Energy efficient renovation in a life cycle perspective

A case study of a Swedish multifamily-building

Ricardo Ramírez Villegas
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. The founding of Reesbe is an initiative of the three universities in close co-operation with industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).

www.hig.se/Reesbe
“As the island of Knowledge grows, so do the shores of our ignorance”
— Marcelo Gleiser
Abstract

Energy use in the European Union is increasing. At the same time, it is estimated that by the year 2050 most of the EU population will be living in currently existing buildings. Some of these buildings are or will be in need of renovation, and they have identified a target to reduce overall energy use. The urgency of climate change also makes it highly relevant and important to improve buildings resource and energy efficiency. This thesis aims to explain how different proposed energy efficient renovation strategies affect the energy use at different system levels, the potential environmental impacts of these alternatives, how they are connected to economic impacts and the implications of using a commercial LCA software to answer these questions from a research perspective.

In order to answer the questions above, the effect of different renovation strategies were studied by combining building energy simulations, energy system simulations, a building environmental assessment tool, life cycle assessment and life cycle cost calculations. These tools are used in order to provide an overview of how the different renovation strategies affect the production of district heating, greenhouse gas (GHG) emissions and the environmental and economic performance of the building.

The results show that the selected renovation strategies reduce energy use by decreasing transmission losses, while reducing the total amount of purchased energy by using solar energy or by changing energy carriers. These different approaches have the potential to reduce the environmental impact, mainly by reducing global warming potential, acidification potential and eutrophication potential and to some extent abiotic depletion potential. However, when changing energy carriers there is a burden shift to radioactive waste disposed. When the economic aspects are analyzed, it is shown that there is no simple correlation between financial and environmental impacts.

To analyze a building from a life cycle perspective can help to identify the advantages and disadvantages of energy efficient renovation from the building owner’s perspective as well as from a societal perspective. Applying a life cycle perspective is therefore important for building owners, building companies and practitioners as well for policy makers to avoid suboptimisation.

Keywords: Buildings, renovation, greenhouse gas emissions, district heating, energy efficiency, building environmental assessment tools, energy use, space heating, life cycle assessment, life cycle costing, payback, scenarios simulation.
Sammanfattning

Energiannvändningen inom den Europeiska Unionen ökar. Samtidigt, beräknas att år 2050 så bor merparten av EU:s befolkning i byggnader som finns idag. En del av dessa byggnader behöver renoveras eller kommer att vara i behov av renovering, och dessa är identifierade som ett mål för att minska energianvändning. Klimatförändringens akuta karaktär ökar också relevansen och betydelsen av att ha mer resurs- och energieffektiva byggnader. Denna avhandlings mål är att förklara hur olika energieffektiva renoveringsstrategier påverkar energianvändningen på olika systemnivåer, vilken är den potentiella miljöpåverkan av dessa alternativ, hur detta är kopplat till ekonomisk påverkan och vika är implikationerna av att använda en kommersiell mjukvara för att besvara dessa frågor ur ett forskningsperspektiv.

För att svara på dessa frågor studeras effekten av olika renoveringsstrategier genom av kombinera byggnadsenergisimuleringar, energisystemssimuleringar, system för miljöcertifiering av byggnader, livscykelnalys och beräkningar av livscykelkostnader. Dessa verktyg används för att ge en överblick över hur olika renoveringsstrategier påverkar produktionen av fjärrvärme, utsläpp av växthusgaser och byggnadens miljömässiga och ekonomiska prestanda.

Resultaten visar att de valda renoveringsstrategierna minskar energianvändningen genom att minska transmissionsförlusterna, och minskar behovet av köpt energi genom användning av solenergi och genom att byta energibärare. Dessa olika strategier har potential av minska miljöpåverkan i termen av klimatpåverkan, förorsurning, övergödning och till viss del utarmning av abiotiska tillgångar. Ett byte av energibärare medför dock att bördan skiftas till deponerat radioaktivt avfall. När de ekonomiska aspekterna analyseras visar det sig att det inte finns en enkel korrelation mellan dessa och miljöpåverkan.


Nyckelord: Byggnadsrenovering, växthusgasutsläpp, fjärrvärme, energieffektivitet, system för miljöcertifiering av byggnader, energianvändning, byggnadsuppvärming, livscykelnalys, livscykelkostnader, återbetalning, scenariosimulering.
I would like to thank my supervisors Ola Eriksson and Thomas Olofsson for their great guidance, support and patience through my work. I also would like to thank my company mentor at Byggpartner, Kristian Haglund for his support during the last years of my work. I’d like to acknowledge the help of Sandra Gossas, Mats Tiger and Thomas Sidhage for acting as my company mentors during my research work.

I am extremely grateful to my colleagues Tina Lidberg and Moa Swing Gustafsson for all the support they give, for their patience, their willingness to contribute and the good discussions we had during this years.

I’d like to recognize the assistance that I received from Ewa Wäckelgård, Mats Rönnelid, and Jonn Are Myhren for the assistance they gave me during my research. I had the pleasure to work with great colleagues at Dalarna University that provided insights, constructive criticism and a great environment to work at. I also wish to thank Eva Wännström, Mathias Cehlin and all the REESBE research school staff for all their practical help.

Finally I would like to extend my deepest gratitude to my family. Many thanks to my mother for pushing me towards the goal, as usual. To my mother-in-law Karin especially for all the care and help she has given me by loving and caring for my children and for cheering me on. To my wife Jenny, for always being there, listening and supporting me being the rock I lean on, without her support the completion of this work would not have been possible. And above all to my kids, Mika, Tuuli and Astrid for turning my life upside down.
List of Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals. The text marked with **bold** is the author’s main contribution:

**Paper I**
Author’s contribution: Conceptualization, **formal analysis**, investigation, methodology, **building energy simulation**, validation, visualization, writing

**Paper II**
Author’s contribution: Conceptualization, **formal analysis**, investigation, methodology, **building energy simulation**, validation, visualization, writing

**Paper III**
Author’s contribution: Conceptualization, **formal analysis**, investigation, methodology, **building energy simulation**, validation, visualization, writing

**Paper IV**
Author’s contribution: **Conceptualization**, formal analysis, investigation, methodology, **building energy simulation**, validation, visualization, writing

**Paper V**
Author’s contribution: Conceptualization, **formal analysis**, investigation, methodology, **building energy simulation**, validation, visualization, writing

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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>BEAT</td>
<td>Building environmental assessment tool</td>
</tr>
<tr>
<td>CEN</td>
<td>European Committee for standardization</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
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<td>LCC</td>
<td>Life cycle cost</td>
</tr>
<tr>
<td>LEED</td>
<td>Leadership in energy and environmental design</td>
</tr>
<tr>
<td>BRE EAM</td>
<td>Building research establishment – environmental assessment method</td>
</tr>
<tr>
<td>DH</td>
<td>District heating</td>
</tr>
<tr>
<td>BES</td>
<td>Building energy simulation</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy system simulation</td>
</tr>
<tr>
<td>SGBC</td>
<td>Sweden green building council</td>
</tr>
<tr>
<td>IDA-ICE</td>
<td>Implicit Differential Algebraic equations system solver - Indoor Climate and Energy</td>
</tr>
<tr>
<td>MODEST</td>
<td>Model for Optimization of Dynamic Energy Systems with Time dependent components and boundary conditions</td>
</tr>
<tr>
<td>GWP</td>
<td>Global warming potential</td>
</tr>
<tr>
<td>AP</td>
<td>Acidification potential</td>
</tr>
<tr>
<td>EP</td>
<td>Eutrophication potential</td>
</tr>
<tr>
<td>ADP</td>
<td>Abiotic depletion potential</td>
</tr>
<tr>
<td>RW</td>
<td>Radioactive waste</td>
</tr>
<tr>
<td>GHP</td>
<td>Geothermal heat pump</td>
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<td>PV</td>
<td>Photovoltaics</td>
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1. Introduction

1.1. Background
Sustainability has become a driving force in the building construction industry, globally. Several countries in the world have a Green Building council to address sustainability at a local level. In order to progress with that aim, it is necessary to test and develop new tools to make the industry and its customers aware that there is an increased need to analyze, understand and react to the impacts of their activities on society.

1.1.1. Sustainable development
In the 1980’s the Brundtland Commission was established to form the foundation of how the United Nations (UN) would work towards sustainable development. The result was the document “Our Common Future”[1], in which the concept of sustainable development was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The concept is a combination of what is called the triple-bottom line; economic growth for people to meet a decent life standard, environmental protection meaning that ecosystems and nature should be preserved and social equality for communities to thrive with a special emphasis that none of these categories should be compromised.

After the work of the Brundtland Commission, the UN held the UN Conference on Environment and Development in 1992. From that meeting a document known as the Rio declaration in 27 points declares how sustainability should be addressed, placing a special emphasis on environmental issues [2].

In 2009 Rockström et al. defined a way to approach the environmental issues. This was called planetary boundaries [3]. These boundaries are defined as the limits within which humanity can operate safely. As shown in Figure 1, nine main categories have been proposed in the concept in order to track and quantify human perturbations in environmental systems [4]
In 2015 the United Nations (UN) adopted the 2030 agenda on sustainable development known as the Sustainable Development goals (SDGs) (Figure 2) which was based on work carried out in previous research projects and commissions. The main objective of this initiative is to decouple economic growth from climate change, poverty and inequality [5]. These goals aims to address sustainability through seventeen different goals, each one divided in measurable indicators.

Figure 1 Planetary boundaries [4]

Figure 2 Sustainable development goals
Believing that buildings and the building construction industry can contribute to meeting the sustainable development goals, the World Green Building Council (WGBC) [6] identified nine of the goals relevant for buildings and the construction industry:

3. Good health and well-being
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation and infrastructure
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life on land
17. Partnership for the goals

In the present thesis, the relevant goals that are addressed are:

7. Affordable and clean energy, as energy efficient renovation is addressed
8. Industry, innovation and infrastructure, as it is expected that this thesis will contribute to a better understanding that can help building owners and construction companies
9. Sustainable cities and communities, as it is expected to contribute with knowledge that can help with renovation of buildings towards sustainability
12. Responsible consumption and production, as this thesis addresses the buildings’ energy use factor
13. Climate action, as there is an analysis from a life cycle perspective that includes different environmental impacts such as global warming potential (GWP).

1.1.2. Policy for sustainable development

Since the Rio Declaration and the work of the Brundtland Commission, worldwide greenhouse gas emissions are still on the rise and this situation has led to an increase in global mean temperatures within a probable range of 0.8 to 1.2°C [7]. Lack of action in different countries around the world led to a historical agreement in the Conference of Parties 21 in Paris, where 194 countries signed an agreement to keep global temperature rise below 2°C by reducing GHG-emissions drastically around the world by 2050 [8]. Since then, international organizations and governments have been implementing policies to comply with this agreement, even if there is a concern that governments are not doing enough to address this issue.

The European Union (EU) stated that in order to fulfill these requirements all sectors need to invest in energy efficiency [9]. Based on the framework of these agreements, the EU has set goals to reduce greenhouse gas (GHG) emissions by 40 % by the year 2030, compared to 1990 emissions [10].
Since the 1990’s the discussion on anthropogenic environmental impacts reached further than to the general public and moved towards government and companies, as a reaction to the increased awareness of our use of resources. Within the building construction industry, this increase in awareness led to the development of Building Environmental Assessment Tools (BEATs). Since then BEATs have been used to evaluate resource use and to assess ecological loading and indoor environmental quality [11]. According to Wallhagen et al. building environmental assessment tools play different roles: marketing for “environmental friendly” buildings, stimulation for better environmental performance, as tools for decision-makers and as tools to measure environmental impacts, among others [11]. There are many tools available such as LEED [12] and BREEAM [13]. In the Swedish case, since the end of the 1990’s there has been a need to develop a tool that could be applicable to local conditions, which has resulted in the development of Miljöbyggnad. This tool is a Swedish BEAT and has certified more than 1500 buildings to date [14]. This tool is the most used in Sweden and is based on national common practices and norms [15]. This BEAT (Miljöbyggnad v. 2.2) focuses on three areas; energy (four indicators), indoor environment (nine indicators) and material & chemicals (three indicators) see Figure 3. The tool is owned and developed by the Swedish Green Building Council. There are three possible grade levels, bronze, silver and gold. The bronze level can be achieved by complying with the current regulations, while the silver needs better environmental practices and the best performing buildings expect gold. [14].

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Aspect</th>
<th>Area</th>
<th>Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy use</td>
<td>Energy use</td>
<td>Energy</td>
<td>BRONZE</td>
</tr>
<tr>
<td>2. Active heating demand</td>
<td>Heating demand</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>4. Energy source</td>
<td>Noise protection</td>
<td>Noise protection</td>
<td>SILVER</td>
</tr>
<tr>
<td>5. Noise protection</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>6. Radon content</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>7. Ventilation rate</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>8. NO2 to indoor air (from traffic)</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>9. Moisture prevention</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>10. Thermal climate winter</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>11. Thermal climate summer</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>12. Daylight</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
</tr>
<tr>
<td>13. Legionella</td>
<td>Air quality</td>
<td>Energy source</td>
<td>BRONZE</td>
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</tbody>
</table>

Figure 3 Example of Miljöbyggnad 2.2 assessment [14]

1.1.3. Energy use in the EU and Sweden

1.1.3.1. Energy use in the EU

In order to reach the target of a 27% reduction of energy use within the EU, different initiatives have been promoted to increase energy efficiency and energy performance in buildings and household appliances, and the use of new
energy technology. Fossil fuel still represents approximately 75% of the primary energy use in the EU (see Figure 4).

The categories in Figure 4 are defined by the OECD as follows;

- Solid fuels – Various types of coal and their derived products
- Petroleum products – All products that are manufactured from crude oil
- Gas – Natural gas, and its derived products
- Nuclear heat – The reported steam generation from a nuclear plant
- Renewable energies – Energy derived from natural processes that are replenished constantly
- Waste – solid waste that contains non-biodegradable material [18].

It is noticeable that the amount of petroleum products and solid fuels within the EU has gradually declined while the population has increased [17].

1.1.3.2. Energy use in Sweden

The total energy supplied in Sweden has remained unchanged from 1990 - 2016 but the distribution of different energy carriers has changed (see Figure 5).
During 1990-2017 the supply of nuclear energy (reported gross, as supplied energy in fuel) has remained unchanged, mirroring the development in the EU, petroleum products have decreased and biomass has grown constantly. This development is due to Swedish policy during the last 20 years, where taxes on emissions have made the use of fossil fuels more expensive and subsidies on biofuels have accelerated the shift to a higher share of biofuels [21]. Wind power has tripled its share during the period 2010-2017, in Sweden. The development is due to the fact that Sweden has large landowners good possibilities for investors, relative ease for obtaining permits and also because wind turbines have become cheaper and have low financial costs [22]. Hydropower has remained constant since the 1980’s [19]. As in the EU, energy use in Sweden has remained constant while the population has increased [20].
The final energy use in the residential and service sectors (households, public administration, commercial, agricultural, forestry, fishing and construction) in Sweden represents around 40% of the totally energy use and 15% of total GHG emissions [21]. Still, there is great interest in Sweden for reducing energy use in buildings, and the latest regulations, such as BBR (Swedish Building Code), demand lower energy use in buildings than previous regulations [23].

In the residential and service sector (where household and non-residential buildings represent 90% of the sector), the use of oil products has decreased by 70% during 1990-2016.

The electricity use in the sector has remained stable since the 1990’s due to different developments; on the one hand, the amount of household and operational electricity use in buildings has increased due to the increase in household appliances and the increase in heat pumps. On the other hand the change to more energy efficient appliances and to district heating which replaces direct electrical heating (and also oil products) counteracts the increase. [24][25].

Half the energy use in the sector goes to heating, due to the relatively cold climate in Sweden. Electricity is the most common source of heat for single family buildings and DH the most common for multi-family buildings and those in the service sector. [26].

**1.1.4. Housing stock**

It is estimated that the EU population will increase until the year 2080, having its peak around 2045 [27]. At the same time, according to the European Commission [28], 80% of the population will be living in already existing buildings by the year 2030. The main reason, according to Botta [29], is that there is a tendency in Europe and North America towards buildings being renovated rather than new ones being built. This trend is noticeable in the EU where the
growth rates of the residential sector are around 1% [30]. In Sweden, see Figure 7, around one third of the total housing stock was built in the period 1965-1975 in the Million Homes Programme (Miljonprogrammet).

The program was characterized by a highly rationalized use of materials as well as by a high degree of experimentation, which, in turn, led to the culmination of roughly one million dwellings (in - at the time - an 8 million inhabitants’ country) making this one of the most ambitious housing programs of its era [32]. Some 50 years after its culmination, and with the new EU energy directives in mind, the way that these dwellings use energy is a rethink challenge. Most of these buildings were finished before the 1973-74 global oil crisis, in an era where oil prices were stable and low.

1.1.5. Energy use in buildings
As stated in 1.1.3.2, approximately 50% of the total space heating and domestic hot water demand in Sweden comes from district heating (DH). For multi-family dwellings, as much as 85% of all buildings being dependent on these systems [33].
Shortage of oil during the first oil crisis and the threat of a shortage of energy due to the dependency on imports also encouraged a massive development of DH systems in Sweden. Many of the buildings built during the Million Homes Programme are connected to a DH system. In 230 of Sweden’s 270 municipalities there is some sort of DH plant [33]. It is important to note that DH systems are local energy systems and the fuel use varies between different municipalities. Figure 8 shows a superposition of all DH systems in Sweden.

1.1.6. Energy efficiency measures in buildings

As construction of new dwellings has been stable at a low level in Sweden since the late 1970’s [34], the existing stock will house most of the population in coming years [35]. Many existing buildings are in need of renovation and there is a great possibility of improving energy performance by renovation [34]. According to Rabani et al. energy efficient renovation within the EU aims to decrease greenhouse gas emissions while improving indoor air quality and the architectural qualities of buildings [36]. There has been a suggestion that most of the potential energy use savings can be achieved in the Million Homes Programme since a considerable share of the building stock was built during this era [35].

However, earlier studies point out, energy efficient renovation would present significant barriers to reducing or even maintaining energy use, due to paradoxes in energy efficiency. According to Copiello [37], there is a weak connection between energy efficiency and lower energy use, and a higher disposable income due to energy efficiency could boost consumption, also known as the rebound effect. The result of the paradox is that energy efficiency is a driver for economic development so that, in the end, driving energy prices down incentivizes higher use. According to Swing Gustafsson et al. renovation
reduces total energy use, but not necessarily the use of primary energy [38]. Blomqvist et al. state that using geothermal heat pumps (GHP) would increase GHG emissions for future energy use scenarios [39]. Some authors argue that reducing the heating demand in a multi-family building in Sweden by changing energy carriers connected to district heating with a large share of renewables, has no environmental advantages from a marginal electricity production perspective, if electricity consumption increases [38] [40] [41]. There is also a discussion on whether the current requirements for near zero buildings favor heat pumps, as they only consider purchased energy as energy use [42][43].

Considering the increase in electricity use, Mangold et al. argue [35], that energy use in the building stock is not decreasing, due to the fact that only purchased energy is accounted as energy use. The increase in energy use, the authors argue, can be linked to user behavior, increased indoor comfort and over-heating.

Most of the research literature focuses on the building energy performance during the operation of the building. There is consensus in the building construction industry that, in most cases, most of the energy use in a building is used during the operation lifetime. However, studies show that when it comes to energy efficient buildings – such as those built to meet the passive house standard – embodied energy can exceed the operational energy by as much as 3 times the operational energy use [37], raising doubts on trade-offs from energy efficiency in buildings. As Copiello states, “as well as the investment cost could be not fully repaid by the operating savings, similarly the energy embodied in the construction could exceed the energy consumption in operation” [37]. This is reinforced by Akander et al. in a Swedish context [40].

Mangold et al. [35] ascertain that analyzing only the energy use in the building narrows the system boundaries and there is a need for life cycle thinking.

**1.1.7. Building environmental assessment tools**

Extensive research has been made regarding Building Environmental Assessment Tools (BEATs). These tools aim to assess the environmental impacts of buildings and improve their environmental performance [44]. Previous research has shown that most Building Environmental Assessment Tools have a limited life cycle perspective and that the flexibility of some tools signal that environmental aspects are exchangeable giving decontextualized assessments that can differ with real environmental impacts [11]. As LEED and BREEAM are intended for the American and British markets [45] there was a need to develop a Swedish tool [11] based on a dialogue between different sectors leading to the development of Miljöbyggnad [46]. However, Mahmoud et al. argue that there is a need to develop a global BEAT for existing buildings to tackle sustainability from an international perspective [47].

**1.1.8. Life cycle perspective**

According to Cabeza et al. [48] there has been a shift in the building construction industry during recent years from focus on energy use to also include materials and the construction process, This change has taken place as buildings
have become more energy efficient, making the environmental impacts for materials and building more significant. The need to analyze the environmental impacts for buildings has led to the development of standards for life cycle assessment of buildings such as the CEN 15878 [49]. This development has led to an increase in research on buildings from a life cycle perspective and also to public initiatives from governmental authorities in which LCA plays an important role.

LCA research on buildings has shown an increasing interest in recent years [50], [51]. The approach for LCA of buildings has shifted from energy use to include the embodied environmental impacts of buildings [52]–[58], calculations have become more transparent [59] and standardization has played a major role in spreading the use of building LCA. Vilches et al. [60], have noticed that the relation between energy use and the building environmental impact has been changing; as buildings become more energy efficient a higher share of the environmental impact is embedded in the building and energy use is mostly related to the global warming potential [54]. By studying energy efficient renovation Piccardo et al. [55] have noticed there is an increased non-operational primary energy use which is linked to material choice when trying to achieve passive house standard. Hasik et al. [56] claim that the choice of energy sources can overshadow the effect of energy efficient renovation. Studies have been carried out for high rise buildings [61], commercial [62] and residential buildings [63]–[67] with some studies focusing on renovation [62]–[65], [68]–[70]. However, Cabeza et al. [48] state that the majority of the research is directed towards new buildings, and specifically to “exemplary buildings” meaning that the LCA is carried out on buildings that have been designed to excel in environmental performance. In a study of a residential multifamily building with a timber building frame, it was found that the selected heat supply had a greater impact than renovating the building to meet the passive house standard [63]. Häfliger et al. [58] performed a sensitivity analysis using different materials, and concluded that material choice has a significant environmental impact for the whole building.

Regarding building renovation, studies suggest that in order to decrease the energy use of a building there are mainly three approaches, by a) changes in the building envelope, b) changes in the architectural properties of the building and c) retrofitting building services [65].

Some studies focus on the development of decision tools based on LCA in order to help building owners tackle environmental impacts when making decisions in a renovation process [71]. Other studies focused on studying the challenges that come with the implementation of LCA [72]–[75].

Malmgren et al. point out that environmental and economic analyses of renovation are rarely evaluated together [76]. This situation has been tackled by studies that combined LCA with LCC [66], [67], [77]–[80]. Still, there is a lack of LCA/LCC studies for multifamily buildings in general [81].
1.2. Aim and objectives

This thesis is motivated by the fact that population and energy use within the EU is increasing. At the same time, by the year 2050 most of the population within the EU and North America will be living in buildings that are already built. In addition, this work aims to approach the urgency of climate change and the need for energy and resource efficiency in buildings. In this thesis, a case study has been used to analyze the environmental impacts of different renovation alternatives; the analysis was performed for a Swedish multi-family building with district heating. The case study and the renovation strategies are taken in a regional context but attention is paid to the international discussion on energy use. The aim of this thesis is to contribute to the understanding of how energy efficient renovation impacts on a building and its surrounding energy system from a life cycle perspective. This thesis focuses on communication for the research community as well as practitioners, construction companies and building owners. Three aspects are considered in this thesis: energy use, environmental impacts and economic impacts. The objectives can be expressed in the following research questions

1.2.1. Research questions

1. How can the proposed energy efficient renovation strategies affect the total energy use at different system levels in the building as well as in the surrounding local energy system?

2. What are the potential environmental and economic impacts for the proposed different energy efficient renovation strategies?

3. How can impacts on energy performance, environmental performance and economic performance correlate for the different energy efficient renovation strategies?

4. What are the methodological implications of using a commercially available software while performing research on life cycle assessment?

1.3. Appended papers

- Paper I (Lidberg et al. 2014) establishes the methodology used in this thesis. This paper addresses research question 1 and lays the ground for the methodology that is used throughout the thesis. Also there is important data that determine the energy use of the building before the renovation and how the composition of the local DH system affects the results.
- Paper II (Ramirez-Villegas et al. 2016) addresses the research questions numbers 1 and 2. This work improves the methodology and uses a differ-
ent energy system simulation in order to understand how the energy efficient renovation would affect the DH system in Borlänge. It also uses the building environmental assessment tool Miljöbyggnad, to determine the building environmental rating by energy use and compare it with the DH local emissions.

- Paper III (Ramirez-Villegas et al. 2019) addresses questions numbers 2 and 4 by using a commercially available software based on a CEN standard. How different renovation strategies affect the environmental impacts of the case study building was analyzed.
- Paper IV (Ramirez-Villegas et al. 2019). This paper addresses research questions 2, 3 and 4, using a commercial software based on the CEN standard for both LCA and LCC. This study aims to assess the economic and environmental impacts of energy efficient renovation and how these aspects can be correlated.
- Paper V (Ramirez-Villegas et al. 2019) addresses research questions 1 and 2, as the work investigates how different renovation strategies affect the environmental impact of the buildings when changes in electricity production are introduced.

In Figure 9 it can be seen how the different papers contribute to answering the research questions.
2. Methodology

The effect on energy use from energy efficient renovation is examined using Building Energy Simulation (BES) and Energy System Simulation (ESS). The environmental impacts of renovations were made by assessing the scenarios with the Building Environmental Assessment Tool (BEAT) and Life Cycle Assessment (LCA), and the economic impact was calculated as the Life Cycle Cost (LCC). These concepts are further described in the following chapter.

In order to make a comprehensive building model, the selected BES software IDA-ICE (Implicit Differential Algebraic equations system solver - Indoor Climate and Energy) [82], was used. This tool is a well-known tool that is used within research and the industry.

The simulation of the district heating system, the selected software, MOD-EST (Model for Optimization of Dynamic Energy Systems with Time dependent components and boundary conditions) [83] was used. This tool was used due to the robustness of the system and is widely used by researchers.

The Building Environmental Assessment Tool selected was Miljöbyggnad (Version 2.1) [44], owned and managed by the Swedish Green Building Council (SGBC). This tool, which is not a simulation tool, was selected as it is based on experience and norms from Sweden, and, as previously stated, has become the most common to use for buildings in Sweden.

The Life Cycle Assessment tool selected was a cloud-based software called OneClickLCA [84], a comprehensive web based tool based on the European life cycle assessment standard for building CEN 15978. The same software was used for the life cycle costs assessment and it complies with the European standard for life cycle cost assessment for buildings CEN 16627.

The proposed methodology intended to combine BES, ESS, BEAT, LCA and LCC in order to provide an overview of how different energy efficiency improvements within the system boundaries would affect the production of DH, GHG emissions and the environmental performance of the building. This is further illustrated in Figure 10.
As seen in Figure 10, the thesis has been developed following some different steps that complemented the analysis.

The first step “Construction and calibration of the selected BES building model” consists of the collection of all relevant information needed to make a model of the selected building. In this study, BES was performed for an existing building. In order to make an accurate model of the building, all data that is related to an energy balance of the building is useful at this point. Set-up temperatures, indoor and outdoor temperatures, are examples of the data being collected. Using this data, it is possible to calculate the heat demand of the building for a selected period with methods such as the “energy demand signature” [86]. By using the output of this analysis, it is possible to adjust parameters in the BES model that are otherwise difficult to collect, such as thermal bridges and air tightness.
The second step “Simulation of renovation scenarios in selected BES” consists of simulating the desired renovation alternatives to reduce the energy demand of the building, using available performance data of installations and materials that are common practice within the building construction industry. Depending on the homogeneity of the dwelling area, it is possible to scale up the results to reflect the energy demand of the whole dwelling area, as if the complete building stock were to be renovated. Alternatively, it is possible to simulate the most representative buildings in a neighborhood. The output of this analysis is the energy demand of the buildings with the proposed measures. The results of these scenarios are the input data for the next step.

In the third step, “Simulations of DH system with Selected ESS”, the municipal DH system is modeled, based on information provided by the municipal energy company. A detailed inventory of production units, fuels and energy use by end users is needed. With the data provided and the results of the previous steps (both the original building and the renovation alternatives), it is possible to identify the reductions in energy use, changes in the different production units and fuels.

In the fourth step “Building Environmental Assessment Tool” a predefined assessment of the different renovation scenarios is made using the selected tool. All the necessary information for this assessment is available from the preparation and the results of the BES scenarios. The result is an environmental rating based on the performance of different renovation scenarios.

In the fifth step “life cycle assessment”, an environmental life cycle assessment of the different renovation scenarios is made using the selected software. The results are the potential environmental impacts in the selected environmental impact categories for the different renovation scenarios (see 3.2.2).

In the final step “Life cycle cost assessment” an economic assessment of the renovation is made, using the data gathered from LCA (regarding the amount of materials and energy use) and the relevant economic information. The result shows the costs for the different renovation scenarios during the lifetime of the building (see 3.3).

With the results of all simulations and assessments it is possible to analyze the different scenarios and their overall performance in terms of local and global environmental impact plus the economic impact of the renovation.

After the whole analysis had been carried out, a sensitivity analysis was made in order to test how changes in the energy system would affect the environmental performance of the different renovation scenarios.

The main features of the combined methodology (building energy simulation, energy system simulation, LCA and LCC) are described in more detail below.

2.1. Building energy simulation
In order to carry out an accurate energy simulation of the building, the heat demand was monitored during November 2014-February 2015, as the energy
balance of the building during the period October to March is dominated by the outdoor temperature variations. The building was monitored using temperature loggers in both the supply and return of the hydronic system of the building, as the substation is located in an adjacent building. Then, the indoor temperature was monitored using a temperature log in the exhaust ventilation air duct. Water flow and also the outdoor temperature were measured directly at the substation. Using this data, and the original drawings of the building provided by the building owner, the heating demand was calculated using a regression method known as the “Energy demand signature” [86]. This method was used in order to minimize the gap between the predicted and the actual energy performance of the building [87], [88]. The regression was compared to the building model in order to adjust the relevant input parameters [89]. With a calibrated model of the case study building, different renovation scenarios were simulated with different combinations of building services installations and building components, based on data from the manufacturers.

2.2. Energy system simulation

In paper II the district heating system was modeled using the selected ESS. The combined district heating system for the municipalities of Borlänge and Falun in Sweden is used. Both municipalities’ city centers have around the same number of inhabitants. The two systems are interconnected by a 30 MW pipeline that enables heat to be transferred both directions. District heating in Borlänge consist mainly of industrial excess heat and municipal household waste incineration, while Falun has a mix of different types of biofuels. The energy system simulation for this paper includes calculation of locally emitted greenhouse gases (calculated as CO₂eq). The emission factors are presented in Table 7.

2.3. Building environmental assessment tool

In paper II the energy use of the building was assessed with the BEAT Miljöbyggnad v.2.1 [44] for the different scenarios. All the necessary information for the assessment is available from BES. The assessment gives an overall rating on energy use based on the criteria established by the methodology. The indicators are based on the Swedish building code and experiences within Sweden. The methodology covers three areas; 1) energy, 2) indoor environment and 3) material and chemicals.

This thesis covers only one of the three categories of Miljöbyggnad; energy. This category is, in turn, divided into four different indicators; 1) energy use, 2) active heating demand, 3) solar heat gains and 4) energy source.

The first indicator is calculated as the annual specific use of bought energy per m² heated area. Energy use for space heating, cooling and facility electricity is included. The starting point for the rating comes from BBR [23]. Two factors affect the rating of the building: the location, as Sweden is divided into three climate zones, and the type of heating system (Table 1).
Table 1. Rating criteria for energy use in multifamily buildings [14]

<table>
<thead>
<tr>
<th>Energy use (kWh/m² year)</th>
<th>Bronze</th>
<th>Silver</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric heating</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>BBR demands</td>
<td>≤100%</td>
<td>≤100%</td>
<td>≤75%</td>
</tr>
<tr>
<td>Climate zone I</td>
<td>≤130</td>
<td>≤95</td>
<td>≤71.25</td>
</tr>
<tr>
<td>Climate zone II</td>
<td>≤110</td>
<td>≤75</td>
<td>≤56.25</td>
</tr>
<tr>
<td>Climate zone III</td>
<td>≤90</td>
<td>≤55</td>
<td>≤41.25</td>
</tr>
</tbody>
</table>

The active heating demand is calculated based on the Dimensioned Winter Outdoor Temperature during the night. The power input is the sum of losses through transmission, air leakage and ventilation.

Table 2 Rating Criteria for active heating demand [14]

<table>
<thead>
<tr>
<th>Active heating demand (W/m²)</th>
<th>Bronze</th>
<th>Silver</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Zone I</td>
<td>≤98</td>
<td>≤63</td>
<td>≤42</td>
</tr>
<tr>
<td>Climate Zone II</td>
<td>≤84</td>
<td>≤54</td>
<td>≤36</td>
</tr>
<tr>
<td>Climate Zone III</td>
<td>≤70</td>
<td>≤45</td>
<td>≤30</td>
</tr>
</tbody>
</table>

The next indicator, solar heat load, is a measure of solar radiation in a given room and is calculated in W/m², floor. This indicator is calculated for the room in which people spend time which has the worst performance. Then 20% of the adjacent floor area is also calculated, and if this has a better performance than the worst room, it is possible to move up one level in the rating system.

Table 3 Rating criteria for passive solar heat load [14]

<table>
<thead>
<tr>
<th>Solar heat load (W/m²)</th>
<th>Bronze</th>
<th>Silver</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤38</td>
<td>≤29</td>
<td>≤18</td>
</tr>
</tbody>
</table>

The last indicator is called energy source. This indicator combines three different environmental quality measures into one. A high premium is put on buildings that largely use energy that is renewable, gives low emissions and low waste amounts. The sources of energy have been divided into four different environmental categories:

1. Solar, wind and hydropower and industrial excess heat lacking economic value which otherwise would be lost. These are constant renewable flowing energy sources, or recycled energy.
2. Biofuels from HWCs (hot water centrals) or CHPs (Combined Heat and Power plants) or small scale boilers fulfilling environmental regulations.
3. Boilers that do not comply with environmental regulations
4. Energy sources that are neither constant flowing nor renewable (oil, coal, peat and uranium)
Electricity without a guarantee of origin is counted as Nordic mix with 55% of electricity use within category 2 and 45% in category 4. When waste incineration is included in the district heating system, the fossil part has to be decided. There are templates available for excess heat, waste incineration, solar collectors, solar cells and wind turbines. Rating levels are designed as percentages of annual energy use with the intention of moving away from categories 3 and 4 towards categories 1 and 2, c.f. Table 4.

Table 4 Rating criteria for energy sources [14]

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Bronze</th>
<th>Silver Alt 1</th>
<th>Silver Alt 2</th>
<th>Gold Alt 1</th>
<th>Gold Alt 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>≥50%</td>
<td>≥10%</td>
<td>≥20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category 2</td>
<td>of categories</td>
<td>≥50%</td>
<td>≤20%</td>
<td>≥50%</td>
<td>≤20%</td>
</tr>
<tr>
<td>Category 3</td>
<td>1,2 and 3</td>
<td>≤25%</td>
<td>≤25%</td>
<td>(3, 4)</td>
<td>(3, 4)</td>
</tr>
</tbody>
</table>

2.4. Life Cycle Assessment

Buildings have different environmental impacts during their lifetimes. Traditionally, in seasonal countries, with cold winters as in Sweden, a great deal of the impact is related to energy use. In this thesis, the environmental rating from the BEAT was compared with the calculated CO₂eq emissions in order to check if the BEAT methodology is consistent with GHG emissions. After this analysis was carried out, a more life cycle oriented environmental analysis was proposed, analyzing the impact of materials and different energy sources.

The goal of the LCA performed in this work is to investigate how different renovation strategies affect the life cycle environmental impacts with respect to building materials and operational energy use. The functional unit selected was the entire building used as a residential building over a period of 50 years, considering that the original building has been in use for 50 years and a renovation is now being considered [48], [51]. This study encompasses all phases from cradle to grave in accordance with the CEN standard (Figure 11); the benefits and loads beyond the system boundaries (D) were calculated but not included in the total results.
As this study complies with the CEN standard, it means that it is an attributional LCA. All the datasets adopted in this study are product-specific environmental product declarations (EPD). When no EPD was available generic data from Ecoinvent [91] and GaBi [92] were used. All data sets were compensated using the CEN/TR 15941 method. All building materials were provided by a local building construction company and all distances were based on average data for the Nordic Countries (60 km, trailer combination 40 tonnes, 100% fill rate). The energy use of the building was assumed to remain unchanged during the next 50 years.

The software used in this thesis is OneClickLCA, a software developed by the company Bionova Ltd. The software complies with the CEN 15978 standard for building life cycle assessment and ISO 14040 [93]. It uses the CML 2012 impact assessment method. The software is third party verified making it possible to be used for BEAT certifications. The software is for commercial use and only uses external, publicly available verified data from producers. The main user group is architects, engineers and consultants with construction and quantity surveying knowledge. It is not possible to input any dataset but it is possible to ask the company to include some information that is not available. The information needs to be third party verified and publicly available. It is possible to include the GaBi and Ecoinvent databases.

For each building, several inputs need to be specified. Firstly, with RIBA/AIA stadium, the design is based on the RIBA plan of work [94]. Then it is necessary to specify the project type (new building, renovation, etc.), what kind of frame the building has and what are the parts included to be considered in the study. This is in order to optimize the search in the database.

When this work is done, the LCA default values for material calculation must be specified, meaning that it is necessary to decide the service life of materials (technical, commercial or product-specific), the transportation distance (in this thesis the Nordic typical transportation values were considered)
and the material manufacturer localization. This is done in order to adjust energy use for manufacture at the chosen location, and finally the end of life (EOL) calculations, that for this software are defined by the Product Category Rule (PCR) that the particular EPD of each material follows. The calculation method for the EOL is specified further in EN 15978.

The input for each scenario is the amount of building materials, energy use of the building, the calculation period, the construction site operations (scenarios that consider the electricity and fuel use, waste and transportation of the construction site based on the building area) and the building area (in this case the gross building internal area).

In order to visualize the results in a different way in paper V, the environmental payback (EP) method was used. The method displays the environmental analysis in economic terms [95]; in this thesis the method described by Nydahl et al. is used [96].

For this thesis, the following environmental impact categories were considered:

- Global warming potential (GWP), that quantifies the non-natural increase of GHG in the atmosphere
- Acidification potential (AP) that characterizes the acid substances increase in the lower atmosphere
- Eutrophication potential (EP) that characterizes the introduction of nutrients to the environment
- Abiotic depletion potential (ADP) that quantifies ores, water and non-renewable energy use
- Radioactive waste (RW) that quantifies the total radioactive waste disposed.

2.5. Life Cycle Costs

To perform the LCC calculations, the software OneClickLCA was used through an automated tool in which the analysis is based on the standards ISO 15686-5 and CEN 16627. The life cycle stages are the same, defined by the standard EN 15978. LCC is a tool that estimates future costs using Net Present Value.

The LCC input is linked to the LCA input data, and it is needed to input additional capital costs and other operating costs.

All costs were calculated in Swedish Krona (1,00 SEK =0,104 EUR). The datasets for material costs are based on data from Müller [97] and Spon’s Architects’ and Builders’ Price ([98] and compensated by the regional material cost index. Labor costs are taken from the International Labor Organization ([99]. Heating and electricity prices are taken from EUROSTAT and the local heating provider [100]. Maintenance costs are calculated based on capital costs [101]. The parameters used are listed in Table 5 and are default data in the software for the selected country. All the input data is based on international literature and from databases that include the rates that are relevant for Sweden. The selected discount rate was the standard used in the software as the software
developers recommend using that rate if the discount rate of the property owner is unknown.

Table 5 Life cycle cost (LCC) calculation parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation period (years)</td>
<td>50</td>
</tr>
<tr>
<td>Discount rate (cost of capital) (%)</td>
<td>7</td>
</tr>
<tr>
<td>Regional material cost index</td>
<td>1.3</td>
</tr>
<tr>
<td>Inflation rate (%)</td>
<td>2</td>
</tr>
<tr>
<td>Energy inflation rate (%)</td>
<td>2</td>
</tr>
<tr>
<td>End of Life (EOL) as capital expenses (%)</td>
<td>2.5</td>
</tr>
<tr>
<td>Hourly labor rate, worker (SEK)</td>
<td>306.1</td>
</tr>
<tr>
<td>Hourly labor rate, craftsman (SEK)</td>
<td>413.3</td>
</tr>
<tr>
<td>Electricity price (SEK/kWh)</td>
<td>2.05</td>
</tr>
<tr>
<td>District heating price (SEK/kWh)</td>
<td>0.69</td>
</tr>
</tbody>
</table>

2.6. Data inventory

2.6.1. Case study building

The neighborhood of Tjärna Ängar, located in the municipality of Borlänge, Sweden, 250 km Northwest of Stockholm is an example of the Million Homes Programme, built between the years 1969-71 that comprises 42 buildings with a total heated area of about 115,000 m².

Figure 12 Case study building

The selected case study is a three story building with 36 apartments and a total heated area of 2,822 m² (Figure 12 Case study building). The buildings’ energy use is approximately the average energy use for buildings built during the same
time period (158 ±21 kWh/m²) [102]. The technical installations are a one-pipe hydronic heating system connected to district heating and mechanical exhaust ventilation.

This building is a representative case of those built during the Million homes programme. Around 50% of all the multifamily buildings built from 1961 to 1975 in Sweden were of this type (three story buildings without elevators and more than 2 staircases) [103]. Also, the case study building was constructed by the company Skånska Cementgjuteriet AB (Now Skanska AB) and this company built roughly 10% of all the buildings completed during this period [104].

Table 6 Case study building information

<table>
<thead>
<tr>
<th>Basic information</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>60.49 N</td>
</tr>
<tr>
<td>Longitude</td>
<td>16.4 E</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>153</td>
</tr>
<tr>
<td>Number of stories</td>
<td>3</td>
</tr>
<tr>
<td>Total heated area (m²)</td>
<td>2,822</td>
</tr>
<tr>
<td>Building gross volume (m³)</td>
<td>8,387</td>
</tr>
<tr>
<td>Number of apartments</td>
<td>36</td>
</tr>
<tr>
<td>Type of space heating system</td>
<td>Hydronic heating system. District heating</td>
</tr>
<tr>
<td>Type of ventilation</td>
<td>Mechanical exhaust ventilation</td>
</tr>
<tr>
<td>Total U-value (W/K m²)</td>
<td>1.47</td>
</tr>
<tr>
<td>Heat demand (kWh/m², year)</td>
<td>152</td>
</tr>
<tr>
<td>External wall insulation</td>
<td>150 mm mineral wool</td>
</tr>
<tr>
<td>Ground insulation</td>
<td>300 mm loose light expanded clay aggregate</td>
</tr>
<tr>
<td>Ground floor</td>
<td>250 mm reinforced concrete</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Forced mechanical exhaust</td>
</tr>
<tr>
<td>Windows</td>
<td>2 pane window casement</td>
</tr>
<tr>
<td>Dimensioned indoor temperature (°C)</td>
<td>21</td>
</tr>
<tr>
<td>Measured indoor temperature (°C)</td>
<td>22.7</td>
</tr>
</tbody>
</table>

The majority of the Tjärna Ängar buildings are built based on the same design and have not been subject to any major refurbishment since then. So, it is reasonable to assume that similar interventions would result in similar energy savings, partly because of the buildings’ physical characteristics (they are all built with exactly the same physical design) and partly because of the parallel layout of the buildings (see Figure 13).
2.6.2. District heating system

The district heating in the municipality of Borlänge consists mainly of domestic household waste incineration with energy recovery and industrial excess heat from local industries. The Borlänge district heating system produces around 360 GWh of district heating per year. There is a 30 MW link to the nearby municipality of Falun, which has a district heating production mainly based on different types of biofuels. In addition to direct fuel use, the DH system annually uses around 20 GWh of electricity for powering heat pumps and other electrical components in the system.

Table 7 Borlänge Energi fuel use (%) for DH 2016 [105]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Use (%)</th>
<th>GHG emission (kg CO₂eq/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled energy</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>Industrial excess heat</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Flue gas condensing</td>
<td>1.6</td>
<td>0</td>
</tr>
<tr>
<td>Heat from heat pumps (Netto)</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Municipal solid waste (MSW) incineration</td>
<td>44.3</td>
<td>137</td>
</tr>
<tr>
<td>Blast furnace gas</td>
<td>0.6</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Renewable energy</strong></td>
<td><strong>30.7</strong></td>
<td></td>
</tr>
<tr>
<td>Secondary biofuels</td>
<td>28.6</td>
<td>11</td>
</tr>
<tr>
<td>Renewable electricity</td>
<td>2.1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td><strong>1.2</strong></td>
<td></td>
</tr>
<tr>
<td>Hot water from other companies, renewables and recycled energy</td>
<td>1.2</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Fossil energy</strong></td>
<td><strong>1.1</strong></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>1.1</td>
<td>302</td>
</tr>
</tbody>
</table>
2.7. Renovation scenarios

The selected renovation scenarios for papers I, II and III were determined to reduce purchased energy in the building (Table 8).

Table 8 Proposed renovation scenarios Paper II

<table>
<thead>
<tr>
<th>Renovation Measure</th>
<th>As built</th>
<th>DEERS</th>
<th>BEnS</th>
<th>HRV21/22.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Recovery Ventilation</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>480 mm outer wall insulation</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>300 mm attic insulation</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>3-glass argon-filled low-emissivity pane windows</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
</tbody>
</table>

All scenarios were selected from projects throughout Sweden and have been proved possible to execute technically. The first scenario called Deep Energy Efficient Refurbishment Scenario (DEERS) is based on a housing area called Brogården (Alingsås, Sweden) [106]. The project aims to reduce a large amount of the purchased energy in the building. The Building Envelope Scenario (BEnS) is a variation of the previous scenario but without considering changes in services installations. The last two scenarios, HRV22.7 and HRV21 (where 22.7 is the measured indoor temperature and 21 is the recommended indoor temperature when the thermal comfort has been improved in °C) consider the improvement of the building services rather than the physical properties of the building.

Then, for papers IV and V (Table 9) the original scenarios were combined with different building services technologies.

Table 9 Renovation scenarios paper IV and V

<table>
<thead>
<tr>
<th>Renovation Measure</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal Heat Pump</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Photovoltaic panels</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Heat Recovery Ventilation</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>480 mm outer wall insulation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>300 mm attic insulation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3-glass argon-filled low-emissivity pane windows</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Scenarios 5, 6, 7 (the same as DEERS) and 8 have improvements in the building envelope by adding extra insulation and changing to energy efficient windows. Scenarios 3 (the same as HRV21), 4, 7, and 8 change the ventilation system to heat recovery ventilation (HRV), scenarios 2, 4, 6 and 8 change district heating to geothermal heat pumps (GHP) and scenarios 1, 4, 5 and 8 include photovoltaics (PV). Note that scenario 0 is the same scenario called “As built”.

The analysis made for this thesis is only on the theoretical energy use. This thesis does not take into consideration the problems that a tighter and more
energy efficient building can have in human health, it does not take into con-
sideration air quality or condensation. These are problems that have been noted
in energy efficient buildings. The different scenarios considered in this thesis
are condensed in Table 10.

Table 10 Type of renovation measure

<table>
<thead>
<tr>
<th>Renovation approach</th>
<th>0/as built</th>
<th>1</th>
<th>2</th>
<th>3/HRV21</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7/DEERS</th>
<th>8</th>
<th>BvAS</th>
<th>HVV22.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvements in the building envelope</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Improvements in building services</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Lower indoor temperature</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Changes in energy carrier</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Data from a local building company quantified the material use for the differ-
ten renovation scenarios (see Table 11) based on similar projects.

Table 11 Building materials dataset

<table>
<thead>
<tr>
<th>Resource</th>
<th>Quantity</th>
<th>Unit</th>
<th>Service life</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry mortar</td>
<td>71,800</td>
<td>kg</td>
<td>50 years</td>
<td>Norway</td>
</tr>
<tr>
<td>Gypsum plasterboard</td>
<td>1,198</td>
<td>m²</td>
<td>50 years</td>
<td>Norway</td>
</tr>
<tr>
<td>Mineral wool. Insulation</td>
<td>1,198</td>
<td>m²</td>
<td>50 years</td>
<td>Denmark</td>
</tr>
<tr>
<td>Radon and moisture membrane</td>
<td>1,198</td>
<td>m²</td>
<td>50 years</td>
<td>Norway</td>
</tr>
<tr>
<td>Calcium silicate block 115 mm</td>
<td>1,198</td>
<td>m²</td>
<td>30 years</td>
<td>Germany</td>
</tr>
<tr>
<td>Mineral wool insulation for pitched roof 300 mm</td>
<td>971</td>
<td>m²</td>
<td>30 years</td>
<td>Denmark</td>
</tr>
<tr>
<td>Triple glazed windows, wood+aluminum frame</td>
<td>298</td>
<td>m²</td>
<td>40 years</td>
<td>Norway</td>
</tr>
<tr>
<td>Heating system</td>
<td>2,822</td>
<td>m²</td>
<td>30 years</td>
<td>Finland</td>
</tr>
<tr>
<td>Ventilation system</td>
<td>2,822</td>
<td>m²</td>
<td>30 years</td>
<td>Finland</td>
</tr>
<tr>
<td>Heat Recovery Ventilation unit</td>
<td>1</td>
<td>pcs</td>
<td>25 years</td>
<td>Germany</td>
</tr>
<tr>
<td>Ventilation exhaust unit</td>
<td>3</td>
<td>pcs</td>
<td>25 years</td>
<td>France</td>
</tr>
<tr>
<td>Electric heat pump (brine-water, geothermal probe), 70 kW (Coefficient of performance (COP): 3)</td>
<td>1</td>
<td>pcs</td>
<td>20 years</td>
<td>Germany</td>
</tr>
<tr>
<td>Pipework for electric heat pump (brine-water, geothermal collector), 70 kW</td>
<td>1</td>
<td>pcs</td>
<td>50 years</td>
<td>Germany</td>
</tr>
<tr>
<td>Photovoltaic panel system for roofs, 300 Wp capacity</td>
<td>134</td>
<td>m²</td>
<td>30 years</td>
<td>France</td>
</tr>
</tbody>
</table>
It is important to note that the building materials are produced in different countries. As all data sets are taken from existing environmental product declarations, producers have declared their operations in different countries. As there is different energy intensities within the producing countries, data needs to be compensated to local conditions. Another aspect is that the heating and the ventilation systems are noted as area, instead of amount of materials. These datasets are based in common practice in the Nordic countries, so a quantification of the amount of materials was needed to provide the building with these installations.
3. Results

The main methodology used for these findings was proposed in paper I and described in the previous chapter.

3.1. Energy performance

3.1.1. Specific energy use

In order to determine how the different proposed scenarios would affect the energy performance of the building, the case study building was initially simulated with the selected BES. The proposed scenarios aim to affect energy use in the building differently; 1) by reducing the active heating demand, 2) by reducing the amount of purchased energy and by changing different installation technologies, 3) by using solar energy and 4) by changing energy carriers (see Table 12 and Table 13). Note that the purchased energy of the different scenarios differ between Table 12 and Table 13 because different weather data were used.

Table 12 Purchased energy in paper I, II and III. Units in kWh/m².

<table>
<thead>
<tr>
<th>Scenario</th>
<th>As built</th>
<th>DEERS</th>
<th>BEnS</th>
<th>HRV 22.7</th>
<th>HRV 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating  use</td>
<td>141</td>
<td>81</td>
<td>105</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Electricity facility use</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 13 Purchased energy, PV electricity production and electricity export in papers IV and V. Units in kWh/m².

<table>
<thead>
<tr>
<th>Scenario</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating  use</td>
<td>134</td>
<td>134</td>
<td>-</td>
<td>109</td>
<td>-</td>
<td>108</td>
<td>-</td>
<td>91</td>
<td>-</td>
</tr>
<tr>
<td>Electricity facility use</td>
<td>6</td>
<td>1.5</td>
<td>47</td>
<td>9</td>
<td>43</td>
<td>1.8</td>
<td>43</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>PV electricity production</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PV electricity export</td>
<td>-</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

In Table 12, the scenario DEERS decreases the transmission and ventilation losses as the building envelope has been improved and a HRV has been installed. Both BEnS and HRV21 have similar energy savings, but with different approaches; BEnS decreases the transmission losses (with a total U-value of 1.22 W/m² K compared to 1.47 W/m² K for the original building) while HRV 21/22.7 decreases the ventilation losses and increases the electricity use in the building.

In Table 13 scenarios 2, 4, 6 and 8 change energy carriers from DH to electricity by installing GHP. This reduces the amount of purchased energy by using geothermal energy. In this study, only purchased energy is accounted for, meaning there is an amount of geothermal energy not being accounted for in the results. Scenarios 3 and 5 have a similar performance but with different
approaches; scenario 3 uses HRV while scenario 5 improves the building envelope and uses PV. Scenarios 2, 4 and 6 have similar energy savings: scenario 2 by installing GHP, scenario 4 by the same approach and including HRV and PV and finally scenario 6 by installing GHP and improving the building envelope. Scenarios 1 and 5 have a purchased energy reduction due to the production of electricity by PV. The total annual production of the PV is 17 000 kWh, but due to the annual load distribution, some electricity needs to be exported to the grid.

3.1.2. Energy performance in Miljöbyggnad

The energy performance of the building was also assessed using the selected BEAT. Energy performance in Miljöbyggnad consists of four indicators; energy use, active heating demand, solar heat load and energy sources.

Table 14 Miljöbyggnad energy rating for the case building

<table>
<thead>
<tr>
<th></th>
<th>As built</th>
<th>DEERS</th>
<th>BEnS</th>
<th>HRV22.7</th>
<th>HRV21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use</td>
<td>Rated</td>
<td>Gold</td>
<td>Silver</td>
<td>Silver</td>
<td>Gold</td>
</tr>
<tr>
<td>Active heating demand</td>
<td>Rated</td>
<td>Silver</td>
<td>Bronze</td>
<td>Rated</td>
<td>Bronze</td>
</tr>
<tr>
<td>Solar heat gains</td>
<td>Silver</td>
<td>Silver</td>
<td>Silver</td>
<td>Silver</td>
<td>Silver</td>
</tr>
<tr>
<td>Energy source</td>
<td>Silver</td>
<td>Gold</td>
<td>Silver</td>
<td>Silver</td>
<td>Silver</td>
</tr>
<tr>
<td>Total</td>
<td>Rated</td>
<td>Gold</td>
<td>Silver</td>
<td>Bronze</td>
<td>Silver</td>
</tr>
</tbody>
</table>

In Table 14 the results from Miljöbyggnad are presented. The five energy rating categories are presented in the table. Rated means that the building does not comply with the current regulation, Bronze, complies with the regulation, Silver means that it is built according to good practice and Gold means that the building is designed and built with the best available practice.

The first indicator “energy use” was ranked as “rated” for the current building as energy use does not comply with the current BBR normative for the building type. DEERS has the highest rating, implying that this scenario reduces energy use to the best practice. BEnS makes reductions that are considered good HRV22.7 as bronze, meaning that the building complies with the current BBR regulations and finally HRV21 is ranked as DEERS, meaning that the scenario can be considered as best practice as well.

For the second indicator “active heating demand” the original building was “rated” meaning that it does not comply with the latest BBR regulations. DEERS is considered as silver, meaning that combining the different renovation strategies makes the building perform better than regulations. When the building envelope is improved without installing HRV, the building is rated Bronze meaning that it complies with regulations. When the indoor temperature set point is reduced to 21 °C and HRV is installed the building is rated bronze as well, meaning that it could be seen as a similar approach to BEnS.

For the third indicator, “solar heat load”, the worst room had a solar heat load of 36 W/m², performance rating Bronze. Then, 25 % of the same floor was analyzed giving the possibility of moving up one level. The whole floor
in this building rated performance Gold, but due to the impossibility of jumping two categories, the building receives a Silver performance rating.

The last indicator, “energy source”, aims to ascertain which energy sources are used in the building. According to their classification, a building is given an environmental performance rating. In the case study building, as well as in three of the selected scenarios, the energy source rating was Silver. Even if the share of renewable energy in the system is large according to Svensk Fjärrvärme, [107] the selected BEAT assesses 45% of the household waste incineration and 25% of the industrial excess heat as category 4, which means that it is the same category as fossil fuels or nuclear power. In DEERS, the energy source performance rating is Gold because the building reduces its use of active heat and most of the electricity used in this case comes from hydro-power, reducing the non-renewable part of the mix. The total rating describes the DEERS scenario as an outstanding one, meaning that this building outperforms the Swedish building code, BEnS and HRV21. It is built according to good practice but is not an outstanding building. Regarding HRV22.7 it is a building that complies with the building code.

3.2. Environmental impact

In paper III four relevant impact categories were considered; global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and abiotic depletion potential of non-fossil elements (ADP). In papers IV and V only two categories were considered; GWP and radioactive waste disposed (RW). RW was included, due to the fact that nuclear power constitutes a large share of power generation in Sweden. In paper V, a sensitivity analysis was done by changing the electricity mix of different Northern European countries in order to see how variations in electricity production affected the environmental performance of the different renovation strategies.

3.2.1. Greenhouse gas emissions from district heating

In paper II the energy use of the building was scaled to represent the total energy use of the neighborhood. Then, the local GHG emissions were calculated using the emission factors for the fuel mix in the selected ESS (Table 7). At first, with all the buildings in the original condition, the estimated CO₂ emissions were 11 kg/m² year. For DEERS there was a reduction of 15% in CO₂eq emissions, although energy use reductions were around 43%. The same occurs with other scenarios, due to the fact that energy use reductions are not coupled to fuel reductions as can be seen in Table 7. It can be clearly seen that the energy savings for the proposed scenarios reduce the use of DH that has almost no fossil fuels.

Table 15 CO₂ emissions reductions

<table>
<thead>
<tr>
<th></th>
<th>As Built</th>
<th>DEERS</th>
<th>BEEnS</th>
<th>HRV22.7</th>
<th>HRV21</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂eq (kg/m²)</td>
<td>11</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>CO₂eq reductions (%)</td>
<td>n.a.</td>
<td>15</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
3.2.2. Life cycle environmental impacts

In paper III, an LCA was performed using OneClickLCA. With the results from energy use and the use of building materials it was possible to determine the environmental performance of the energy efficient renovation scenarios. In the paper, four environmental impact categories were assessed; GWP, AP, EP and ADP.

Figure 14 Global warming potential Co2eq paper III

Figure 14 shows how all renovation alternatives will result in GWP reductions. DEERS and BEnS, the scenarios that improve the building envelope, are the scenarios that have most savings from energy use. It can be seen that including building services in the renovation scenario, as in DEERS, results in higher reductions from energy use. In HRV 21 it can be seen that reducing the indoor temperature by 1.7°C increases the energy savings. Total reductions in DEERS are due to the large reductions in energy use, even if the impact of construction materials is considerably higher than for the HRV scenarios. HRV 21 has less energy use reductions but also has a smaller material use and has fewer impacts on the construction process which makes the total GWP savings comparable.
Given these findings, in Paper IV changes were made in both the renovation scenarios and the assumptions about the energy carriers. In paper IV, more renovation scenarios including both PV and GHP were analyzed, and for the LCA the national electricity mix was taken into consideration, including its share of renewables, fossil-fuels and nuclear power (in paper III it was assumed that the purchased electricity was 100% renewable). In this paper it was shown that the renovation scenarios that reduce GWP the most were the ones that change the energy carrier from district heating to electricity. This is due to the electricity mix in Sweden having a lower GWP factor than district heating (see Table 7) (Figure 15). AP and EP showed a similar trend for GWP and for the same reasons, as described above.
Figure 16 shows that materials have a relative low impact on the building, and that the largest ADP is from energy use. Two groups can easily be identified in these results, the ones that change the energy carrier (2, 4, 6 and 8) and the ones that rely on DH. The ADP difference mirrors the scale of the energy systems. Basically, large energy systems are more resource efficient than locals systems.

Figure 17 Radioactive waste disposed paper IV
In terms of disposed RW the pattern is different. It is clearly shown (Figure 17) how the Swedish electricity mix relies heavily on nuclear power. The scenarios that only rely on electricity as an energy carrier (scenarios 2, 6) increase the amount of RW disposed. The only scenario that relies on changing the energy carrier that does not show the same trend is scenario 8, due to the reduction of the transmission losses (Figure 17).

3.2.3. Sensitivity analysis of environmental impacts

In order to check the robustness of the simulated scenarios and to identify how they perform considering different northern European electricity mixes, a sensitivity analysis of the different renovation strategies was made. It is interesting to note how these electricity mixes are coupled to energy policies, and that countries that are similar in resource availability and climate have different energy systems (Table 16). To show, graphically, the differences between the energy systems, the environmental payback was used. This was in order to simplify graphically the different environmental impacts.

Table 16 share of electricity generation by fuel on % 2018 [108]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Sweden (SE)</th>
<th>Denmark (DK)</th>
<th>Norway (NO)</th>
<th>Estonia (EE)</th>
<th>Finland (FI)</th>
<th>Germany (DE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>40.4</td>
<td>0</td>
<td>0</td>
<td>33.9</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>0.3</td>
<td>1.1</td>
<td>0</td>
<td>2.1</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Waste</td>
<td>2.1</td>
<td>5.1</td>
<td>0.3</td>
<td>1.1</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Hydropower</td>
<td>39.8</td>
<td>0.1</td>
<td>96.4</td>
<td>0</td>
<td>23.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Solar PV</td>
<td>0.1</td>
<td>2.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5.9</td>
</tr>
<tr>
<td>Wind power</td>
<td>9.9</td>
<td>41.9</td>
<td>1.4</td>
<td>4.9</td>
<td>4.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Biofuels</td>
<td>6.3</td>
<td>13.3</td>
<td>0</td>
<td>7.3</td>
<td>16.1</td>
<td>7</td>
</tr>
<tr>
<td>Coal</td>
<td>0.7</td>
<td>29</td>
<td>0.1</td>
<td>83.8</td>
<td>15.3</td>
<td>42.2</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.4</td>
<td>7.1</td>
<td>1.7</td>
<td>0</td>
<td>5.5</td>
<td>12.7</td>
</tr>
</tbody>
</table>

In order to simplify visualization, only the five scenarios from paper V with the most noticeable impacts are shown. The results for the excluded scenarios lie between the displayed scenarios.
As with GWP, changing the energy carriers results in increased GHG emissions for the selected scenarios. The scenarios that rely heavily on electricity as the energy carrier have a higher emission potential (increase in GWP) than the ones that rely on decreasing the active heating demand of the building (Figure 18).

For GWP, three patterns were identified. Sweden and Norway have the electricity mixes with a low carbon content. Then Denmark and Finland have a moderate carbon content and finally Estonia and Germany have a large share of carbon in their electricity mixes. For low carbon electricity mixes, renovation scenarios that rely on electricity (2, 4, 6 and 8) as energy carrier are the ones with higher environmental payback potentials, due to the simplicity of the solutions and the electricity mixes performance. In moderate carbon mixes it
was interesting to note that renovations that reduce active heating demand and/or use geothermal energy were the ones that reduced most GWP (scenarios 2, 7 and 8). Finally, with high carbon mixes the renovation scenarios proposed do not improve the performance compared to the building in its original state. This shows that just a small increase in electricity, when it is produced by fossil fuels, does not present benefits compared with the use of the selected DH (Figure 18).

Figure 19. RW payback for scenarios 1, 2, 6, 7 and 8, paper V

Regarding RW, there were two identified groups, the high nuclear power mixes of Sweden and Finland and the rest with low or no nuclear power mixes. The results show that in order to get reductions in RW the only possible way for high nuclear power cases is to reduce the active heating demand. For countries
with low to no nuclear power all renovations strategies end in reductions in RW (Figure 19).

3.3. Economic impact

In paper IV the LCC of the different renovation alternatives was analyzed. There are two groups with different levels of LCC. One with almost unchanged costs (scenarios 1 to 4), due to the simplicity of the installation of the service and the others (scenarios 5 to 8) with a high level of costs that included construction that would increase the costs drastically (Figure 20).

Figure 20 Nominal life cycle costs in comparison with the building as built

Renovation scenarios 1 to 4 show that the life cycle stages A 0-5 (construction and material costs) are low, this can be seen as relative prices of both PV and GHP are low and installation is relatively simple; it only takes a couple of days. The work force needed is also small. Then, for categories C1-C4 (end of life) the cost increases as it is expected that PV and the GHP will have to be replaced during the lifetime of the building. Energy savings during the lifetime of these renovations are considered to be equal to the investment and replacement costs, while for renovation scenarios 5 to 8 the life cycle stages A0 to A5 are higher, due to the need for more materials such as windows and extra insulation, and due to the high cost of construction. In life stages C1-C4 it is expected that installations need to be replaced and maintenance of the façade, attic insulation and windows would be required.

3.4. Economic and environmental impacts

In order to check how different environmental impacts were correlated with LCC, the results were plotted in such a way that it would be possible to see if
there was a simple linear or exponential correlation. Regarding GWP, it was found that there were different groups that could be associated with different levels of GWP; 1) the ones that rely on PV (1 and 5), 2) the ones that use district heating (3 and 7), and 3) the ones with changed energy carriers (2, 4, 6 and 8). Figure 21 shows that scenarios 2 and 4 are the “low hanging fruit” when it comes to GWP savings and LCC savings. However, the results are scattered with no correlation with LCC. However, doing a 2 dimensioned analysis it was possible to see how scenario 8 could have a 30 % higher LCC but also has a good performance regarding GWP.

The situation was different for RW. Scenarios 3 and 7, which rely on district heating which has a small proportion of electricity in its production, reduce RW disposal. Scenarios that change the energy carrier to electricity (2, 4, and 6 with the exception of scenario 8) would have a negative impact on RW and in some cases, as in scenario 6, a high LCC. Scenario 8 decreases the amount of RW disposal, due to the fact that it reduces the active heating demand of the building (Figure 22).
Figure 22 Radioactive waste disposal against life cycle costs in % compared to the original building
4. Discussion

In this thesis, different renovation scenarios were studied in order to analyze the life cycle consequences of energy use (electricity and district heating), the environmental impact (GWP, AP, EP, RW) and the financial costs of carrying these out. As listed in Table 10 the proposed scenarios were different combinations of

- Improvements in the building envelope,
- Improvements in services,
- Lower indoor temperature set-points,
- Changes in energy carriers,
- Installation of solar PV.

4.1. Energy performance

The results of this work indicate that the proposed energy efficient renovation scenarios affect the total energy use at different system levels. The different renovation approaches led to a reduction in purchased energy for the different renovation scenarios. Nevertheless, it is important to discuss the benefits and disadvantages that these savings have for building owners and society in general.

As seen in 3.1.1 the strategy with a higher reduction of purchased energy is a combination of all the renovation measures proposed, as in Scenario 8. In addition, in 3.1.1 it can be seen that changing service installations (e.g. HRV or GHP) could be beneficial from a house owner’s perspective due to the simplicity of installation and the relative low cost compared to other renovation measures, even if doing this would increase electricity use. From a societal perspective, increasing electricity use at the building level can have significant impact on electricity transmission. Sweden has a significant amount of renewable energy available in the north, but most electricity use is in the southern part of the country, making electricity transmission a challenge. Also, if electricity prices start to fluctuate with the electrical generation load, the potential benefits of changing energy carriers for the building owner could disappear.

District heating companies also argue that reducing the use of district heating in order to benefit electricity would reduce their ability to produce electricity from CHP [41]. As CHP has a fixed relation between generated heat/electricity there would be a problem in reducing heat generation, as this would also reduce the amount of generated electricity, when the actual electricity demand increases. The Swedish regulations have tried to overcome this problem by using primary energy factors. However, as Swing-Gustafsson et al. state [38], there is a lack of consensus regarding these factors showing that this can be influenced by different policy measures. Another aspect is that CHP plants are found within the built environment, posing less stress on critical power transmission.
One way to reduce purchased electricity use is to install PV. There is, however, still the problem of the electrical generation load during the winter. Building owners are interested in this technology as it is seen as a way to generate clean electricity at the local level. Building owners also argue that that there is the risk of having to pay higher taxes if the installed effect of PV exceeds 255 kW [109], even if there is a chance of receiving subsidies for installation [110]. However, the sensitivity analysis made in paper V shows that, independently of how electricity is generated, the benefits of PV are negligible, due to the heating demand of buildings in Sweden. As more energy is needed during the winter months, when the PV electricity production is at its lowest level, it would not solve the problem of the electricity generation load.

In this thesis, the use of household electricity is not considered nor is the effect of renovation on thermal comfort, apart from assuming a lower indoor temperature. According to the Swedish norm, household electricity is not considered as part of the building energy use. This has implications on the localization of PV electricity. For example, building owners cannot sell PV electricity to tenants without paying generation taxes due to the current regulations.

As seen in paper IV, changes in energy carriers from district heating to electricity seem a good alternative from a building owner’s perspective as scenarios 2, 4, 6 and 8 show. The results suggest that changing energy carriers can be the best alternative for reducing purchased energy used for heating. Based on the findings of studies on DH production and exergy, a more plausible explanation is that increasing electricity use can increase marginal electricity production [38]. Also, it seems inappropriate to use a high exergy energy source for low exergy processes such as space heating [111]. Electricity is an energy source with high exergy, while low temperature heat is a low exergy source, which makes it a source of energy with no commercial value. The case study lies within reach of a DH network with a high content of industrial excess heat, a source of energy that otherwise would not be used. Some of this industrial excess heat is from the pulp and paper industry, where biofuels are used. Even if it is desirable to make industrial processes more energy efficient, there is still a considerable amount of excess heat available. Also, electricity is often more expensive to produce than heat [112]. Increasing electricity use means a higher peak demand when the temperature drops and the COP of GHP is lower, increasing the demand for backup energy used for intermittent loads [113]. When increasing the backup energy use, there is an increase in the marginal electricity production [38]. Also, the buildings and services sectors are the main users of electricity in Sweden, but plans for increasing the use of electricity within the industry and transportation sectors would increase the total amount, making the demand even higher [19].

4.2. Environmental impacts

The results of this study demonstrate that there are different environmental impacts related to energy efficient renovation. These impacts can be noted in two groups; one that relates to the building process and materials and the other related to energy use.
4.2.1. Emissions vs. resource use

In this study, it has been important to analyze the implications of the renovation scenarios for both emissions and resource use. The results indicate that building materials have a relatively low ADP and that most of the resource use is related to the energy system. This situation can be understood in relation to the lifetime of the building; the resource use in materials is small compared to the ones used for the energy use (some fuels are also limited resources). In renovation, many of the resource intensive materials are already in place (basically concrete and steel) [114]. This shows that compared with the effects of the energy use during its lifetime, a building can be renovated several times from a resource efficiency perspective. It is also shown that renovation is a more resource efficient alternative than demolishing and erecting new buildings.

It is important to observe that the scenarios with the lowest environmental impacts in both GWP and RW are the scenarios that reduce heating demand. This situation is in line with the hypothesis that improving the building envelope results in overall energy savings, both for DH and electricity. As seen in figure 15, PV has significantly higher resource use for the energy output than the national electricity grid, which is in line with the results presented for the Norwegian context by Kristjandottir et al. [115] and by Petrovic et al. [116] for the Swedish context. This observation, however, is only valid for countries with a low share of fossil fuels in their electricity production for the grid as is not the case in many continental European countries.

Also, as all energy export is classified in the standard EN 15978 as a benefit beyond the system boundaries, the use of PV electricity shows no potential environmental benefits (in this case 459 kg CO₂eq that cannot be accounted as an environmental benefit). This classification aims to make the results of building LCA more transparent as the potential benefits are not within the building. The exclusion helps to prevent duplication of the amount of potential benefits, but, at the same time, discourages the use of potentially better environmentally-friendly alternatives.

The findings of this study suggest that focusing on emissions when renovating a building can result in stressing limited resources as stated in [117] and [74]. As Eriksson states [118], nuclear energy is not resource efficient. Thus, relying on an abundant amount of nuclear power reduces GHG emissions, but the increased need for resources stresses other environmental impacts.

The generalizability of these results is limited by the selected renovation scenarios and the energy systems selected, as has previously been stated, the use of PV or other technologies can change when different renovation alternatives or energy systems are analyzed. Also, if the household electricity is considered one could end up with different results.

4.2.2. Energy use vs. building materials

The results of this study show that there is a relation between energy use and building materials, where there seems to be a point where increasing the energy efficiency of the building counteracts the environmental benefits. This situation can be clearly seen in DEERS, as this is the alternative that reduces most
GWP from energy use. However, when the environmental benefits from energy savings are weighted against the environmental impacts, HRV21 seems a good alternative, as it needs lesser amounts of materials than DEERS.

In renovation projects, as the results show, a small amount of materials are needed, as most of the building is already in place, while the energy use will have an impact in the following years. This is shown to be in accordance with the observations made by Vilches et al. [53]. When installing a GHP, the total impact is about the same as improving the building envelope. However, even if scenarios 7 and 8 have higher environmental impacts from materials and the construction stage, it is shown that they result in significantly higher environmental savings and are less sensitive to changes in the energy system. This confirms the statement of Hasik et al. [56] that energy sources dominate the effect of energy efficient renovation. It is also necessary to decide between super insulated buildings and energy efficient installations [117].

Building materials have a significant environmental impact in energy efficient renovations and this has to be compared with the impact that energy use has during the lifetime of the building. For this study, the material environmental impact was lower than the impact of energy use. However, with the transformation of energy systems towards lower environmental impacts, the impact of material use would have a more significant share of the total impact of the building. So, in renovation projects the impact of the surroundings can be reduced by using services that are already in place, such as DH.

4.3. Combined economic and environmental assessment

When renovating buildings, it is important to analyze the costs of renovation. Housing companies are interested in improving the energy efficiency of existing buildings, but only in a way that is economically feasible for them to make these investments.

The results of this thesis show that even if the hypothesis that there would be a correlation between economic and environmental impacts, the relatively low energy prices in Sweden (compared to the EU) make the life cycle costs related rather to the construction costs than to the energy use.

As seen in 3.2.2, the electricity mix in Sweden has a low GWP impact, favoring its use to reduce GHG emissions. However, small changes in the way that electricity is generated can increase GHG emissions, as seen in paper V. In contrast, there are no such impacts for DH, being an attractive choice due to its low price and the fact that there is a robust system already in place, most of the investment having already been made. It is interesting to note that it is difficult to justify deeper and more powerful energy efficient renovation strategies due to the high labor costs in Sweden (36.6 EUR per hour compared to 27.4 EUR for the EU [119]), the relative low electricity prices (0.2015 EUR/kWh compared to 0.2159 EUR/kWh for the EU [120]) and the low carbon content of the electricity mix (13.3 g CO₂eq/kWh compared with 295.8 g CO₂eq/kWh for the EU [121]). Decreasing the transmission losses in a building has high life cycle costs and is not economically advantageous. In order to make renovation more attractive there is a need to reduce labor and energy
taxes to give companies incentives to make renovations that can be beneficial from both emissions and resources perspectives. For example, introducing carbon taxes could contribute to making renovations more interesting from an economic perspective. At the beginning of the analysis of LCC in this thesis, a sensitivity analysis was made for the different electricity prices in the included countries. However, the differences in energy prices depend on taxes rather than the actual energy costs, showing that there is no relation between energy prices and emissions. So this was excluded from this thesis.

The possibility that energy prices can increase significantly in the coming years has not been studied in this thesis, so the uncertainty about the assumptions made on energy prices is high.

4.4. Methodological aspects

Even if there are several methodological issues connected to using OneClick-LCA, one of the main advantages of using commercial simulation tools is that it is possible to make detailed analyses with limited data and to be able to watch in real-time how results change due to changes of input parameters.

LCA as a tool helps to give a better understanding of the environmental impacts for the different scenarios. However, it is important to discuss the limitations of the chosen methodology. First, the selected methodology, defined by the CEN 15978, does not allow the inclusion of the benefits and loads beyond the system boundaries in the total results. This has been observed as a challenge in the Nordic countries [122]. This is due to the uncertainty that the final user would give the proper treatment to the various materials used. In this thesis, there are negligible amounts of recyclable materials, so the impact of this aspect is insignificant.

4.4.1. Data issues

As the local provider of the DH system had not reported its environmental impact (when the article was written), it was necessary to use the “best possible” verified data (in this case from Gothenburg). In the data used, the share of fossil fuels was higher and the use of biofuels lower compared with the local DH. Modification of the input data was not optional. This situation led to an analysis where a higher GWP from fossil fuels added a certain level of data uncertainty. As the use of local data is not allowed, due to the impossibility of verifying this, the quality of the specific project data is poorer, due to incorrect representation of the local data. As this situation was shown in the analysis in the article, the software developer was contacted, and as DH companies in Sweden disclose publicly their energy mixes, it is in line with the software policy to include this information. As a result of that conversation, the 50 biggest DH systems in Sweden were added to the program, showing that data from research can help to improve products and services.

The software uses the CEN/TR 15941 methodology to compensate data for local conditions based on statistical data on energy intensity. The data from other countries was compensated using this methodology. Nevertheless, this compensation ends up with higher uncertainties in the results. A methodology
of how to cope with those uncertainties has been proposed by Ylmén et al. [123]. The CEN/TR 15941 methodology can lead to GWP's higher than the ones from the local system as the use of DH accounts for most of the total resulting impact.

In order to be fully transparent with LCA calculations, practitioners need to use data generic or data from other manufacturers than those specified in a project. This leads to uncertainties about the actual impact of a particular building. This is in line with the conclusion of Schlanbusch et al. [122]. When it comes to the material used, it was not possible to use some specific producers’ data as the software only allows publicly available EPDs; this makes it impossible to use data for producers that have not made any EPDs. This situation can have different effects, both beneficial and adverse. As the selected software and methodology is to the advantage of materials with EPDs, it could be easy to bypass materials that are produced in a more “environmentally friendly” way by companies that do not have the economy to produce an EPD, thus forcing the use of other products. On the other hand, the ambition seems to be to encourage companies to disclose the environmental impacts of their products, so consumers can take decisions that are fact-based.

4.4.2. System borders

As can be seen in the CEN methodology, there are potential environmental gains beyond the system boundaries that cannot be included in the result. In this way, potential environmentally friendly technologies and practices can be bypassed because the methodology only accounts for the environmental impacts and benefits of the building itself. This can discourage a building owner from carrying out some renovation alternatives that can have potential environmental benefits in a societal context, as has been discussed by Ylmén et al. [123] and Schlanbusch et al. [122]. This could be seen in this thesis regarding the use of PV, DH and some other materials that have a high recycling potential. When it is only possible to account for the impacts of the building itself, good practices and technologies can be bypassed to favor lower impacts within the system, that can led to sub-optimization of resources.

As it was discussed in papers I and II, the energy system and the building interact with one other, and changes in any of these systems have consequences at a meso level, impacting the way the marginal electricity mixes should be determined as seen in [124] and [125]. In this thesis, only one building has been analyzed, but the building owner has the intention of renovating the whole building area, which uses 5% of the total DH produced in the municipality. Changes in the energy use of the whole building stock would have consequences on how planning for future DH and electricity projects would be shaped. At the same time, the intention of developing a 4th generation DH and changes in electrification in the country can influence the way dwellings would need to be renovated. Including the energy system within the system boundaries would increase the understanding of how different renovation scenarios have an impact on the surrounding system by allocating different fuels and energy carriers. This would give a result that could show those impacts from a society level perspective.
4.4.3. Time perspectives

4.4.3.1. Energy

Another issue in this study is the time perspective. As energy systems are always changing, considering a system in a steady state during the next 50 years is unrealistic. Energy systems play a key role in energy efficiency in buildings. In this study it is possible to see how the energy system is configured has an effect on how energy efficiency in buildings should be addressed. As seen in 3.2.2 the share of renewables in electricity production can change the total impact of the different renovation strategies.

As was described in 1.1.3.2, the energy sources for both electricity production and DH have changed in Sweden during the last 50 years, as shown in figure 5. If possible changes in the future are not considered, this leads to misleading potential future environmental impacts [70]. Although the shortcomings in neglecting consideration of possible changes are understood, this thesis used that approach because the analysis was made to be compliant with the current EN standard for buildings. It is understood that the energy system would change during the following 50 years and that is the reason why the sensitivity analysis was made. So, in this thesis the building with the now available technology is analyzed as business as usual for the total lifetime of the building. The question that remained unanswered when assuming no changes during the following 50 years is how the energy system would change in the future. However, a possible answer to the outcomes of the energy systems can be found by analyzing the different electricity mixes in the sensitivity analysis. No changes in district heating were considered.

LCC scenarios are also problematic as they are based on gradually rising energy prices without any possible future influence; energy prices are not static and energy systems are becoming more complex. As has been seen with the development of wind power and PV, the technologies have higher costs at the beginning than other technologies, but these later decrease. This kind of price dynamics is not considered for the CEN standard, nor in the software used, but it would be desirable that this should be included. After carrying out a sensitivity analysis of different energy prices in the Nordic context, it was not clear how considering scenarios with different energy prices could contribute to a better understanding of the complexity of this phenomenon. As was seen during the analysis, prices are rather tied to external and political factors than to the actual production of electricity, this led to such disparities in the correlation between emissions and energy prices that it has been decided to let this be outside the study.

As shown in the introduction, more renewable sources and the 4th generation of DH (low energy supplies, smart grid technology, 2-way DH [126]) would have an effect on GWP and RW results [127] as would the development of renewable electricity generation in the final years considered in this study.

4.4.3.2. Materials

Another consideration is the conflict between the technical and commercial life span of materials. It is a well-known fact in the construction industry and
the real estate branch that building often uses the commercial life span, with a consequence that would not be according to the manufacturers’ recommendations. In these studies, all lifespans were set by default, meaning the one recommended by the manufacturer.

An extra aspect worth considering here is the complexity of the lifespans of different components and the fact that from an owner’s point of view, it is not possible to carry out a renovation at the end of each component’s lifespan. Some components would be replaced before the end of their technical service life and others would stay in place way beyond their “best before” date.

Also, there are issues with the production of construction materials and service installations. During long time spans, materials and installations can become more resource efficient with better manufacturing processes. Some materials that are known and used now can be replaced with alternative materials, or can become banned from construction due to hidden health hazards, such as asbestos.

Also, in LCC analysis, it is expected that materials and installations have costs that gradually increase with time, without considering, again, more efficient production, availability of raw materials and considerable early life cycle replacements due to changes in regulations. The analysis in the program is made on the information available in the product’s EPD so, for example, the performance change with time of PV is not considered.

4.4.4. Type of LCA

As it has been described previously, this study uses the standard CEN 15978 to perform the LCA. This standard uses an attributional LCA approach. As a building can be located in what the International Reference Life Cycle Data System ILCD handbook [128] calls a situation for “micro level decision support”. However, when considering bigger system boundaries and including the local energy system it can be listed as a “Meso/macro level decision support” which would need a consequential LCA. The problem with this approach is that if there is a possibility of renovating several buildings using the same model, there would be a considerable impact on the surrounding energy system. This would lead to a situation of a “meso decision level” where the energy use would impact the surrounding energy system. Thus, if the renovation is expected to be reproduced in several buildings the results can be misleading.

Using an attributional LCA can be used correctly in line with what is described in Cabeza et al. [48]. In the case study it was assumed that making changes in a single building would not cause changes in the local energy system.

4.4.5. Use of commercial software

The software used for LCA (OneClickLCA) can be used as a tool to increase the awareness and competence of building owners and practitioners to assess environmental and economic impacts of their projects during the decision stages and make it possible to benchmark the results. Previous knowledge of quantity surveying and building construction is needed when used in the software, and the developers offer customers a streamlined training in the basics
of LCA and LCC: The tool helps building owners to assess proposed investments from a life cycle approach. The software is easy to use, and the results are straightforward making it easy to present.

One of the shortcomings of the tool is that just one specific impact assessment method makes it less applicable for LCA practitioners. This has a significant impact in the results, as the software only uses CML2012 as an impact method. Since this study was carried out, the methodology used, CM2012, has become obsolete so that ReCiPe should be used in future studies.
5. Conclusions

This work aims to analyze how energy efficient renovation affects a building from a life cycle perspective. Different scenarios were assessed in this study, and the results of the different annexed paper are connected, complementing the study as a complete methodology. The conclusions of this thesis answer the research questions as follows.

1. How can the proposed energy efficient renovation strategies affect the total energy use at different system levels in the building as well as in the surrounding local energy system?

The proposed renovation scenarios result in a reduction of the amount of purchased energy. In the energy results it can be seen that reduction in transmission losses and ventilation losses can be comparable to reductions in purchased energy when energy carriers are changed in Sweden. The case study shows that it is problematic to promote electricity as an energy carrier when DH is available, for example from industrial excess heat or biomass from tops and branches. Using electricity as an energy source for heating would result in increasing the use for the residential and services sectors when the transport and industrial sectors see it as an alternative for reducing their GHG emissions. Also, industrial excess heat has no other monetary value and risks being dissipated in the surroundings.

2. What are the potential environmental and economic impacts for the proposed different energy efficient renovation strategies?

As seen in the results, some scenarios are identified as the “low hanging fruits”. Those scenarios have significant improvement on the LCA results for a low or moderate cost.

If the goal is to reduce GWP, changing the energy carrier to electricity in Sweden is a good alternative. However this also causes an increased RW for disposal. In all the energy mixes studied in this thesis (apart from those in Norway) it appears that affecting the use of electricity by changing the energy carriers can produce tradeoffs with environmental impacts.

This study was consistent in showing that the installation of PV at the proposed scale cannot compensate for the environmental impact during production, due to a limited energy output.

From the economic perspective it was seen that there is no simple correlation between the renovation strategies’ economic and environmental performance. Building renovations with a good performance in both GWP and RW can have higher life cycle costs.

One of the findings of this study is that the construction process and materials have a high negative environmental impact in general, while energy savings during the building’s lifetime affect the environment differently depending on the buildings’ energy carrier and the electricity production mix selected.
3. **How can impacts on energy performance, environmental performance and economic performance correlate for the different energy efficient renovation strategies?**

Studying energy efficient renovation from a life cycle perspective provides tools for building owners and construction companies with a broader perspective. This allows them to take early decisions decreasing both costs and environmental impacts focusing beyond energy savings and towards sustainability.

The results show that energy performance and environmental performance are directly connected. In Sweden, energy savings result in lower GHG emissions. However, when the sensitivity analysis is performed it can be seen that changes in electricity production can result in increased emissions.

When it comes to the economic impacts, it is shown that energy prices in Sweden are low compared with EU levels and as labor prices are high, labor intensive renovations are costly and not economically preferred in the Swedish context.

4. **What are the methodological implications of using a commercially available software while performing research on life cycle assessment?**

Using commercial software presents many methodological disadvantages. When working on LCA and LCC, one of the main problems was found in data issues. As the software producers want to show transparent calculations, all the data used in the program is externally verified. This leads to the paradox that when no data can be found for the specific project, “best available” data needs to be chosen, which in turn increases the uncertainties of the used data.

Also, as the software complies with EN standards for LCA and LCC the system boundaries and the methodologies used are locked, so there is no possibility of using another Life cycle impact assessment (LCIA) methodology, or of making another type of LCA.

The advantages are that it is possible to perform a detailed analysis based on limited data, the preliminary results are displayed in real time, making it possible to check the data and present the results in a way that is easy to understand for building owners and construction companies.

Analyzing energy efficient renovation from a life cycle perspective can help stakeholders to identify the potential benefits from, and disadvantages of a selected strategy. This helps to identify the impacts and trade-offs of different alternatives, contributing to a better understanding of the impacts of building construction in the environment. Even with the methodological issues that are implicated in using attributional LCA, using a standardized methodology could help the construction industry to increase its environmental ambitions and that can help stakeholders to avoid sub-optimization.
6. Future research

This research aimed to understand energy efficient renovation of a multifamily building from a life cycle perspective. Some factors have been identified as interesting for future research.

In this thesis two of the three components of sustainability have been studied; the environmental and economic impacts of renovation. However, the social aspects of energy efficient renovation have not been considered. The approach in this thesis does not consider the expectations or the experiences of users, as it is a pure technological approach. The community included in the boundaries of the system is affected by the implementations of these technologies, and including the user’s perception and interaction with these technologies can be of great interest.

When it comes to living standards, the renovation strategies proposed in this research do not consider soft values, such as the standard of living and user satisfaction. It is known that most renovation projects include raising the standard of the building and that the building inhabitants like to perceive their homes as more modern. It would be interesting from a cost analysis perspective to consider how energy efficient renovation can be included in scenarios when the buildings are going to be altered in order to improve comfort, thus linking the potential rent increase to the analysis.

Sensitivity analysis of building materials can be an interesting approach. There are many materials that have similar characteristics but differ in the way they used resources. For this research only traditional materials were considered, however, there are more materials on the market with better environmental performance that are being adopted by construction companies and housing companies. A closer analysis of the trade-offs of materials would be beneficial in future work.

This study only used commercially available tools, and found that the European standard contributes to big uncertainties in the study. This point could be addressed by performing consequential LCA, due to the long time perspectives of renovations. Also, broadening the system boundaries including the impacts of energy use, especially for big scale renovations within district heating, can add an extra perspective for municipalities that want to analyze different renovation alternatives.

In the same way, making a more detailed LCC would be beneficial, taking into consideration different future scenarios for energy prices and the development of new materials. Considering other hidden costs of renovation that are not considered in this thesis could also be beneficial.

Finally, it would be interesting to include the perception, barriers and possibilities that building owners and construction companies have when considering energy efficient renovation which would improve future research.

Analyzing the building as a system is beneficial for the building owner, showing the potential benefits from an individual perspective. Nevertheless, this analysis does not consider the societal benefits that an energy efficient renovation can have such as improving the living standard of the occupants.
Several observations on the need for interdisciplinary research in sustainable renovation projects have been discussed in [129]. As stated in [129], all renovation projects are unique and it is important to analyze how they benefit different actors/stakeholders beyond the limits of the environment specified in the analysis.
References


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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-34484