demands and the DH system using a system approach. Future work in this project will continue studying the interaction between the buildings and the DH system by investigating how consumption data of the substations’ meters can be further utilised. An adaptive procedure will be developed to automatically determine regression parameters from the substations’ meter and weather data.
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References


