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LICENTIATE THESIS NO. 4

Influences from Building Energy Efficiency Refurbishment on a Regional District Heating System

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*This thesis is based on work conducted within the industrial post-graduate school Reesbe – **R**esource-**E**fficient **E**nergy **S**ystems in the **B**uilt **E**nvironment. 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.*

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The front cover illustration shows a multifamily building situated in Tjärna Ängar, Borlänge. Source: AB Stora Tunabyggen. (2017)

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Abstract

Improving energy performance of existing buildings is an important part in decreasing energy use and in turn reduce the greenhouse gas emissions caused by human activity and the primary energy use.

To be able to evaluate how energy refurbishment influences the greenhouse gas emissions and the primary energy use a wider system perspective is needed that puts the building in its context. This thesis deals with energy refurbishment packages performed on multi-family buildings within district heated areas and how they influence greenhouse gas emissions and primary energy use when the district heating use is altered.

A simulated building is used to evaluate several energy refurbishment packages. The results are used as input data for models of district heating systems to cost optimize the district heating production. The results from the cost optimization are used to evaluate the impact on greenhouse gas emissions and primary energy use.

The results show a difference between measures that saves district heating without increasing the use of electricity and measures that increases the use of electricity while district heating is saved. For example, a building refurbishment package including only building envelope improvements saves the same amount of district heating as a package including only mechanical ventilation with heat recovery. Despite this, the emissions of greenhouse gases and the use of primary energy is to a greater extent reduced in the first package because the use of electricity remains unchanged.

Comparing energy refurbishment packages performed on the same building, but within different district heating systems, show the importance of the design of the district heating system. Depending on the fuel types used and to which extent electricity is co-produced in the district heating system, the results of implementing the energy refurbishment packages vary. The largest reduction of greenhouse gases and primary energy use occurs when a refurbishment package is performed on a building in a district heating system with high share of biofuel and no electricity production.

Keywords: District heating, energy efficiency, building refurbishment, greenhouse gases, primary energy.

Sammanfattning

Att förbättra energiprestanda hos befintliga byggnader är en viktig del i arbetet med att minska energianvändningen och i sin tur minska utsläpp av växthusgaser orsakade av mänsklig aktivitet samt att minska användningen av primärenergi.

För att kunna utvärdera hur energieffektivisering av byggnader påverkar växthusgasutsläpp och primärenergianvändning behövs ett brett systemperspektiv som sätter byggnaden i sitt sammanhang. Denna avhandling handlar om hur paket av energieffektiviseringsåtgärder som utförs på flerfamiljshus inom fjärrvärmeuppvärmda områden påverkar växthusgasutsläpp och primärenergianvändning när fjärrvärme-användningen förändras.

Resultaten visar på skillnader mellan åtgärder som sparar fjärrvärme utan att öka användningen av el och åtgärder som ökar användningen av el medan fjärrvärme sparas. Till exempel sparar ett energi-effektiviseringspaket som endast omfattar byggnadsskalsförbättringar samma mängd fjärrvärme som ett paket som endast omfattar installation av mekanisk ventilation med värmeåtervinning. Trots detta minskar utsläppen av växthusgaser och användningen av primärenergi i större utsträckning i det första paketet på grund av att elanvändningen förblir oförändrad.

Vikten av fjärrvärmesystemets utformning visas då en byggnad där olika energieffektiviseringspaket testats, flyttas runt till olika fjärrvärmesystem. Beroende på vilka bränsletyper som används och i vilken utsträckning som el produceras i fjärrvärmesystemet så varierar resultaten. Den största minskningen av växthusgaser uppstår när ett renoveringspaket utförs på en byggnad i ett fjärrvärmesystem med hög andel biobränsle och ingen elproduktion.

Nyckelord: Fjärrvärme, energieffektivitet, byggnadsrenovering, växthusgaser, primärenergi.

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A special thanks to my PhD colleagues Moa Swing Gustafsson and Ricardo Ramírez Villegas for your great patience with all my questions and for all the fruitful discussions we have had.

List of papers

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

Paper I

Lidberg, T., Ramírez Villegas, R., Olofsson, T., Eriksson, O. (2014). An approach to illustrate strategies for improved energy efficiency at the municipal level. *The 14th International Symposium on District heating and Cooling,* September 7-9, Stockholm, Sweden.

Paper II

Lidberg, T., Olofsson, T., Trygg, L. (2016). System impact of energy efficient building refurbishment within a district heated region. *Energy*, 106 (2016):45-53.

Paper III

Lidberg, T., Gustafsson, M., Myhren, J.A., Olofsson, T., Ödlund (former Trygg), L., (2017). Environmental impact of energy refurbishment of buildings within different district heating systems. *Applied Energy*, in press.

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Author's contributions

The author of this thesis has contributed with the following:

- Paper I - The formulation of the research question and the study design, data collection, carrying out the building energy simulations and writing the paper was made in collaboration with Ricardo Ramírez Villegas.
- Paper II - Formulation of the research question, all energy system modelling, all calculations and most of the writing.
- Paper III – Formulation of the research question, all district heating system modelling, the primary energy calculations and most of the writing.

Publications not included in the thesis

Lidberg, T., Gustafsson, M., Myhren, J.A., Olofsson, T., Ödlund (former Trygg), L., (2016) Comparing different building energy efficiency refurbishment packages performed within different district heating systems. Energy Procedia, 105 (2017):1719-1724.

Nomenclature

Abbreviations

CCP	Coal condensing power
CHP	Combined heat and power
CO_2-eqv.	Carbon dioxide equivalents
DHS	District heating system
EAHP	Exhaust air heat pump
IWH	Industrial waste heat
MSW	Municipal solid waste
MVHR	Mechanical ventilation heat recovery

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1. Introduction

Climate change is one of nine planetary boundaries, and also one of the four that is exceeded [1]. The reason is human activity [2]. At the same time, our use of natural resources far exceeds our planet's ability. The average human of today lives as if we had 1.6 Earths available [3]. In order to keep the world as we know it, our way of living have to change. A conversion from a fossil fuel based energy system to a renewable one is necessary and we need to increase the efficiency of our use of energy. At the same time, the use of natural resources have to reach a sustainable level.

An important area of improvement is the building and service sector, which on a global basis stands for nearly one-third of the final energy use and consequently the same amount of energy-related greenhouse gas emissions [4]. The same applies to the country of Sweden (Northern Europe), where this sector counts for almost 40 % of the country´s total energy use [5]. The trend in national statistics show that the specific energy use per square meter is decreasing in Swedish residential and non-residential premises [6]. However, energy efficient refurbishment of buildings is not certainly a straight road to decreased climate impact and use of natural resources. In order to evaluate the impact of the refurbishment in terms of climate impact and natural resources, a broad system perspective is needed, including not only limited to the building but also including the energy supply system.

A common situation in Swedish cities is that the municipality owns the local energy system in terms of district heating production and distribution and sometimes also the local electricity distribution system. Almost 70% of the district heating systems in Sweden are municipality owned. It is also quite common with co-generation of electricity in combined heat and power (CHP) plants [7]. Concurrently, 17% of the total residential building stock in Sweden is owned by public housing companies [8]. Improved energy performance in these buildings is important not only to decrease the energy use in the buildings themselves, but in line with policies and regulations, also to contribute with good examples, inspiration and to go ahead to support research and development.

1.1. Primary energy and greenhouse gas emissions

One way of evaluating resource use is to examine the use of primary energy. Primary energy can be explained as the total energy in terms of natural resources that is used to produce energy for final use, e.g. electricity or heat. A common way to calculate the use of primary energy is using primary energy factors, defined as the ratio between final energy use and primary energy use. Though, these factors can be very different, depending on the method used to define them. Different methods take different parameters into account and they also have different system boarders and use different values in the calculations, mean or marginal values. As for today, there is no international agreement of which factors to use. The difference between primary energy calculation methods has been compared is Swing et al [9].

Unlike many other environmental issues, the climate change (also known as global warming) is a global phenomenon. Due to emissions of greenhouse gases induced by humans the average temperature increases globally [10]. Regardless of where on Earth the emissions occur, the impact on and the change of the climate will affect the entire planet. This is why it is important to study emissions of greenhouse gases and its impact from a global point of view.

1.2. Electricity and district heating

The electricity production in Sweden mainly consists of hydro power (40%) and nuclear power (40%) along with some wind power (10%) and thermal power (10%) from the industry and the district heating systems [7]. The thermal power is mainly supplied by biofuel and municipal waste [11]. Thus a very small part of the electricity produced in Sweden comes from fossil fuels. To be able to maintain a stable and secure electricity supply, Sweden is interconnected with adjacent countries which make us a part of the European network. Recent years Sweden has been a net exporter of electricity on an annual basis, despite this import of electricity occurs as well [7]. Even though electricity generation from renewable sources contributed with almost 30 % to the total gross electricity consumption within the European Union in 2015, fossil fuels still stands for almost half the electricity generation [12].

District heating is a technical system that provides heat production and distribution on a large scale, e.g. a city or a municipality. A district heating system usually consists of one or a few heat producing units, a distribution network and end users i.e. the buildings or other facilities in need of heat. In large systems there are often CHP plants supplying the systems with heat in the same time as electricity is produced. Waste heat from industries, solar thermal plants, large scale heat pumps, hot water boilers and other technical solutions might also be included in the district heating system production parts [13]. A large advantage with district heating and centralizing the heat production is that fuels difficult to manage like secondary bio fuels or municipal solid waste (MSW) can be used. Another benefit is that the combustion process is optimized, which results in less emissions. The district heating production in Sweden mainly consists of biofuel (51%) and MSW combustion (27%). According to statistics from 2016 the use of fossil fuels is 10 % in the Swedish district heating production. Beyond this industrial waste heat (IWH) (9%) and some electricity for heat pumps and electrical boilers (3%) is used [14].

1.3. Energy use in multifamily buildings

In Sweden, district heating is the most common way to provide multifamily buildings with space heating and domestic hot water. According to statistics from 2015, 92 % of the total energy demand in multifamily buildings was met with district heating [5]. Generally, the energy use per square meter is larger in older buildings [15].

A large share of the Swedish building stock was produced during the Million Homes Program (in Swedish Miljonprogrammet) during the years 1965-1975 see Figure 1 [16]. Many of these buildings are in general in need of refurbishment due to age and wear, and their often high energy use speaks for the need of energy conserving measures as well [17]. In Sweden, extensive efforts are being made to increase the knowledge about how existing buildings can become more environmentally, economically and socially sustainable from a lifecycle perspective. An example is Nationellt renoveringscentrum (the National Renovation Center) and the research network SIRen [18].

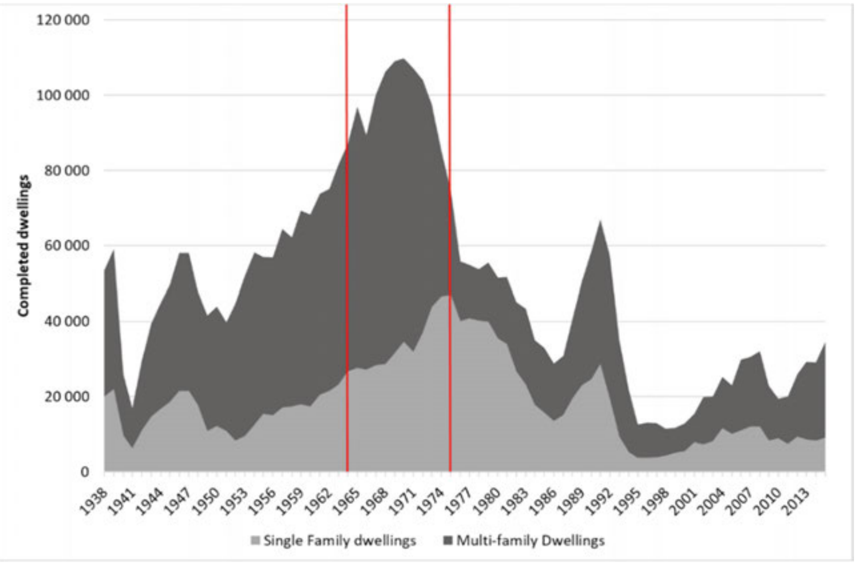

Figure 1. Completed dwellings in Sweden for each year. The Million Homes Program occurs between the vertical lines [16].

When implementing energy conserving measures in multi-family buildings connected to district heating systems, it is likely that it will affect the use of district heating and the use of electricity. Measures aimed at saving heat, i.e. district heating, can be divided into active or passive measures depending on their use of electricity. Active measures are defined as measures that increase the use of electricity in order to decrease the use of district heating and passive measures are defined as measures that decrease the use of district heating without increasing the use of electricity. As an example, all kind of building envelope improvement such as additional insulation of walls or attic, change of windows or eliminating cold bridges are passive measures. Active measures can be, for example, change of ventilation system from mechanical exhaust air to mechanical supply and exhaust air with heat recovery (MVHR), or to exhaust air heat pump (EAHP). This type of measures increases the recycling of heat in the building, but also increases the use of electricity mainly due to an additional fan (MVHR) or to power the heat pump (EAHP).

1.4. Previous research

Several studies have examined energy efficient refurbishment of buildings within district heated areas and addressed the energy saving potential along with the impact on primary energy use and global greenhouse gas emissions [19]–[27]. Difs et al [19] studied the implementation of three different energy saving measures from both a district heating user and supplier perspective. The measures had different heat load profiles and the results show that measures that reduced the use of electricity or the use of peak load boilers also contributed with the largest reductions of greenhouse gas emissions. When the measures reduced the electricity produced within the CHP plants, the result was the opposite. When the heat load in district heating systems with CHP plants is decreased, it is likely that also the electricity production decreases. Gustavsson et al [20] concludes that primary energy savings of energy efficient refurbishment measures is larger when reducing peak load than base load in district heating systems with CHP electricity production. When the base load is reduced, the electricity produced in the CHP plants is also reduced, resulting in that the electricity needs to be produced elsewhere.

Like Difs et al [19] and Gustavsson et al [20], there are several studies that point out the importance of analysing both the demand and the supply side of the energy system when considering energy efficient refurbishment [19]–[26]. For instance, Dodoo et al [21] examines the impact of ventilation heat recovery on primary energy use in residential buildings, finding that the energy supply system has major impact on the results. When district heating with a large share of CHP electricity production was considered, the benefits of ventilation heat recovery was small. Truong et al [22] compared energy efficient refurbishment measures performed on building heated with small, medium or large sized district heating systems. The small system was the only one without CHP electricity production and also the one with the highest primary energy savings when implementing energy efficient refurbishment measures. In another study, Truong et al [23] compares energy efficient refurbishment measures in two different buildings, one concrete-framed and one wood-framed building. The results show that the primary energy savings depends rather on the type of measure, combined with the composition of the district heating system than the type of building.

Liu et al [27] investigates energy efficient refurbishment in eleven Swedish multifamily buildings. The results show that the possibility to reduce greenhouse gas emissions is larger in buildings outside the district heating systems. Despite this, most multifamily buildings are situated within the district heated areas. The study concludes that it is important to find the balance point between energy savings and the heat demand within the district heated areas. A study made by Gustafsson et al [24] shows that there is a major difference in global greenhouse gas emissions between energy efficient refurbishment measures that saves heat or electricity, compared to measures that uses electricity to save heat. When electricity is used for heat savings the electricity use in the building increases along with reduced electricity generation in CHP plants. Also Lundström et al [25] and Rolfsman [26] addresses that energy conserving measures in district heating systems with a high share of CHP production will rather increase the emissions of global greenhouse gases. The contribution of this thesis to the research area is to evaluate energy efficient refurbishment measures from both a climate and resource perspective. The studies performed within this work takes into account the impact of refurbishment measures on primary energy use as well as global greenhouse gas emissions.

1.5. Aim and objective

This thesis aims to show how various energy-saving refurbishment strategies influence the emissions of global greenhouse gas as well as the use of primary energy.

The hypothesis for this thesis is as follows:
For clarification of climate impact and reduction of natural resources from energy saving measures in buildings, the regional energy system prerequisites must be taken into account.

The objective of this thesis is to demonstrate the importance of expanding the system boundaries from the building itself to include the surrounding energy system into account in the field of energy efficient refurbishment of buildings.

Research questions

1. How can a method be developed for comparisons between energy-saving refurbishment strategies of buildings in a district heating system?
2. How do different energy-saving refurbishment strategies influence global greenhouse gas emissions and primary energy use in a district heating system, based on different fuel mix and CHP electricity production alternatives, when biofuel is considered a scarce resource?

Table 1. Overview of which research question that was dealt with in each paper.

Research question	Paper I	Paper II	Paper III
1	X		
2		X	X

1.6. Scope and limitations

The scope of this thesis is to analyze energy efficient refurbishment of multi-family buildings within the district heated area and how this affects the global greenhouse gas emissions and the use of natural resources.

The system boundaries of the work is described in Figure 2. System boundaries distinguish the studied system from its surroundings and they are important to define in order to understand the studies that have been made. This thesis includes several systems and it is primarily the connection between these systems that are studied.

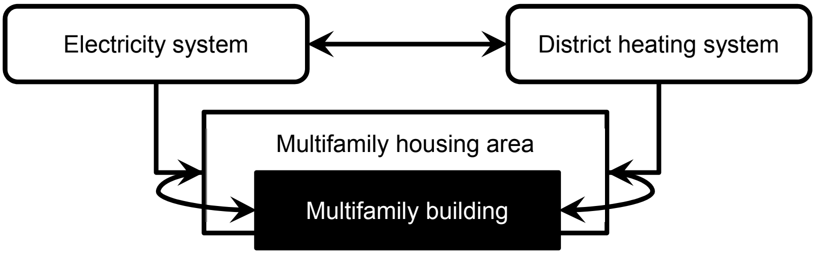

Figure 2. Schematic figure of the systems included in this thesis and the connections between them.

Two different multifamily buildings have been used as case study buildings. The buildings are situated in the same multifamily housing area and they are similar to each other. Six different district heating systems have been used as case study systems. The electricity system considered is the North European system and the studies are made with a short-term time perspective.

Global greenhouse gas emissions where calculated in both paper II and paper III. Primary energy use was originally only calculated in paper III. The results from paper II have been complemented with primary energy calculations for this thesis. Biofuel considered to be a scarce resource was originally only included in paper II, but the results from paper III have been complemented with this assumption for this thesis.

1.7. Paper overview

The following section describes the contribution of each paper included in this thesis.

Paper I analyses how a method can be developed to make comparisons between energy-saving refurbishment strategies for buildings in district heating systems. The aim is to answer research question 1. A method where building simulation is combined with district heating system, cost optimization is tested and evaluated.

Paper II continues to improve the method used in paper I, and aims to answer research question 2. Packages of energy efficient refurbishment measures are simulated and the impact on global greenhouse gas emissions is studied. Biofuel is considered to be a scarce resource.

Paper III also aims to answer research question 2. Other refurbishment packages than in paper II is used and the modelled district heating systems in this paper are created from statistics including all district heating systems in Sweden.

2. Case studies

2.1. The studied buildings

Two real buildings have been studied in this thesis as case study. Both buildings are situated in a multifamily housing area named Tjärna Ängar in the city of Borlänge, 250 km North West of Stockholm, Sweden.

Building 1 was examined in paper I and II. A model of the building was constructed in the building simulation software IDA-ICE and the simulations were validated against measured data. The building is a three-story building with 36 apartments and a heated floor area of 2800 m². Building 2 was examined in paper III and simulated with the software TRNSYS 17. Also this building is a three-story building with 36 apartments. This building is slightly larger than the former with a heated floor area of 3900 m² and unlike Building 1 this building has a cellar that is included in the heated floor area.

Both buildings were simulated in original setup and with four packages of energy conserving measures each. The measures included in each package, referred to as A to H are presented in Table 2.

Table 2. Refurbishment measures included in each refurbishment package (A-D for building 1 and E-H for building 2) for each building.

	Building 1				**Building 2**			
	A	B	C	D	E	F	G	H
Insulation of roof and facade, new windows	X	X			X	X	X	X
Hot water saving measures	X	X	X	X	X	X	X	X
Lowered indoor temperature	X	X		X				
Installation of ventilation radiators						X	X	X
Energy efficient exhaust air fans						X		
Heat recovery ventilation	X		X	X	X			
Exhaust air heat pump for heating							X	X
Exhaust air heat pump for domestic hot water								X

2.2. The district heating system of Borlänge and Falun

The city of Borlänge has approximately 50,000 inhabitants. The district heating system in Borlänge is well developed and most large buildings as well as many single family buildings are attached to the grid. The production consists of a large share of excess heat from the local paper mill and steel industry. In addition to that a waste incineration plant provides most of the heat demand. The total delivered district heating in Borlänge 2013 was 370 GWh and the allocation between fuels and other heat sources is presented in Figure 3[28]. The district heating system of Borlänge was modelled with FMS in paper I. FMS are further described in section 3.1.

In 2014 a district heating pipeline with a capacity of 30 MW was built to the nearby city of Falun. The pipeline enables both cities to deliver heat to the other one at a time and the operation of the common district heating system is optimized continually to keep the production costs at a minimum. Falun is situated 20 km North-East of Borlänge and has approximately the same number of inhabitants. The district heating system of Falun is newer and slightly smaller than the district heating system of Borlänge. During 2016 the total production of the cities common district heating system was 770 GWh. The allocation between fuels and other heat sources is presented in Figure 3[14]. This common district heating system of Borlänge and Falun was modelled with MODEST in paper II. MODEST are further described in section 3.1.

2.3. The statistic based district heating systems

Åberg et al [29] has defined four models of typical district heating systems to represent the Swedish district heating sector. These models are used in paper III to examine how energy efficient refurbishment differs between different district heating systems. The models are based on statistics of fuel use, delivered district heating and electricity produced by CHP units included in the district heating systems which is available through the Swedish energy company association. The fuel mix of the four statistic based district heating systems are presented in Figure 3 and the system characteristics are presented in Table 3. The district heating system optimization tool FMS was used to model the statistic based district heating systems in paper III. FMS are further described in section 3.1.

Table 3. System characteristics of the statistic based district heating systems [29].

	I	II	III	IV
Share of the Swedish district heating sector	27.5 %	10.0 %	18.5 %	44.0 %
Share of heat/electricity production	100/0 %	76/24 %	87/13 %	82/18 %
Total heat demand [GWh/year]	13 000	5 000	11 000	23 000

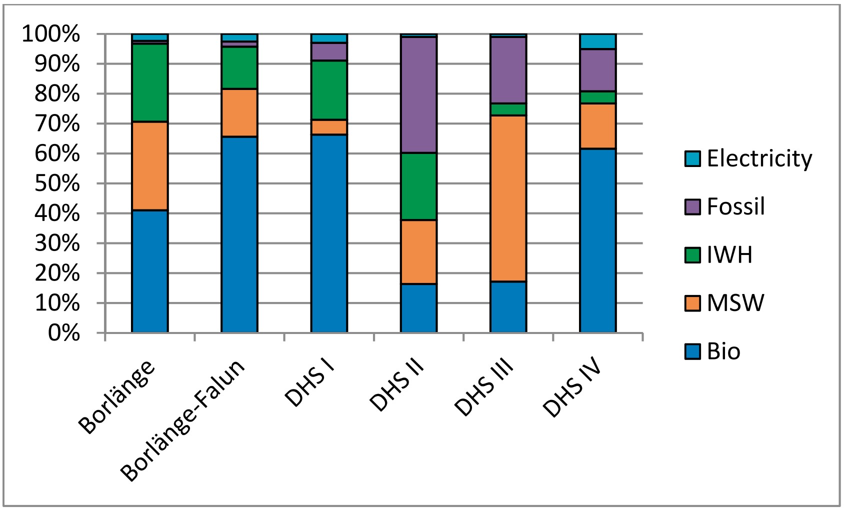

Figure 3. Fuel mix in the studied district heating systems.

3. Methodology

The methodology of this thesis is based on a combination of building simulation and district heating system modelling. Beyond this, calculations have been made to estimate greenhouse gas emissions and primary energy use. The working process that was developed in paper I and later on used for case studies in paper II and paper III is illustrated in Figure 4. The first section of this chapter describes the developed working process, followed by descriptions of the simulation and modelling tools that was used. A description of the greenhouse gas emission calculations and the primary energy calculations follows.

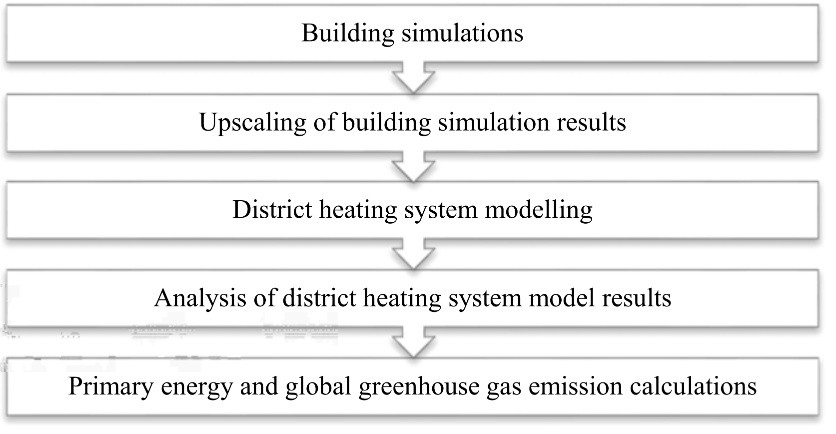

Figure 4. Schematic figure of the working process developed in paper I and used for case studies in paper II and III.

In the building simulation part of the working process, a building model is constructed, using a real physical building as a case study building. The building model is therefore based on data and statistics from the building owner, and the model is also validated against measured data to ensure the models representation of the building. The completed building model is used for simulation of different refurbishment measures, either as single measures or as packages, where several measures are included.

The case study building used for this study is situated in an area with several similar buildings; see more detailed description in the case study section. This enables the possibility to examine the impact of an entire housing area, just by scaling up the simulation results onto a larger heated floor area. As the buildings in the housing area are equally built, situated in the same geographical direction and approximately the same size, an assumption has been made that all buildings in the area have the same energy performance. The upscaling of the building simulation results becomes input data for the district heating system model calculations.

The district heating modelling part of the working process is based on statistics from existing and fictive district heating systems. The heat load of the district heating system model is depending on the results from the building simulations. The changes in energy use in the building simulations are passed on into the district heating system model. The results from the district heating system optimization are used to calculate the changes in primary energy use and global greenhouse gas emissions. Not all steps of the working process were used in all papers. Table 4 show the steps included in each paper.

Table 4. The steps from the working process included in each paper.

	Paper I	**Paper II**	**Paper III**
Building simulations	X	X	X
Upscaling of building simulation results	X	X	
District heating system modelling	X	X	X
Greenhouse gas calculations		X	X
Primary energy calculations			X

3.1. Simulation and modelling tools

Two different building simulation tools have been used in this thesis; IDA-ICE [30] and TRNSYS 17 [31]. Table 5 show which tool that was used in each paper. The building simulations are further described in the appended papers.

For the district heating systems, two different modelling tools were used as well. Table 5 show which modelling tool that was used in each paper. MODEST (Model for Optimization of Dynamic Energy Systems with Time-Dependent Components and Boundary Conditions) was developed at Linköping University, Sweden, and it is a linear programming model for cost-optimizing energy systems. MODEST aims to minimize the system cost of the studied energy system in every time period while fulfilling the energy demand. MODEST has a flexible time division which makes it possible to include detailed time division during demand peaks[32]. MODEST have been used in several studies for modelling district heating systems but can also be used to cost optimize other types of energy systems[33]–[41].

FMS (Fixed Model Structure) is also a cost optimization tool that was developed in MATLAB by Åberg and Widén [42]. The purpose of FMS is to be able to do cost optimization calculations for a district heating system with a small amount of input data. FMS uses linear programming and unlike MODEST, FMS is only designed to cost optimize district heating systems and is not suitable for other energy system modelling.

As MODEST requires more input data, it also brings the opportunity for the user to design the energy system quiet freely. FMS, on the other hand is easier to use as the amount of input data is small and it is timesaving not to have to design an own model. The disadvantage of FMS is though that the model is designed for a traditional district heating system, without possibilities for the user to add custom modifications.

Table 5. The simulation and modelling tools used in each paper.

	Paper I	Paper II	Paper III
IDA-ICE	X	X	
TRNSYS 17			X
FMS	X		X
MODEST		X	

3.2. Greenhouse gas emission and primary energy calculations

The changes in greenhouse gas emissions were calculated in paper II and III and the emission factors used for the calculations can be found in each paper. In both papers coal condensing power (CCP) have been considered as the marginal production in the electricity system. The greenhouse gas emissions considered in this study are both on a local and global level. Local emissions are defined as emissions appearing in the geographical same place as the studied energy system and global emissions are defined as emissions that occur elsewhere. The greenhouse gas emissions were calculated in terms of carbon dioxide equivalents (CO_2-eqv.), including carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O). Methane and nitrous oxide were calculated as CO_2-eqv. using the GWP100 (Global Warming Potential) method [2]. The global greenhouse gas emissions will from here be referred to as the CO_2eqv. emissions.

In this thesis biofuel has been considered to be a scarce resource. This means that if biofuel is saved due to the energy conservation in the buildings it is assumed to be able to replace fossil fuels by co-firing of biofuel with coal in CCP plants. If the use of biofuel would increase in the studied energy system, more coal is considered to be needed instead. This entails that the changes in biofuel use is calculated as changes in use of coal. Hansson et at estimated a technical potential of co-firing biofuel in CCP plants resulting in a possible generation of electricity from renewable fuels to 50-90 TWh/year for EU27[43].

The valuation of biofuel as a scarce resource is included in both the global greenhouse gas emission and the primary energy calculations. Originally, biofuel as a scarce resource was only included in paper II. However, the results from paper III have been complemented with this assumption as well within this thesis.

Primary energy is calculated by using primary energy factors, one for each fuel type. The primary energy factors used for this thesis can be found in paper III. The changes in primary energy use was originally calculated only in paper III, but is added for the results from paper II in this thesis.

4. Results

The result of the refurbishment of a multifamily housing area in the Borlänge-Falun district heating system (paper II) is presented in section 4.1. The result of the refurbishment of one multi-family building in different statistic based district heating systems (paper III) is presented in section 4.2.

4.1. The multifamily housing area in Borlänge-Falun

The impact of the refurbishment packages on the district heating system, the net electricity balance, the primary energy use and the CO_2eqv. emissions are presented in Figure 5. The district heating production is decreased with all refurbishment packages, where package A gives the largest decrease, and package C the least. Package B and D gives almost the same result in terms of decreased district heating production. The net electricity balance is defined as the sum of the changes of the electricity produced in CHP plants, the electricity used for district heating production and the electricity used in the housing area. The net electricity balance is decreased for all packages, which means that the sum of electricity available in the local system is decreased. The largest decrease occurs with package A and the least with package B. Package D gives the second largest reduction and package C the second smallest. The net electricity balance is also presented in
Figure 6, where the individual parts of the concept are shown.

The CO_2-eqv. emissions are decreased with all refurbishment packages. The largest reduction occurs with package A, followed by package B, D and C. The CO_2-eqv. emissions presented in Figure 5 is the sum of the CO_2-eqv. emissions from several sources. Figure 7 presents the individual parts included in the CO_2-eqv. emission calculations and the amount of emissions from each source. The use of primary energy for each refurbishment package that is presented in Figure 5 is the sum of changes in primary energy use from fuel used in the district heating production, biofuel valued as a scarce resource and the net electricity balance. Refurbishment package A decreases the use of primary energy the most, followed by B, D and C. The trend is the same as for the CO_2-eqv. emissions.

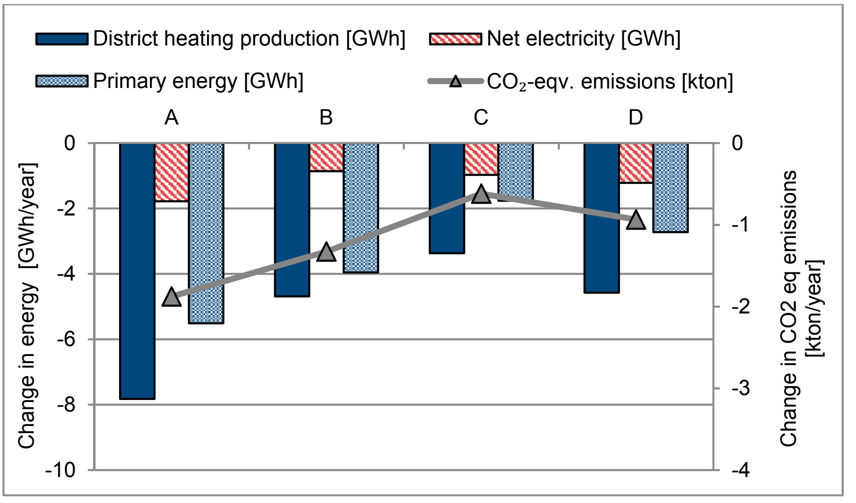

Figure 5. Change in district heating production, net electricity balance, primary energy use and CO_2eq emissions for the refurbishment packages in paper II.

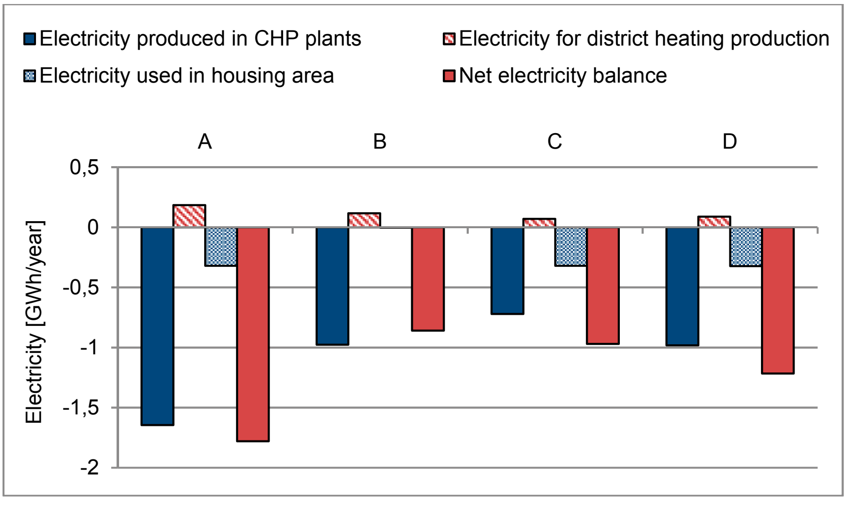

Figure 6. The net electricity balance is defined as the sum of the changes of the electricity produced in CHP plants, the electricity used for district heating production and the electricity used in the housing area.

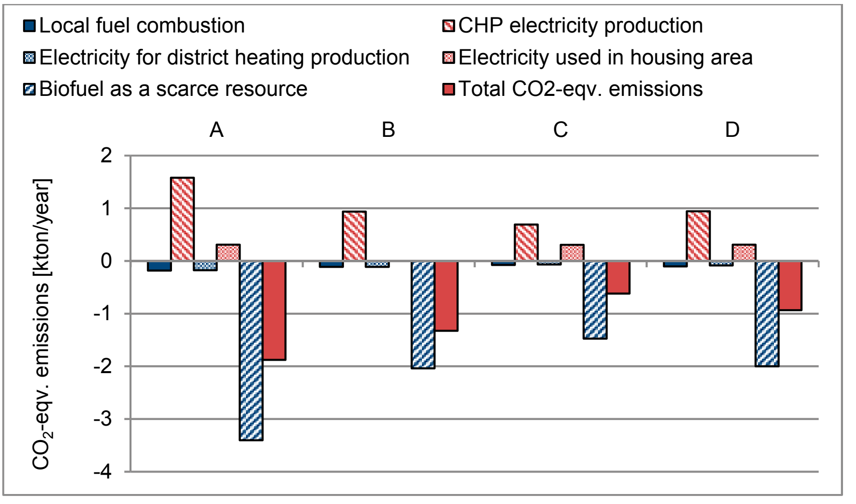

Figure 7. The total CO_2-eqv. emissions for each refurbishment package is the sum of CO_2-eqv. emissions from diffident sources in the energy system.

4.2. The statistic based district heating systems

The changes in purchased district heating and electricity are presented with the red and blue bars in Figure 8. The purchased district heating is the district heating demand of the building and it is not dependent on to which district heating system the building is attached. The purchased electricity is the electricity demand of the building. Refurbishment package H decreases the use of district heating the most, followed by package G, E and F. Refurbishment package H is on the other hand the one that increases the use of electricity the most, followed by G and E. Refurbishment package F is the only one decreasing the use of electricity.

Figure 8 also presents the changes in CO_2-eqv. emissions occurring for each package in each district heating system. For all district heating systems, package E decreases the CO_2-eqv. emissions the most and package F the least. Package G decreases the CO_2-eqv. emissions the second most for all district heating systems but DHS I, where package H decreases the CO_2-eqv. emissions the second most. Figure 9 shows the CO_2-eqv. emissions from each source included in the calculations. Increased electricity use in the building along with decreased electricity production in the CHP plants contribute with an increase in CO_2-eqv. emissions. Lower heat production in the district heating system along with savings in biofuel contribute with a decrease in CO_2-eqv. emissions.

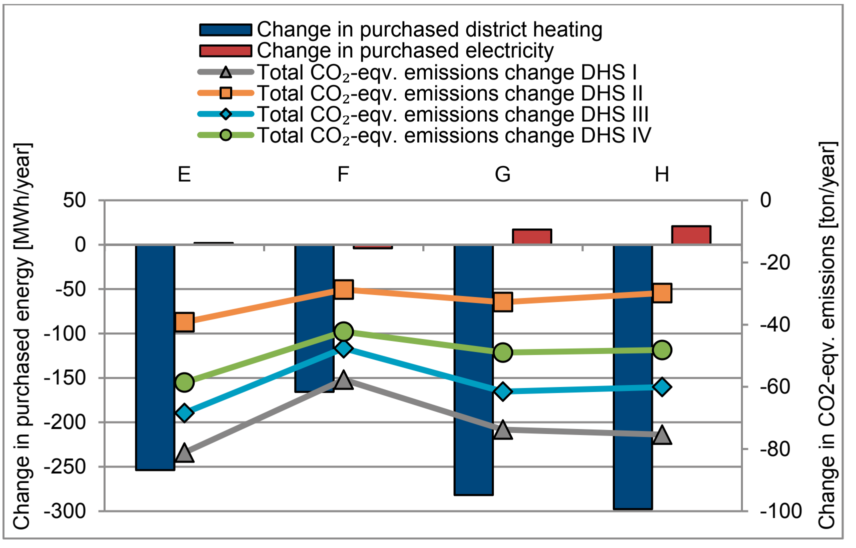

Figure 8. The changes in purchased district heating and electricity for each refurbishment package compared to the changes in CO_2-eqv. emissions for each refurbishment package in each district heating system.

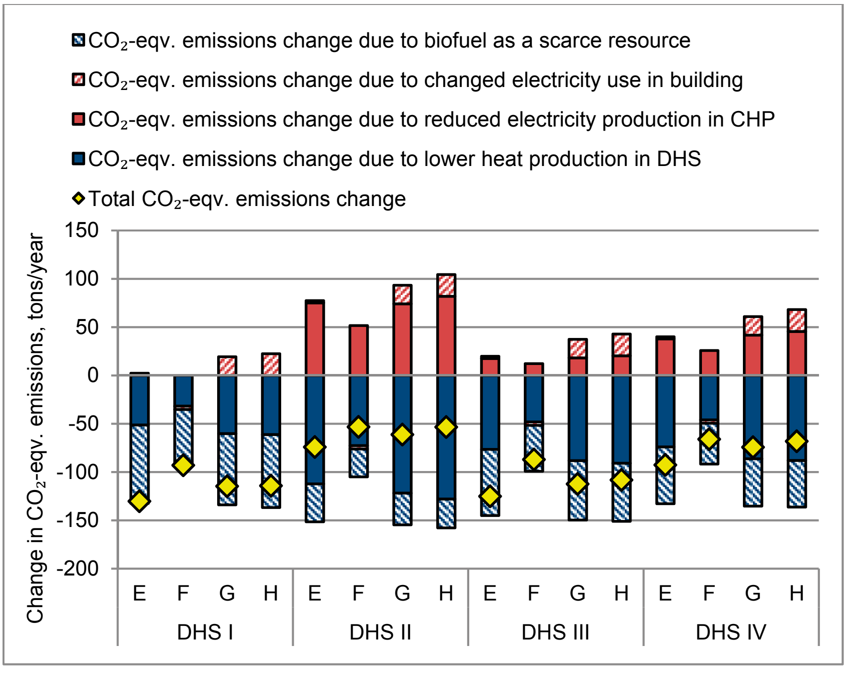

Figure 9. The CO_2-eqv. emissions from each refurbishment package in each district heating system divided into sources of origin.

The changes in primary energy use for each refurbishment package in each district heating system are presented in Figure 10. The changes in purchased district heating and electricity for each refurbishment package are the same results that were presented in Figure 8. As well as for the changes in CO_2-eqv. emissions, package E decreases the use of primary energy the most and package F the least in all district heating systems. Also the ranking of package G and H is the same as for the CO_2-eqv. emissions. Package G decreases the primary energy use the second most for all district heating systems but DHS I, where package H decreases the primary energy use the second most.

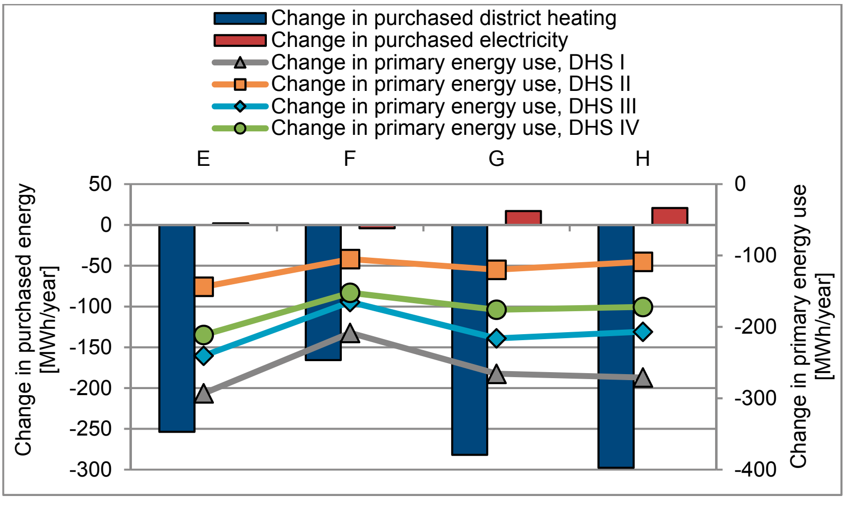

Figure 10. The changes in purchased district heating and electricity for each refurbishment package compared to the changes in primary energy use for each refurbishment package in each district heating system.

5. Discussion

This work has been carried out in close cooperation with the municipal housing company and the municipal energy company in Borlänge which has resulted in good opportunities for taking part in statistics and data for buildings as well as the local energy system. The building models and the district heating system models used in these studies has been validated against statistics and measured data available from the companies. One exception is the four statistic based district heating systems that are based on a study made by Åberg [29].

The refurbishment packages that are examined in this thesis all provide decreases in CO_2-eqv. emissions and primary energy use, but to a different extent.When the same refurbishment package is modelled within different district heating systems differences is shown between the systems. This indicates that the local prerequisites needs to be taken into account when energy efficient refurbishment is considered. On the other hand, if saved biofuel was not assumed to be replacing coal in CCP plants, the results of the refurbishment in the Borlänge-Falun system would be an increase of CO_2-eqv. emissions for all refurbishment packages. This confirms results from previous studies where CCP is considered to be the operational margin but biofuel as a scarce resource is not included, see for example Rolfsman [26].

As CCP is considered to be the operational margin in these studies, the changes in the net electricity balance also provides considerable changes in CO_2-eqv. emissions and primary energy use. Compared to the fuels used for district heating production and thus also for electricity production by CHP plants, coal and CCP have a high impact on the CO_2-eqv. emissions as well as the primary energy use. The same applies for the assumption of biofuel valued as a scarce resource, as this assumption equals the savings in biofuel with savings in fossil fuels i.e. coal. Considering CCP as the marginal electricity production is an assumption with a short-term perspective. When considering the impact of energy efficient refurbishment from a longer time perspective, alternatives to CCP can be used as a complement. As for an example, natural gas combined cycle plants has been used in previous studies with a longer time perspective [44], [45].

Considering biofuel to be a scarce resource has major impact on the results. When comparing the CO_2-eqv. emissions from different sources in Figure 7, biofuel as a scarce resource is the single largest source to changes in CO_2-eqv. emissions followed by changes in the electricity production from CHP. If the assumption of biofuel as a scarce resource was not included, the total result of the CO_2-eqv. emissions would be an increase instead of a decrease for all refurbishment packages. This occurs because of the large impact that CCP as an operational margin has on the results. When the refurbishment packages decrease the heat demand in the district heating system, they also decrease the possibility to co-produce electricity in the CHP plants. Figure 6 show the changes in the net electricity balance, where the single largest change is the decrease in produced electricity.

Typical for district heating systems are that they are individually developed and customized for the local prerequisites at where they are situated. The access to different types of fuel and heat sources, the base for the heat demand and the geographical conditions are things among others that affect how the district heating system will be designed. So also applies for the common district heating system of Borlänge and Falun and the possibilities to generalize the results of this research, as for any research where case studies of district heating systems are involved, is hampered due to this. Although, the methodology used for these studies can be used to study other buildings, energy efficient measures and packages as well as other district heating systems.

The difficulties in generalizing results from studies including district heating system is a general issue in this research area. The study where energy efficient refurbishment packages are applied to a building in four different statistic based district heating systems is nevertheless an attempt to generalize the results from this kind of research. However, the main outcome of this study is that local conditions play a major role. The importance of taking the local energy system prerequisites into account when considering energy efficiency improvement is crucial to ensure that the refurbishment will not sub optimize the energy system. Depending on the design of the district heating system, the results of the energy efficient refurbishment might vary and so also the savings in CO_2-eqv. emissions and primary energy. Another most important factor to the results is whether biofuel is considered to be a scarce resource or not. If not, the results from implementing the refurbishment packages would in some cases be an increase of CO_2-eqv. emissions and primary energy use. This also depends strongly on the assumption of CCP as the margin of electricity production.

6. Conclusions

The regional energy system prerequisites are essential for the results in CO_2-eqv. emissions and primary energy use. By using the method developed in this work to analyze energy efficient refurbishment measures within district heating systems, differences between various measures can be identified. This information can be useful when considering how to improve energy efficiency in buildings and how to reduce CO_2-eqv. emissions and primary energy use. The hypothesis of this work is well in line with this.

With the first research question in this thesis, the answer is sought as to how a method could be developed to make comparisons between energy-saving refurbishment strategies for buildings in a district heating system. A method was successfully developed and has been used in the appended papers. The method could also be used for other studies where the impact of energy efficient refurbishment of buildings within district heated areas are to be studied.

With the second research question in this thesis, the answer is sought how different energy-saving refurbishment strategies influences global greenhouse gas emissions and primary energy use in a district heating system, based on different fuel mix and CHP electricity production alternatives when biofuel is considered a scarce resource. The result shows that all refurbishment packages for all district heating systems, decreases the CO_2-eqv. emissions and the primary energy use. Variations in the savings of CO_2-eqv. emissions and primary energy are identified between the refurbishment packages when modelled in the same district heating system. The same accounts for when one refurbishment package are modelled in different district heating systems, showing that the design of the district heating system influences the impact of the refurbishment packages to a large extent.

The assumption of biofuel as a scarce resource as well as the assumption of CCP on the margin of electricity production also have a major influence on the results.

7. Future Work

This thesis deals with how energy efficient refurbishment within district heated areas influences the emissions of greenhouse gases and the use of primary energy. Within this PhD project these two areas are meant to be connected with a third one; economics. Since projects, no matter how environmentally friendly they are, tends to be realized (at least not in larger scale) without a beneficial economic situation. In the remaining part of this project economics are planned to be included.

This study is made with a short term perspective, analysing the energy system in its present design. Though, the buildings that are built or renovated today, are planned to be standing for many years and the present energy system situation that we have today are not necessarily the same as in 30 or fifty years. An interesting development of this research could be to look at energy efficient refurbishment with the same methodology as used in this study, but with a longer time perspective.

This thesis focuses on refurbishment of existing buildings but the same concept as used in this study could be used to look at new buildings or building areas. Studies of that kind could increase the possibilities for optimization from the start by constructing buildings and living areas with high performance in energy efficiency, low climate impact and primary energy use. All from a system perspective on energy use.

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Papers

Associated papers have been removed in the electronic version of this thesis.

For more details about the papers see:
http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-26499