Cost-effective and energy-efficient renovation measures of multi-family apartment buildings constructed during the Million Program

Where carbon dioxide emissions minimization is a key issue

Christofer Svensson

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Keywords: Energy efficiency, Cost-effectiveness, Carbon dioxide minimization, Co-benefits, IEA EBC Annex 56, Renovation, The million program

Abstract

The Swedish construction and real estate sector has a significant impact on the total national carbon dioxide emissions and energy consumption. Thus, energy efficient and environmentally friendly renovation measures of existing buildings in Sweden plays an important role in the attempt to mitigate the climate changes. By applying the methodology developed by the IEA EBC Annex 56, this study focused on optimization of renovation measures to define energy, environmentally and cost-efficient renovation measures of multi-family apartment buildings located in southern Sweden. The analyzed reference building presented in this study is a high-energy consuming multi-family apartment building constructed during the mid 60's in the city of Malmö. The present study includes an investigation of the current energy need of the building and compares it with different renovation alternatives with different intervention levels. The renovation measures studied within this project includes modifications to the building envelope, the ventilation system as well as an implementation of an individual metering and price charging system of the domestic hot water. The main aim of this project was to analyze different renovation alternatives in order to determine their effects on the energy consumption in the building, their financial profitability and their effects on the overall environmental impact of the building. Moreover, an additional analysis was conducted in order to study the potential co-benefits that may arise from the implementation of the renovation measures. The secondary aim of the project was to try to find renovation measures that would successfully reduce the annual energy consumption of the studied reference building down to a level where the current energy requirements established by the Swedish building sector was fulfilled.

The annual energy consumption of the studied reference building was assessed by the use of a dynamic energy simulation software. The effects of the linear thermal bridges were calculated separately under steady-state conditions. Moreover, the cost-efficiency of the studied renovation measures were evaluated by several conducted life cycle cost analyzes. In order to assess the environmental impacts related to the implementation of the studied renovation measures, a life cycle impact assessment, *LCA,* was conducted. The resulting co-benefits that arise from the implementation of the renovation measures were evaluated by using an assessment matrix provided by IEA EBC Annex 56.

The results of the study showed that it is possible to reduce the annual energy consumption of the building down to a level where the current energy requirements established by the Swedish building sector are fulfilled by implementing comprehensive renovation measures. The results of the life cycle cost analyzes indicates that the financial profitability of the renovation measures is mostly dependent of the balance between the initial investment costs, the saved energy costs that the measures entails and the assessed evaluation period. However, the life cycle cost analyzes conducted within this project shows that by combining the renovation measures with a number of legal aids, such as governmental subventions and increased monthly housing rent will radically affect the cost-effectiveness of the renovation measures in a positive way. The results of the life cycle assessments conducted within this project indicates that renovation measures that significantly reduces the dependence of district heating will also significantly reduce the annual CO_2 emissions and primary energy consumption of the building over time. Although the results showed that the comprehensive renovation measures contributes to a rather high environmental impact in the upstream and core process, their implementation will still reduce the environmental impact of the building from a long-term perspective. Thus, the general conclusion is that the energy carrier and the quantity of the overall energy use in the building is the two biggest determining factors of how environmentally friendly the building will be from a long-term perspective.

The general conclusion of this research is that comprehensive renovation measures including modifications to the building envelope combined with ventilation and domestic hot water measures are preferable when retrofitting buildings with features similar to the studied reference building from a long-term financial and environmental perspective.

Acknowledgement

Foremost, I would like to express my sincere gratitude to my supervisor lecturer Åke Blomsterberg at Lund University for the continuous support of my degree project, for his patience, motivation, enthusiasm, and immense knowledge. The door to Mr. Blomsterberg's office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it. I could not imagined having a better supervisor and mentor for my degree project.

Besides my supervisor, I would like to thank Jonas Larsson and Jens Celind at Stena Fastigheter for all the time spent on this degree project and for providing me with crucial data and information regarding the studied reference building in this project.

I would also like to acknowledge all lecturers who have participated in the *Master's Programme of Energy-efficient and Environmental Building Des*ign at Lund University the past two years. You have given me an advanced knowledge within the area of energy-efficient and environmental building design in cold climates. This accomplishment would not have been possible without your help. No one mentioned, none forgotten.

Finally, I must express my very profound gratitude to my family and my friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Thank You.

Christofer Svensson

Table of Contents

1. Introduction

Sweden has set a national goal to reduce the specific energy use in buildings by 50% until the year of 2050. The reasons for this is to avoid unnecessary energy costs, increase the robustness in the Swedish society by becoming more independent to energy prices and to reduce environmental load. A reduction of carbon dioxide emissions within the Swedish energy sector is inevitable in order to reach this goal. Energy efficiency is currently the cheapest and the most environmentally friendly solution to phase out fossil energy and it creates opportunities to use power generated from wind turbines as well as solar energy. And the potential is huge. Sweden has currently the fifth highest energy use per capita in Europe; an unflattering top location for a country that likes to call itself a leading country in energy efficiency (Eurostat (a), 2016). The buildings and service sector in Sweden currently accounts for nearly 40% of the total final energy use in Sweden (Energimyndigheten, 2015). The Swedish Parliament has set a national goal, as a result of an energy directive from the European Union, to reduce the energy consumption in buildings by 20% until year 2020. The greatest energy savings potential in the Swedish building sector lies in the buildings that were constructed during the ambitious public housing programme most commonly referred to as *The Million Programme* (Swedish: Miljonprogrammet) during the years from 1960 to 1975. (Regeringskansliet, 2008)

However, the refurbishment of the so-called "*Million Programme Buildings*" are currently going rather slow in Sweden and the chance to implement energy efficient renovation measures in these buildings are often missed by many property owners (Kääntä, 2013). It is often quite difficult for the property owners to recoup higher energy savings in their financial calculations. However, it can be socioeconomically justified to reduce at least 50 per cent of the energy consumption in the building due to the 2050 national climate goal. Thus, the value of a comprehensive energy efficient renovation of a building is more socioeconomically beneficial than an ordinary business economical calculation takes into account. Therefore, it is necessary to not only adjust the national policies of the renovation projects for these types of buildings but also to develop cost-effective energy saving measures for these types of buildings. (Regeringskansliet, 2008)

1.1 Energy Use in Europe

The energy use in Europe varies a lot between the different countries. A research made by the European Union in 2014 showed that Italy, The United Kingdom, Ireland and Denmark use the least amount of energy in relation to the countries overall economic size (based on gross domestic product, GDP). The largest energy consumers in Europe, in relation to the overall economic size of the countries, are Bulgaria and Estonia. Furthermore, according to a study conducted within the EU-28 in 2014 there are three dominant categories where the majority of the fossil fuel based energy is being used. These three categories are: transport (33.2%), industry (25.9%) and households (24.8%). (Eurostat, 2014)

The threat of global climate change resulting from increased greenhouse gas emissions, which is primarily caused by the use of fossil fuels for energy, has made the decision makers within the European Union (EU) to act forcefully. In 2006, the EU issued the so-called Energy Services Directive (ESD), which aims to reduce the final energy consumption in Europe by 9 percent until 2016. In addition to this directive, the EU established the so-called 2020 objectives which, in relation to energy, means that the member states will have to lower the primary energy consumption by 20 percent by the year of 2020, calculated on a the projected level of primary energy use in 2005. The two other main targets of the 2020 directive are to lower the greenhouse gas emissions by 20% by 2020 as well as meet a 20% improvement in energy efficiency compared to the energy consumption forecast for year 2020. These three key targets are often referred to as the 20-20-20 targets. The 2020 directive is the first set of binding legislation from the EU regarding European energy policy. (European Commission (a), 2016)

These actions of the EU, have been implemented with the aim of preventing a global temperature from rising by more than 2°C compared to the global temperature in pre-industrial times. (European Commission (a), 2016)

1.2 Energy Use in the Swedish Building Sector

The building sector account for a significant part of the global greenhouse gas emissions. Approximately 20% of the global greenhouse gases (GHG) emissions are directly related to energy in buildings (United Nations, 2016). The production and operation of buildings account for about half of all the extracted materials and half of all the energy use within the EU (European Commission, 2016). The Housing and services sector account for approximately 40% of the final energy consumption in Europe (Eurostat, 2014). It is suggested on a global scale that energy- and material efficiency in the building sector should be a priority in all building projects in order to achieve a significant reduction of greenhouse gas emissions at low reduction costs (IEA, 2013). In Sweden today, the residential and service sectors accounts for approximately 35 percent of the total final energy consumption (IEA, 2014). However, the residential and services sectors have reduced emissions of greenhouse gases fastest of all sectors; in total 83% reduction from 1990 to 2013. The decrease is primarily due to the fact that the use of oil in buildings has decreased and been replaced by biofuels, district heating, electricity and heat pumps (See Figure 1.1). However, it may be noted that the Swedish Energy Agency's statistics on the residential and the services sectors do not include so-called "upstream" emissions of greenhouse gases e.g. emissions arising in connection with the production of building materials and the actual construction process. Thus, the 83% reduction of greenhouse gases in the residential and services sectors only refers to the emissions connected to the operation- and demolition phase of the buildings.

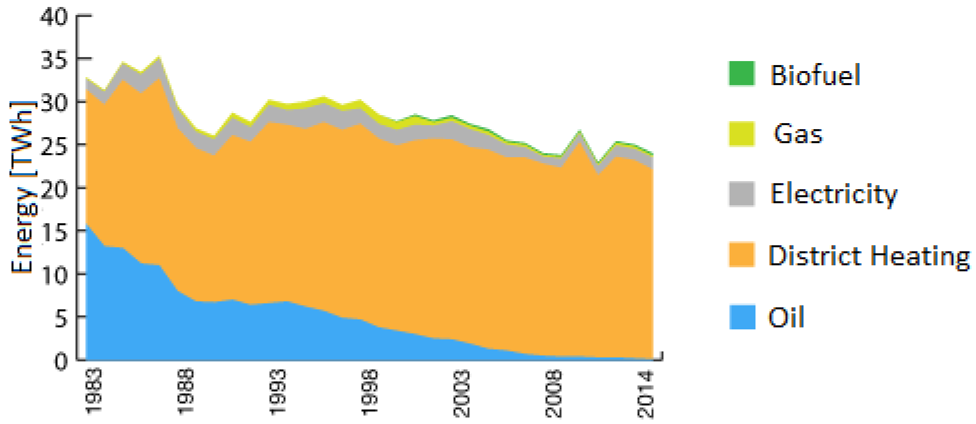


Figure 1.1. Energy use for space heating and domestic hot water in Swedish multi-family apartment buildings from 1983 to 2014. (Energimyndigheten, 2015)

The biggest contributors to the overall energy use of residential buildings in Sweden during the operation phase are space heating, domestic hot water (abbreviated as DHW), and household electricity. The most common energy carrier in multi-family apartment buildings in Sweden is district heating which accounts for nearly 90% of the energy consumption for space heating and DHW. In single family houses in Sweden the energy carrier are mainly electricity, biofuels as well as district heating. (Energimyndigheten, 2015).

Today there are approximately 4.7 million residences in Sweden where 51% of the residences consists of apartments in multi-family apartment buildings. This is an increase of approximately 12.5% of new built residences since 1990. However, it can be noticed that the energy consumption in Swedish households, except for the electricity use, has not changed significantly in the last decades. This can be explained by the fact that the vast majority of both the single family houses and the multi-family apartment buildings where built between the years of 1950 and 1980. Many of these buildings have not been renovated since they were constructed. Thus, they still have poor thermal features due to e.g. rather high U-values of the building envelope, high infiltration rates, the constant presence of thermal bridges, low efficiency ventilation systems and high U-values of the installed windows. Therefore, there is still today a great potential for cost-effective and energy saving measures within the Swedish building sector (Energimyndigheten, 2015).

1.3 Legislative Framework

The main legislative frameworks regarding energy performance and energy efficiency in European buildings are developed by the European Union during the past decade. The three following directives are the main legislative instruments for buildings in Europe (BPIE, 2013):

1. The 2002 Energy Performance in Buildings Directive (EPBD)

2. The 2010 recast of the Energy Performance in Buildings Directive (EPBD)

3. The 2012 Energy Efficiency Directive (EED)

1.3.1 The Energy Performance in Buildings Directive

The Energy in Buildings Directive (EPBD) is a European Union directive on the energy performance of buildings which provides main tools in order to improve the energy efficiency of buildings in Europe. The directive was initiated by the European Union in 2002. The directive provides the following main demands on its member states (European Commission (b), 2016):

- *A method to calculate and rate the energy standard of buildings.*
- *An energy certification system of new and existing buildings, with the requirement that the system is assigned to all public buildings.*
- *Regular inspections of the heating and ventilation systems.*
- *A minimum standard on the energy performance of new buildings and existing buildings conducting major renovations, provided that the operating area is over 1000 m^2.*

The Energy in Buildings Directive was updated in 2010. The new text clarifies, strengthens and extends the earlier directive from 2002. The main changes in the updated version of the directive were (European Commission (b), 2016):

- *Development of a framework for a comparable method to calculate the cost levels at a minimum level of energy performance of buildings.*
- *Extension to all buildings (limitation of 1000 m^2 operating area was deleted) requiring a minimum level of energy performance when a thorough renovation is carried out, which also includes both extensive renovations and replacement of the building envelope.*

- *All new buildings must be nearly zero energy buildings in December 2020 (December 2018 for public buildings).*

- *All member states have a requirement to collect financial instruments to facilitate the process of becoming near-zero energy buildings.*

- *Mandatory energy declaration for all buildings that are constructed, sold or rented out and for all public buildings with a floor area of more than 500 m^2 and has a number of visitors.*

- *Increased demands on inspections and reporting of the heating and cooling systems in all buildings.*

- *Requirement for all member states to determine the sanctions for infringements of the directive.*

There are however a number of different issues in the directive that are still being discussed in the member states and at the European parliament. These issues include e.g. the maximum limit of allowed energy use in buildings, which the allowed renewable energy sources should be and how geographically local the energy production shall be in each country. There are also nationally independent definitions of near-net-zero energy buildings in each country. The internationally accepted passive house standard are, in many countries, a reference for the definition for near net-zero buildings in terms of end-use of energy. (European Commission (b), 2016)

1.3.2 The Energy Efficiency Directive (EED)

The *Energy Efficiency Directive* was established and initiated in 2012 by the European parliament. The directive was developed in order to help the member states of the European Union to reach the energy efficiency targets by 2020. There are a number of mandatory measures described in the Directive where the main goal of the measures is to lower the energy use in all buildings within the European Union. However, the main mandatory measure in the EED Directive is to make central governmental buildings more energy efficient and requiring all member countries to establish nationally independent renovation plans for the overall building stock. These renovation plans are referred to, in the EED Directive, as the National Energy Efficiency Action Plans (NEEAPs). In these plans, the member states report all nationally established policies that encourage energy efficient renovation measures in renovation projects within the country. The NEEAP also provides an overview of the country`s building stock and an estimation of the future potential energy savings in the country`s building sector. (European Commission (c), 2016; European Commission (d), 2016)

Another aim described in the *Energy Efficiency Directive* is to reduce the primary energy consumption within the European Union to approximately 17247 TWh/Year until year 2020. The annual primary energy use within in the European Union accounted for approximately 17526 TWh in 2014. Hence, The EU needs to further pursue energy efficiency improvements in order to fulfill the primary energy goals presented in the *Energy Efficiency Directive.* (Eurostat (b), 2016)

1.4 The Million Programme

1.4.1 Background

The following text in this paragraph is based on two different literature references including Martin Rörbys book *En miljon bostäder* as well as the article *Miljonprogrammet* by SABO.

In Sweden today there are a significant amount of multi-family buildings that are in great need of renovation. Many of these buildings where constructed during the ambitious public housing programme most commonly referred to as *The Million Programme* (Swedish: Miljonprogrammet) during the years from 1960 to 1975. Despite the increased construction of residential buildings after World War II the housing crisis still persisted in Sweden during the 1960`s. In the first years of 1960`s the residential queues for rental apartments was getting longer and longer and the housing crisis was once again the great political debate topic in Sweden. Criticism grew against the government and especially towards the former Swedish Prime Minister Tage Erlander. Therefore, the *Million Programme* was initiated by government (The Swedish Social Democratic Party) in 1964 in order to solve the housing crisis. The programme was an audit of the reform program referred to as *The combined program for social housing and land policy* (Swedish: Samlat program för samhällets bostads- och markpolitik). The main goal of the programme was that approximately one million new homes would be built between 1965 and in 1975. The name "The Million Programme" are, however, not used in any public documents from this period. The name probably originated from the Swedish media that often described the large public investments in Sweden in the 1960s as "The period of major governmental programs ". During this period, the Swedish building industry was required to rationalize and industrialize the construction process in order to reach the target of one million new homes in ten years. The new construction technique had a totally different expression in terms of architecture than what the people were used to. The building elements and the large scale in both height and length characterized the appearance of the new buildings. Even the different apartments' design was influenced by the new production system. The dimensions of the building elements determined the size of the rooms, which often resulted in disproportionately depths of the rooms. The buildings were also placed so that the assembly work could be facilitated with cranes, elevators and other mechanical aids. However, high-rise buildings were not the only type of buildings that were built in *The Million Programme.* In the period between 1965 and 1975 more one- and two-story buildings were constructed than ever before in Sweden. Terraced houses had a breakthrough, as well as apartment buildings of public housing. Even low-rise buildings could be made in industrialized forms. About a third of the million new homes in this period was made up of small houses, one-third of low apartment buildings, and a third of large-scale high-rise apartment buildings (See Figure 1.2). (Rörby, 1996; SABO, 2017)

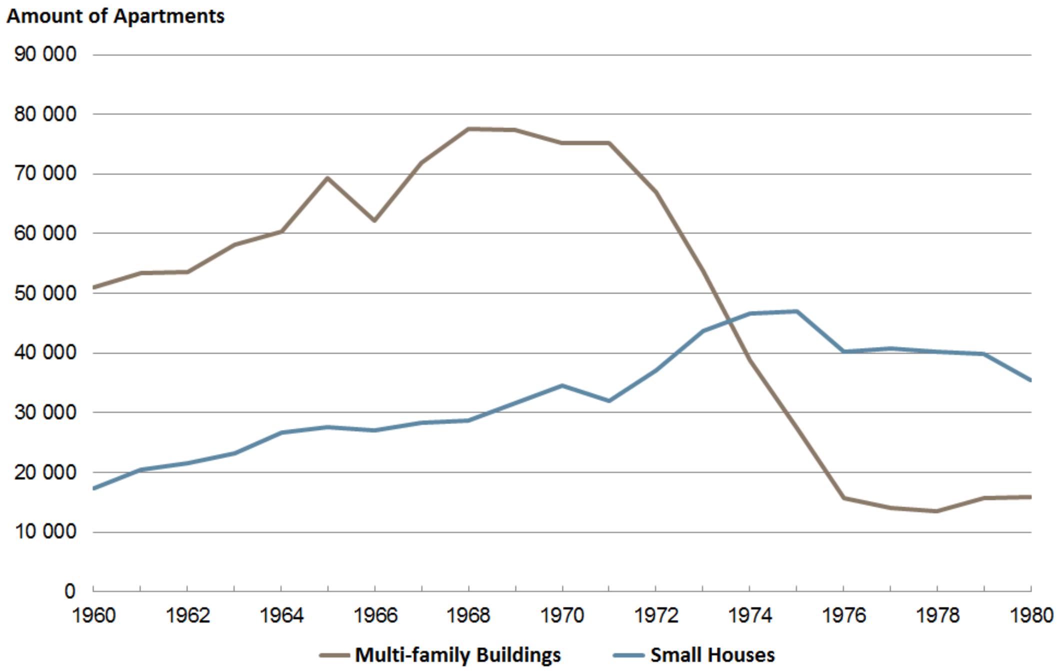


Figure 1.2. Number of completed apartments in multi-family apartment buildings and single-family homes between the years of 1960 to 1980 in Sweden. (Boverket, 2014)

1.4.2 Current Status of the Million Programme Buildings in Sweden

Today, a large proportion of the buildings that were built between the years of 1965 and 1975 are in great need of renovation (Boverket, 2014). Many of the multi-family residential buildings are especially in great need of pipe replacements, façade renovations, air tightening and supplementary insulation of the building envelope. The initial isolation in walls and ceilings of the buildings constructed during this period, often 10-12 cm of mineral wool, are significantly better than in older buildings, but worse than the standard today. The ventilation system installed in these buildings were often natural ventilation or a mechanical exhaust air system without heat recovery and the windows installed were usually simple 2-pane windows. Moreover, the lack of airtightness and insulation in the building envelope results in a rather high energy consumption of the buildings constructed during the *Million Programme* compared to the current Swedish construction standards. However, renovations of million programme buildings may cause a lot of problems for both the property owner as well as the tenants. Renovation measures such as pipe replacement, replacement of windows and insulation are major projects for the property owners but these measures are not always regarded as standard-raising measures. Thus, the tenant association (Swedish: Hyresgästföreningen) may appeal against a potential increase of the monthly housing rent (Grahn, 2005). However, it is convenient in many cases for the property owner to carry out standard raising measures such as refurbishing the bathrooms and kitchens to a higher standard at the same time as the other renovation measures are carried out. As a direct result of the extensive renovation measures and the simultaneous standard-raising activities, the rent of the properties will most likely increase. An extensive renovation resulting in significant increase in the quality and accommodation standard will, most likely, result in a significant increase of the housing rent, and when it happens then a new financial situation will appear for the tenants. The tenants are forced to, more or less, choose between keeping their residence under the condition that they are able to pay the new housing rent or move to a cheaper area. The problem with the multi-family residential buildings constructed during the *Million*

Programme is that the majority of the buildings are located in areas that today are characterized by a low socioeconomic status. Thus, the tenants living in these areas are more sensitive to increasing financial costs than other areas with a higher socioeconomic status. Because of this particular reason, it is especially important to find cost-effective renovation solutions for buildings constructed during the *Million Programme.* (Formas Fokuserar, 2012; Westin, 2011; Westin, 2012)

1.5 Regulations regarding energy performance in renovation projects in Sweden

There are a couple of decisive factors that may influence the requirements on the energy efficiency measures in connection with renovation projects in Sweden. For buildings that are labeled as cultural heritage and for renovation measures that may have an adverse effect on other features of the building the energy efficiency requirements may be lowered. Renovation measures applied to a building shall not cause a degradation of the energy efficiency, unless there are an acceptable reasons why the renovation measures should be carried out. However, the energy efficiency may be degraded if the building after the applied measures still meets the energy requirements for new constructed buildings. Exceptional circumstances can be e.g. when it is required to meet other technical requirements, such as a good indoor environment. In the case of new installations in the building that require electrical energy such as ventilation systems, electric heaters, circulation pumps, permanently installed lighting and engines shall be designed so that the power requirement is limited and the energy is used efficiently, according to the requirements set by the national board of housing (Swedish: Boverkets Byggregler). (Boverket, 2016)

Furthermore, all newly constructed buildings in Sweden must be constructed according to the requirements set by Boverket which is the Swedish national board of housing. This also applies to all extensive renovations and extensions of buildings in Sweden. The person responsible for the building, in general, the property owner, is responsible for following these mandatory rules established by Boverket. The energy requirements in buildings have been tightened significantly by Boverket in recent years. Today, there are defined regulations of the maximum allowed specific energy use in newly constructed buildings in the requirements from Boverket. Furthermore, the regulations mainly include the construction of new multi-family apartment buildings and small houses. However, the requirements for the specific energy use differs depending on the geographical location of the construction site. Boverket has therefore defined four different climate zones in Sweden where each climate zone has individual requirements regarding the maximum allowed specific energy use in newly constructed buildings (See Figure 1.3). (Boverket, 2016)

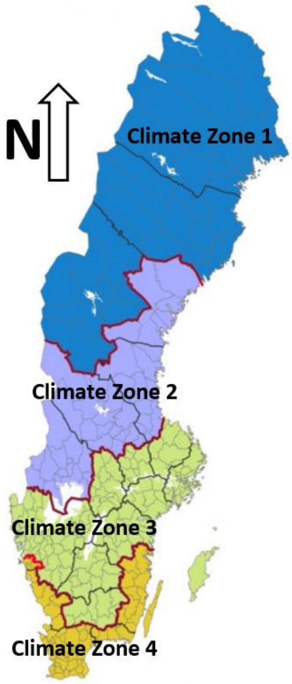


Figure 1.3. View of the four different climate zones geographical position in Sweden. (Saint-Gobain, 2015)

A newly constructed building must be well insulated and airtight in order to meet the requirements of the specific energy use. However, Boverket gives no recommended limit on the airtightness. The general guidelines however emphasizes the importance of good ventilation, since a good ventilation reduces the risk of moisture damage and ensures a healthy indoor climate. To obtain a well-functioning ventilation requires that the building is airtight. A widely accepted benchmark value for newly constructed passive houses is; 0.3 L/s and m^2 at a pressure difference of +/- 50 Pa. This value is actually a requirement for passive houses, where airtightness is a very important feature for the overall energy performance of the building (SVEBY, 2012). However, there are no requirements from Boverket regarding specific airtightness values for regular types of buildings, only a recommendation that the building owner should strive for the most airtight construction as possible. Boverket also provides guidelines of the appropriate U-values on the building envelope that should be aimed for in order to achieve the energy requirements. The proposed U-values of the building envelope are presented in Table 1.1 (Boverket, 2016)

Table 1.1. Boverkets guideline of appropriate U-values on the building envelope.

Building Element	**U-value (W/m^{2}K)**
Roof Construction	0.13 [1]
Exterior Wall	0.18 [1]
Ground Slab	0.15 [1]
Windows	1.2 [1]
Entrance Doors	1.2 [1]
References: 1. (Boverket, 2016)	

Boverkets requirement of the total specific energy use of newly constructed multi-family apartment buildings in different climate zones are presented in Table 1.2 below.

Table 1.2. The energy requirements established by Boverket for the different climate zones.

Requirements For The Specific Energy Use	Climate Zone 1	Climate Zone 2	Climate Zone 3	Climate Zone 4
(kWh/A_{TEMP} and year)				
Multi-family apartment buildings with other energy carriers than electric heating	115 [1]	100 [1]	80 [1]	75 [1]
Multi-family apartment buildings with electric heating	85 [1]	65 [1]	50 [1]	45 [1]
References: 1. (Boverket, 2016)				

Furthermore, the energy requirements, presented in Table 1.2 above, includes only the total annual energy use for space heating, domestic hot water and the facility electricity combined. Thus, it does not account for the annual household electricity consumption. (Boverket, 2016)

1.6 Scope and Objectives

This study, unlike other similar studies, presents not only different energy efficient renovation measures in multi-family apartment buildings, but also takes into account the environmental-, economic- and co-benefit perspective as well. Thus, the report's main objective was to find cost-effective renovation solutions that also generates a carbon dioxide minimization to the building as well as improves the overall co-benefits of the building. Another objective was to try to fulfill, if possible, the energy requirements for newly constructed and extensively renovated apartment buildings by applying energy efficient renovation measures to the reference building. Thus, the results of the renovation measures applied to the reference building was compared to the energy requirements established by Boverket. Thus, the main objectives of this project can be broken down into the following issues:

- To analyze the possibility to energy optimize a high energy consuming multi-family apartment building (by the means of implementing different renovation measures) to the extent where the current energy requirements established by Boverket are fulfilled.
- Try to find cost-effective renovation measures that will not only fulfill the energy requirements by Boverket but will also yield a financial profitability for the private investors within a reasonable time period.
- To analyze the possibility to reduce the overall environmental impact of the building by applying energy-efficient renovation measures to the building.
- To analyze if the implemented renovation measures entails other positive co-benefits to the building besides reduced energy consumption, saved life-cycle costs and reduced environmental impact.

The scope of this report is to show whether, and to what extent, energy efficient renovation measures are economically viable for the property owners to invest in. Thus, all applied renovation measures were compared in order to determine which alternative is the most cost-effective. The scope of this report also includes a determination of the most ideal energy efficient renovation measure from an environmental point of view. Furthermore, this report also aims to be an example of a correct implementation of the methodology suggested in IEA EBC Annex 56. Hence, both LCA and LCC analyzes was carried out in order to find the most cost-effective and environmentally friendly renovation solution for the reference building.

1.7 Overall Approach

To begin with, all input data and all the measures implemented in this report are based on the current technical- and physical properties of the studied reference building. Thus, updated construction drawings and input data concerning the energy use in the reference building has been gathered from both the property owner as well as from the city archives. The gathered data was then compiled in an energy simulation file which further on generated a simulated result of the energy use of the reference building. The result of the energy simulation was then compared to the measured energy use in the building. This comparison was feasible since all necessary input data in the simulation model were defined. However, some input data were difficult to define in the energy simulation model. This input data were considered as missing variables and a rough estimation had to be made for these specific variables.

The next step was to find appropriate renovation measures in order to reduce the energy use in the reference building. Thus, a literature study was conducted where previous renovation projects of similar buildings were studied. All relevant information and data regarding previous conducted renovation measures was collected from the literature study and this data was then used as a guideline in this project. The renovation measures that were studied affected only the building envelope and the HVAC system, as mentioned earlier. The evaluation of the reference building was based on an overall point of view, where the energy, economic, co-benefits and environmental aspects were taking into account. To begin with, all renovation measures were implemented in the energy simulation model in order to study the effects of the renovation measures on the final heating and electricity use of the building. A number of different renovation measures were studied and compared with each other by simulating them separately in different simulation models. The results from the energy simulations were considered as the total heating and electricity use in the building for each renovation case studied. The resulting energy use of the studied cases were also compared to the Swedish energy requirements, set by Boverket, for newly constructed multi-family apartment buildings. After the energy use had been simulated for each studied measure, or combination of measures, it was then possible to access the relative global costs and the environmental impacts of the implemented measures by following the methodology of IEA EBC Annex 56, which are presented in the next chapter. Furthermore, both the operational energy and the embodied energy of the building was studied in order to perform a qualified environmental impact assessment of the building. This approach, when addressing the environmental impacts, are often referred to as the *Cradle-to-Grave* approach. The global costs of each studied renovation measure, or combination of measures, were calculated by taking into account the initial investments and all costs related to the implemented measures throughout the whole life cycle of the building. Once the energy use, the global costs and the environmental impact for each studied renovation measure were assessed, it was then possible to determine the most suitable renovation measure to implement in the studied reference building. Finally, conclusions and discussions on the obtained results were drawn.

1.8 Limitations

A number of limitations and assumptions had to be implemented in this study in order to be able to finish the study in the given time frame. The most important limitations and assumptions in this study are as follows:

- There was only a limited amount of detailed data and information available for the reference building due to its age. Thus, some of the input values implemented in the analyzes conducted within this project was gathered from previously conducted scientific studies of buildings with similar features as the studied reference building.

- The measured energy use was measured for two buildings on the property by the use of one energy meter. Thus, the measured energy use in kilo-watthours per heated area and year ($kWh/A_{TEMP} \cdot Year$) was measured for the heated area of two buildings on the property. Since only one building was studied in this project a rough assumption was made that the two buildings consumed the same amount of energy for the heated area during the whole year. Thus, the same measured values of the energy use were used as a reference value for the studied reference building in this report.

- The measured energy use for heating was not divided into separate values for the domestic hot water and the zone heating but was provided as a single value. Thus, no comparison between the measured and simulated values of the domestic hot water and the zone heating was carried out. Instead, a comparison was made between the measured and the simulated values of the total district heating energy consumption (Zone Heating + DHW).

- There was no specific air flows written down in the ventilation protocols of the mechanical exhaust air ventilation system in the building. Thus, the exhaust air flows had to be assumed.

- The LCC analysis performed in this study considered only the private perspective, hence the social perspective was neglected.

- No moisture safety analyzes were conducted for the renovation measures regarding modifications to the building envelope. The moisture movement within the building materials included in the building envelope might have a decisive impact on the building physics and also the tenants' comfort. However, this effect was not analyzed within this project.

- The lack of ventilation and tap water pipe drawings of the studied reference building made it difficult to properly estimate the location of the installed ventilation ducts and the installed tap water pipes. Hence, only the vertical ventilation duct connection to the air handling unit has been described in this project.

- Merely fixed input values were used for the LCC analyzes conducted within this project such as e.g. the real interest rate, energy prices and annual price growth rates.

- The presented work in this report is a case study project. However, certain general conclusions could be drawn from this project.

- Seven potential co-benefits have been studied within this project. These co-benefits were carefully selected according to recommendations in IEA EBC Annex 56.

- There are a number of different building integrated technical systems which could have been analyzed in this study such as, for example, different types of heat pumps. However, only replacement of the existing ventilation system with a new more energy efficient ventilation system have been analyzed in this project.

2. IEA EBC ANNEX 56 Overview

2.1 The International Energy Agency

The International Energy Agency, usually abbreviated to the IEA, was founded in 1974 after a major oil crisis the year before. The organization is an independent agency within the *Organization for Economic Co-operation and Development* (OECD) and the main objectives is to reduce society's dependence on oil. The IEA acts as political adviser regarding energy issues to its 28 member states, including Sweden. However, the IEA currently collaborates with countries outside the OECD circle, such as China, India and Russia, which is seen as strategically important partners on energy issues. The IEA conducts its business in a secretariat in Paris, where most of IEAs work is conducted through 40 Implementing Agreements, in which participation is voluntary. Sweden has been a member of the IEA since its foundation in 1974 and is currently very active in the IEA cooperation. (IEA Annex 56, 2014)

2.2 The IEA Energy in Buildings and Communities Programme

The IEA initiates and co-ordinates a variety of research projects in different areas that are directly related to energy. The various research projects within the IEA are divided into different programs, where the individual programs focuses on one or more field categories. *The Energy in Buildings and Communities Programme* (EBC) is a program within the IEA that focuses primarily on research projects related to energy issues in the building sector. The main aim of the IEA-EBC Programme is, through innovation and research, to develop and facilitate the integration of technology for energy efficiency and conservation into low emissions, healthy and sustainable buildings and communities. The research and development strategies of the IEA-EBC Programme apply to office, residential and commercial buildings and community systems. The research and development strategies within the EBC will affect the building in five focus areas:

- *Building energy systems*
- *Building envelope*
- *Integrated planning and building design*
- *Real building energy use*
- *Community scale methods*

The IEA-EBC Programme is controlled and maintained by an Executive Committee whose primary task includes monitoring of active and existing projects and identify new strategic areas that may be beneficial to investigate in. The research projects within the IEA-EBC Programme is referred to as Annexes and they are all legally established to the IEA-EBC Implementing Agreement. Currently, there are 66 different projects active within the IEA-EBC Programme. Thus, the different research projects are listed from Annex 1 to Annex 66. The numerical order of the projects are based on the date that they were initiated by the IEA-EBC Executive Committee, where Annex 1 is the first initiated research project and Annex 66 is the latest. (IEA Annex 56, 2014)

2.3 Annex 56: Cost Effective Energy & CO_2 Emissions Optimization in Building Renovation

2.3.1 Objectives

The Annex 56 is an ongoing and almost completed research project within the IEA-EBC Programme. The aim of Annex 56 is to develop a new methodology for renovations of existing buildings where cost-effective solutions, energy optimization and reduction of greenhouse gas emissions are key issues. The most important objective of Annex 56 includes the development of guidelines, tools and recommendations for residential buildings. Another important objective of Annex 56 is to develop a broader approach in renovation projects that extends beyond cost-effectiveness, reduction of greenhouse gases and energy use. One of these measures in Annex 56 includes the co-benefits and overall added value achieved in the renovation process. Furthermore, the various issues assessed in Annex 56 is prioritized differently between the participating countries. (IEA Annex 56, 2014; Lund University, 2016)

The following three issues are prioritized within the Swedish participation:

- *LCC- and LCA-calculations of different renovation alternatives for single-family and multi-family buildings constructed during "The Million Programme" where cost efficient energy and greenhouse gas emission optimization are key issues.*

- *Studies of tenants' acceptance of deep renovations of different buildings constructed during "The Million Program".*

- *Compilation of advantages and disadvantages of deep renovations of buildings constructed during "The Million Program".*

2.3.2 Methodology

The methodology suggested in Annex 56 can be divided into five separate phases:

1. Calculation of assessed primary energy need and carbon emissions

Initially, the definition of *Primary Energy* according to Annex 56 is defined as the energy that has not been subjected to any type of transformation or conversion process.

In Annex 56, the calculation of primary energy in a specific building starts with calculating the total energy need of the specific building i.e. the energy use for each end-use (DHW, lighting, space heating, ventilation, appliances etc.) as well as for each energy carrier (electricity, fossil fuels, non-fossil fuels etc.). This calculation process is often carried out by using a specific energy simulation tool; in this case study the energy simulation tool IDA ICE has been used. Furthermore, the calculated energy need of the studied building is then converted into primary energy by using a so-called *primary energy conversion factor*. The conversion to primary energy use is performed per energy carrier and takes into account the energy use for extraction, processing, transportation and distribution of each studied energy carrier. Thus, the primary energy includes all gross inland energy consumption except energy carriers employed for non-energy purposes such as e.g. petroleum or gas used for producing plastics. Moreover, non-renewable energy sources continues to dominate the primary energy consumption in the European Union. In 2014, approximately 72% of the European

Unions total primary energy use consisted of non-renewable energy sources (EEA, 2016). Thus, the methods established within Annex 56 highlights the importance of reducing the non-renewable primary energy use when renovating or retrofitting existing buildings. Moreover, the carbon dioxide emissions related to different renovation measures can be derived from the primary energy use by using a carbon emissions factor. The primary energy conversion factor varies by country, where the national conversion factor is often determined by specific energy and emission data for each energy carrier. This data is often received from LCA databases within the particular country. (IEA Annex 56, 2014)

2. Life Cycle Assessment (LCA)

An LCA study can be conducted in a variety of ways. Thus, it is important to define and explain the system boundaries of the LCA study. According to the methodology suggested in Annex 56, an LCA should only compare the environmental impact of the energy that is directly connected to the renovation measures for the studied building. Thus, the LCA study will take into account only measures that affects the energy performance of the building. The results from an LCA study are time-dependent, which means that the LCA study has to be carried out with a chosen reference study period. A common viewpoint in Annex 56 is that the reference period should correspond to the expected residual lifetime of the building at the start of the renovation. If the residual lifetime of the building is unknown then Annex 56 suggests a reference study period of 60 years. Furthermore, an LCA study in Annex 56 is suggested to take into account a number of relevant phases of the so-called "cradle-to-grave" lifecycle. The cradle-to-grave lifecycle can be defined as the entire lifecycle of e.g. a material. In other words, the entire process from the extraction of the raw materials to the end-of-life waste treatment of the material. The relevant stages suggested by Annex 56 for the cradle-to-grave lifecycle is presented in Figure 2.1 below. (IEA Annex 56, 2014)

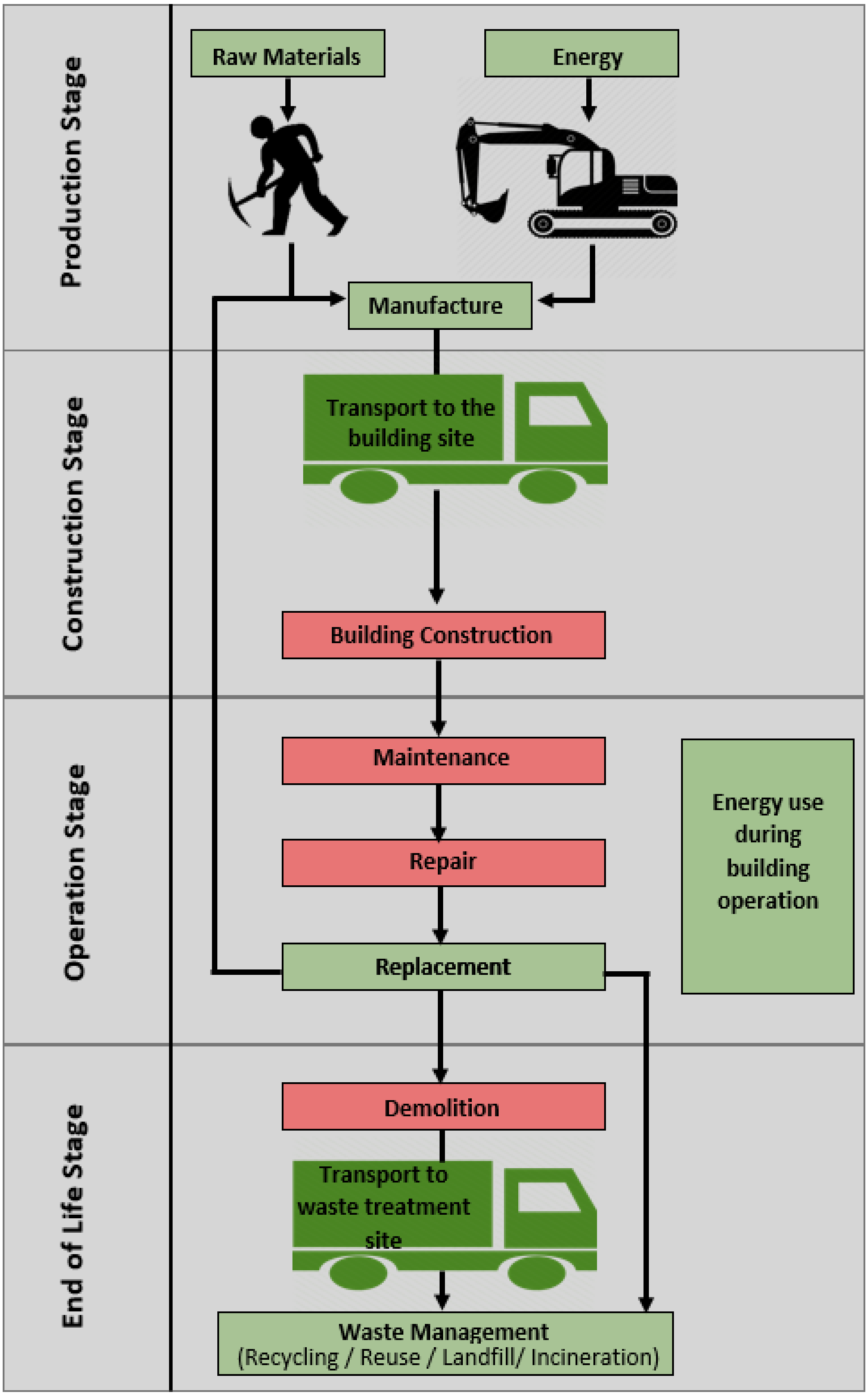


Figure 2.1. Schematic breakdown of a building's lifecycle into elementary stages.

3. Life Cycle Cost Assessment (LCC)

An LCC study calculates future financial profits and/or expenses using net present value calculations. The net present value method enables future estimations of financial profit and/or expenses by using today's currency value throughout the studied time period.

In order to find effective renovation solutions for reducing the carbon dioxide emissions and energy use in buildings a life cycle cost analysis is crucial to include in the study. A life cycle cost analysis (LCC) usually includes initial investment cost, replacement cost during the lifetime of the building, energy cost, operational and maintenance cost. In most LCC-studies the private cost or the benefit perspective is assumed. The cost assessment is performed dynamically, which means discounting the future costs and benefits by using either the global cost method or the annuity method for the parametric calculations. (IEA Annex 56, 2014)

The annuity method is a method for investment calculation. It is closely related to the net present value method. This method indicates how profitable an investment is during the lifespan of the investment. The obtained value, the annuity, is specified as a value of money per year (e.g. SEK/year). The annuity method is advantageous if various investment options with various economic lifespans should be compared, as the output of the method is obtained per year. The annuity method has been used in the life cycle cost assessment in the case of the present study. (Lasher, 2008)

4. Valuation of the Co-benefits

Before a renovation project begins, there might be many different barriers that may prevent the building owners from initiating the renovation projects. A common barrier for the building owners to overcome is the financial profitability of the renovation project. Therefore, it has been decided that all projects in Annex 56 should include a valuation of the resulting benefits of the renovation projects that are not directly related to the financial savings or costs of the project. These benefits are more commonly referred to as the *co-benefits.* Furthermore, the co-benefits of a renovation project can include e.g. both the tenant- as well as the owner perspective of the building. The International Energy Agency (IEA) has developed a model that describes the resulting co-benefits of building renovations where energy efficient measures are key elements. The model is called the "*Multiple Benefits of Energy Efficiency* "and shows an overall level of 15 different co-benefits that energy efficiency improvements can result in. These co-benefits, according to the IEA model, is presented in Figure 2.2 below. (IEA Annex 56, 2014)

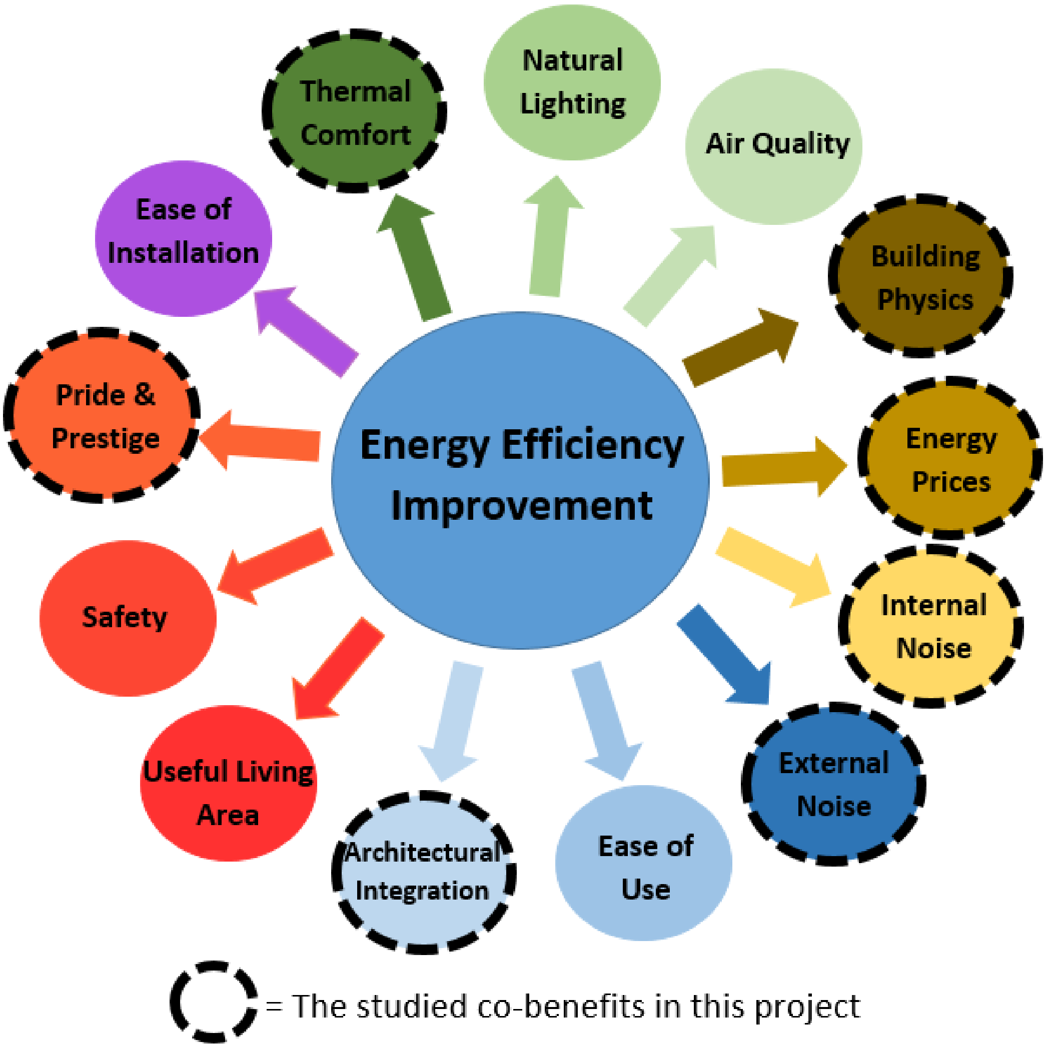


Figure 2.2. Co-benefits for energy efficiency improvements according to the IEA Annex 56 model.

5. Cost effective energy and carbon emissions optimization in building renovation

After both the LCA and the LCC study are completed, it is now possible to proceed with the cost and carbon dioxide minimization process of the project. Furthermore, Annex 56 works to develop a broader approach towards cost effective and carbon dioxide emission minimization in renovation projects. Thus, it is important to know the difference between cost optimal packages and cost effective packages of renovation measures. The cost optimal packages of renovation measures yields the lowest global costs in a renovation project. However, all the other measures that has lower global costs compared to the so-called “Anyway” scenario are also considered as cost effective packages. The “Anyway” scenario is a term used in Annex 56 to describe a renovation project that does not include any renovation measures to reduce the carbon dioxide emissions or to make the building more energy efficient. Thus, no renovation measures will be carried out that affects the primary energy consumption of the building. Furthermore, the solution with the lowest global costs does not usually result in the greatest reduction of the primary energy consumption. The relation between the primary energy consumption and the global costs of a renovation project is presented in Figure 2.3 below. (IEA Annex 56, 2014)

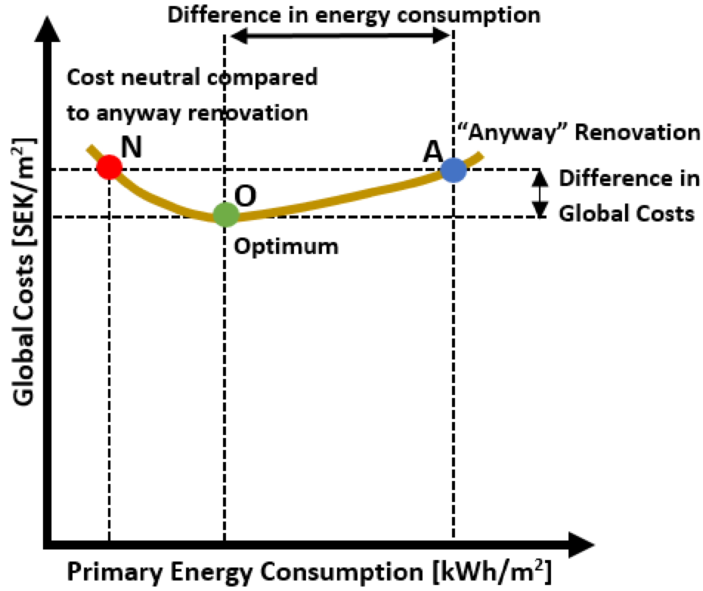


Figure 2.3. Suggested approach in Annex 56 to determine the most cost effective and primary energy minimization measures in a renovation project.

The different member countries of Annex 56 are allowed to set national energy and carbon dioxide emission targets, this means that the best solution is directly related to the renovation measures that generates the lowest global costs that comply with the national targets set by the specific country. However, even if it is not required by the normative, one can choose a solution which is not the cost optimum solution but is still considered economically viable if it yields to a greater extent of carbon emission and/or primary energy reduction (IEA Annex 56, 2014). A low primary energy use indicates low carbon dioxide emissions. This is the main reason why Annex 56 highlights the importance to study the primary energy use in connection with renovation projects of existing buildings. However, the main focus of this project has been towards carbon dioxide emissions minimization instead of primary energy use.

3. Strategies for improving the energy performance of existing buildings

The development of technological components and solutions allows an upgrade of existing equipment which continuously contributes to a reduction of the energy use in buildings. Some constructional areas, such as the building envelope, has reached a high level of technological maturity. The existing level of energy efficient renovation measures for the building envelope is currently sufficient enough to reduce specific energy use in the Swedish building sector by 50 percent until year 2050. Furthermore, the following chapter provides varies examples of renovation measures and installations that are essential in order to reduce the energy use in existing buildings. However, as mentioned in the previous chapters, the renovation measures that have been implemented to the reference building in this study focuses mainly on the building envelope. Nevertheless, a brief study of the individual metering and price charging system of the domestic hot water and changes to the existing ventilation system have been performed as well. Thus, this chapter will mainly focus on different strategies for improving the energy performance in the building by implementing changes to the building envelope and the ventilation system. (IEA, 2013)

3.1 Measures applied to the building envelope

In countries with a cold climate, like Sweden, the heating load accounts for up to 60% of the total energy use in residential buildings. However, the thermal properties of building envelopes often varies a lot in countries with cold climate. The primary drivers that determine the optimal design of the building envelope are climate, the heating system type and efficiency, the cost of energy and the installed cost of the insulation. The main features that are relevant in order to improve the thermal properties of the building envelope are (IEA, 2013):

- *Minimization of the thermal bridges*
- *Properly air sealed building envelope to ensure low infiltration rates*
- *High-performance windows with low thermal transmittance values*
- *Optimal level of thermal insulation in the building envelope*

These measures can be implemented in different ways, either simultaneously or separately depending on their economic feasibility.

In the following paragraphs are a number of possible measures presented which includes different methods of improving the thermal properties of the building envelope. The presented measures in the following paragraphs have been a very helpful guideline for the implementation of the renovation measures to studied reference building in this project. (IEA, 2013)

Insulation (roofs, external walls, and foundations)

Adding exterior insulation to the building envelope changes the building's appearance. It is therefore important to think about the aesthetic values of the building before implementing the additional insulation to the building envelope. However, in terms of improving the thermal properties of the building, it is of great importance to choose a suitable insulation material with good thermal features. Other key features to think about when choosing an insulation material are the cost of the material, resistance to microbiological growth due to moisture exposure, mechanical strength, sound insulation and resistance to fire. (IEA, 2013; Energimyndigheten, 2009)

External Walls

From a moisture- and energy perspective, it is best to add additional insulation on the exterior side of the external wall. Adding additional insulation to the exterior side of the external walls leads to the existing wall is becoming less moist and the thermal bridges in the junctions between the interior walls and ceilings are almost eliminated. The chosen thickness of the insulation is not only an economic issue. A too thick additional insulation can affect the buildings appearance negatively, windows disappears into the facade, the external wall is hanging out of the foundation and eaves becomes shorter. One can overcome such negative changes by moving out the windows in line with the new facade, widening the original foundation and extend the eaves, but these measures are very expensive. When choosing a more moderate insulation thicknesses then these measures become almost not noticeable to the overall appearance of the building. Moreover, when a certain thickness of the added additional insulation is reached the improvements of the thermal properties of the wall fades out. This thickness varies depending on the insulation material used and the thermal properties of the existing wall before the implementation of the additional insulation (See Figure 3.1). (IEA, 2013; Energimyndigheten, 2009)

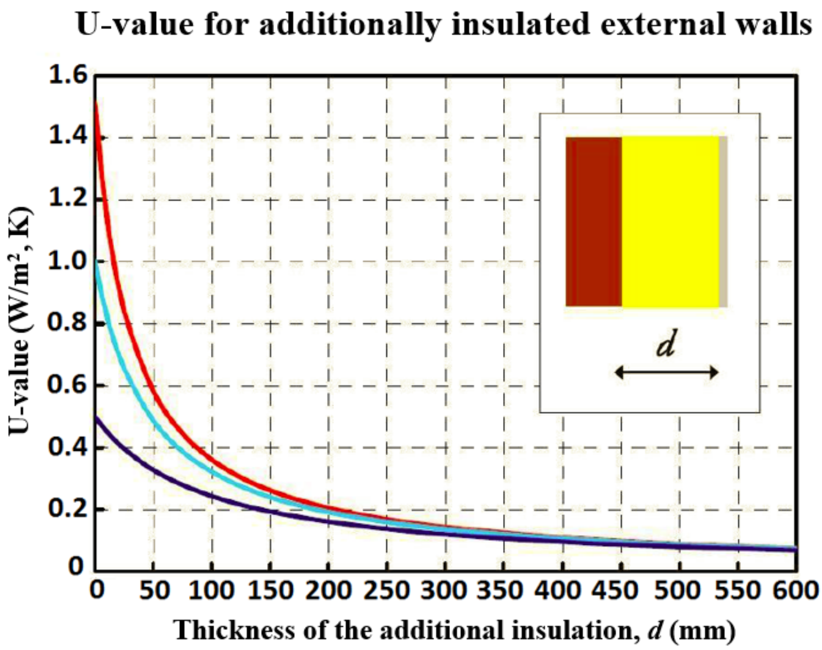


*Figure 3.1. Approximate relationship between the U-value of the external wall and different thicknesses of the added mineral wool insulation. (*Bülow-Hübe, 2010)

Furthermore, adding insulation to the external walls from the inside is an option which may be relevant if there is no possibility of adding the additional insulation to the external wall from the outside. However, adding insulation to the interior side of the external walls could be problematic. This measure results in the existing wall becoming cooler which can lead to moisture problems. Moisture generated from the outside e.g. driving rain does not dry out as quickly on the façade as before because of the reduced amount of heat transfer from the inside. This might result in frost damages on the façade of the building especially for buildings with brick facades and wooden coatings. Moreover, the moisture generated from the inside might also become a problem when additional insulation is added to the interior side of the external walls, since there is a risk that the moisture from the inside will condensate closer to the interior in the external walls. Furthermore, an internal insulation could also be problematic from an aesthetic point of view since ceiling moldings and baseboards often have to be removed. Moreover, adding insulation to the interior side of the external walls also reduces the internal floor area and thus the living area for the tenants. (IEA, 2013; Energimyndigheten, 2009)

Roofs

Adding additional insulation to the roofs or the attic space is, in many cases, the most cost-effective energy saving measure for older buildings with poor thermal properties. The insulation thickness in the attics is often no more than 10-15 centimeters in many multi-family apartment buildings constructed in Sweden during the Million program. The most common insulation material in these types of buildings are mineral wool. However, the recommendation for newly constructed buildings in Sweden is 50-60 centimeters of insulation on the attic floor. A total insulation thickness up to 50 centimeters may be recommended if the moisture risk and other technical preconditions on the roof or in the attic are accounted for. (IEA, 2013; Energimyndigheten, 2009)

Foundations and basement

Adding additional insulation to the basement and the foundations can cause moisture problems in the basement. Moisture problems in the basements of old buildings are often a result of poor a drainage system since the moisture mainly comes from the outside through the basement floor and walls. External insulation of the basement walls is the best option in order to keep the basement dry. This measure is, however, quite expensive and should preferably be performed in connection with the replacement of the drainage system. Another good option is to add insulation to the floor above the basement ceiling. This measure turns the basement into a semi-conditioned space which is beneficial since it will reduce the heat losses towards the ground.

Adding insulation to the internal side of the basement walls generates a significant risk of moisture and mold problems in the basement. A prerequisite for successful internal insulation is that the basement walls are completely dry when the insulation material is applied. (IEA, 2013; Energimyndigheten, 2009)

Air Sealing

In all buildings the ambient air is moving continuously in and out of the building. This phenomenon is mainly driven by pressure differences between the interior and exterior surfaces of the building. A commonly used name for this air movement in buildings is *air leakage* and it is usually measured by using the unit *air changes per hour (ACH).*

The most common way to measure the air tightness is to perform a pressure test of the building. This pressure test is usually performed by exposing the building to a pressurization by using a large fan (blower door). This creates a significant pressure difference between the inside and the outside which enables the measurement of the air tightness in the building. The measurements are made at a number of pressure differences in order to finally determine the average air tightness at 50 Pa.

The best time to properly air seal a building is during the construction phase of the building. It is both much easier and more economically viable to properly air seal a building during the construction phase compared to doing it afterwards. Air sealing of a building involves all the structural components of the building envelope where all connections and all potential penetrations in the building envelope must be sealed. Thus, air sealing of the building envelope is both a challenging and tedious task.

Furthermore, higher levels of air sealing is difficult, sometimes impossible, to achieve in connection with renovation measures of the building. The best option to improve the air tightness after the building has been constructed is to air seal around windows and doors which are relatively simple to unmount from the building envelope. However, this measure is often time consuming to perform and are therefore usually a quite expensive procedure. (IEA, 2013; Energimyndigheten, 2009)

Windows and doors

Windows and doors that are poorly air sealed can at over-pressurized areas in the building, which usually occurs on the top floors of the building, result in that the warm and moist air is squeezed out between the window and door frames or the wall connection. This can lead to severe moisture and mold problems. Thus, it is important to properly seal both windows and doors in the building. The specific areas around the window that are particularly important to seal is shown in Figure 3.2. (IEA, 2013; Energimyndigheten, 2009)

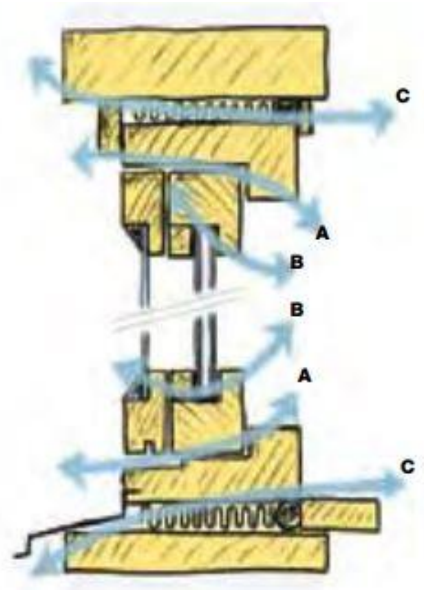


Figure 3.2. The most important areas to seal around the window. (A = Window frame/window sash, B= Window sash/the glass, C= Window frame/ the wall). (Energimyndigheten, 2009)

Furthermore, if the windows and doors are sealed well then the overall energy need for heating in the building as well as the noises and drafts from the outside will be reduced. Today there are a variety of sealing stripes with different thicknesses and in various materials on the market. The most commonly used material used to seal windows with today are the rubber-based stripes. The rubber-based stripes are currently produced in different profiles and thicknesses intended for gaps around the window of different sizes. Moreover, if the existing windows have poor thermal properties then window replacement might be necessary. Replacing windows with poor thermal properties with new energy-efficient windows might have a significant impact on the overall energy need in the building since the windows are, usually, the components with the highest U-values on the building envelope. Thus, by significantly improving the thermal properties of the windows will also improve the overall thermal properties of the entire building envelope. (IEA, 2013; Energimyndigheten, 2009)

3.2 Measures regarding the ventilation system

The ventilation systems main function is to remove moisture, cooking odors and emissions from building materials, furniture and tenants. Contaminated air shall always be ventilated away from the building and be replaced by fresh air from outside. According to the Building Regulations (BBR), the ventilation systems in new buildings shall be designed for a minimum outdoor air flow of 0.35 L /s per m^2 floor area. This corresponds to approximately 0.5 air changes per hour for a building with a ceiling height of 2.4 meters. In other words, all the air in the building is replaced with fresh air from the outside within two hours. Additional insulation and air sealing of walls and floor joists usually means the air leakages through cracks and gaps in the building envelope are reduced. This can result in a reduction of the supply air into the building which further results in a reduced air circulation in the building.

There are several options to compensate for the reduced fresh air intake after a renovation. One can e.g. ignore to seal the upper edge of the window frames of some windows. Another alternative is to mount ventilation valves in the window sash or the window frames upper part. A third option is to mount special supply air valves above some windows, or high up on the walls in some rooms. These measures are mainly carried out in the living rooms and bedrooms. However, the most preferable alternative is to implement a new balanced mechanical ventilation system in the building since this measure makes it possible to use a heat exchanger.

Furthermore, in buildings with poor exhaust air ventilation features, the warm and moist indoor air is transported through the building envelope to the colder air outside. This air movement increases the risk of condensation in building components especially during the winter period when the temperature difference is large between the indoor- and outdoor temperatures. This phenomenon is usually referred to as convection. However, one can prevent this air movement by creating a negative pressure in the building. Thus, the pressure condition in a building is a decisive factor that determines the probability for moisture damages due to convection in the building. However, even if the pressure condition in a building is on an acceptable level, there might still be a risk for moisture damages in the building components due to diffusion if there is no vapor barrier installed.

The installed ventilation system in a building has a significant impact on the overall energy performance of the building. Sometimes the ventilation accounts for up to 30% of the heat losses from the building depending on the airtightness and installed ventilation system in the building. There are, however, many different types of ventilation systems currently on the market that can be installed to retrofit old buildings with poor ventilation properties. A brief explanation of the most common ventilation systems installed in Swedish households are presented in the sub-chapters below. (IEA, 2013; Energimyndigheten, 2009)

Passive stack ventilation

This ventilation system, which was very common in Sweden until the 1970s, is based on the physical principle that warm air has a lower density than cold air. The warm exhaust air rises upwards and out through the exhaust ducts in e.g. a chimney or in separate ventilation channels. This process is completely natural and does not require any type of mechanical installations. Thus, the system is relatively cheap to install. However, it is not possible to regulate the ventilation flow and the natural ventilation is therefore very dependent on the outside temperature and the wind. On a warm windless summer day the natural ventilation does not work at all. However, during a really cold and windy winter day the natural ventilation will be way too perceptible. (Autodesk, 2012; Energimyndigheten, 2009)

Mechanical exhaust ventilation

The mechanical exhaust ventilation system is common in Swedish buildings constructed from the late 70s. A fan is usually placed in the attic or on the roof and ventilates, via a pipe system, the air from kitchens, bathrooms and laundry rooms in the building. The heat from the exhaust air can then be extracted in buildings with installed exhaust air heat pumps. The extracted heat is then re-used for the domestic hot water and zone heating in the building. Furthermore, a negative pressure in the building can be accomplished by combining natural ventilation and mechanical exhaust air ventilation in the building. If the building has no fresh air valves installed, which is very common, then the air intake is mainly provided to the building through cracks and gaps in the walls and floors and around the windows. This may result in that the building feels draughty. Thus, it is important to install fresh air valves in the building especially if additional insulation and air sealing is added to the building envelope. (Green Building Advisor, 2016; Energimyndigheten, 2009)

Balanced mechanical ventilation

The most comprehensive ventilation system is called balanced mechanical ventilation (Swedish: FTX-system). It is a fan-driven supply and exhaust air system with heat recovery. This system requires that an extensive duct system is installed in the building, if not already installed, which transports the exhaust air out of the building and simultaneously provides the building with fresh supply air. But before the heated exhaust air leaves the building, it passes through a heat recovery unit, which extracts the energy from the exhaust air and heats up the cold incoming supply air. In this way, the user saves energy while providing pre-heated supply air to the building. However, there are many components that needs to be installed in a balanced ventilation system and the filters to the fan must be replaced on a regular basis in order for the system to work efficiently. This makes the system quite expensive to invest in especially if there is a limited amount of space to install the duct system in the building. (VVS Företagen, 2009; Energimyndigheten, 2009)

Exhaust air heat pumps

An energy efficient alternative to recover some of the heat from the exhaust air system is to implement an exhaust air heat pump. This heat recovery system has been common to implement in buildings with an exhaust air ventilation system since the late 80's in Sweden. An exhaust air heat pump extracts the sensible and latent heat from the exhaust air of a building and transfers the heat to either the supply air, the domestic hot water and/or the hydronic heating system (e.g. radiators or underfloor heating). This system requires at least that a mechanical exhaust air ventilation system is installed in the building. Additionally, this type of heat pumps require a certain air exchange rate to maintain its output power. Since the indoor temperature is usually 20-22 degrees Celsius all year round in Sweden, the maximum output power of the heat pump is not varying with the seasonal outdoor temperatures. (Energikontoret Skåne, 2010)

4. Description of the case study building

This chapter introduces the chosen case study building for this project. The studied reference building is one out of the two buildings within the property designation referred to as *Professorn 11.* The property consists of two multi-storey buildings, one being a four storey building and the other one is a three storey building. Both buildings were constructed during the same year with a similar design and with similar constructional details. Hence, the studied reference building is the three storey building placed on the south side of the property (See Figure 4.1). The building was constructed in 1965 on the street of Professorsgatan 9 in the city of Malmö, which makes it a well-represented multi-family apartment building of the *Million Programme*.

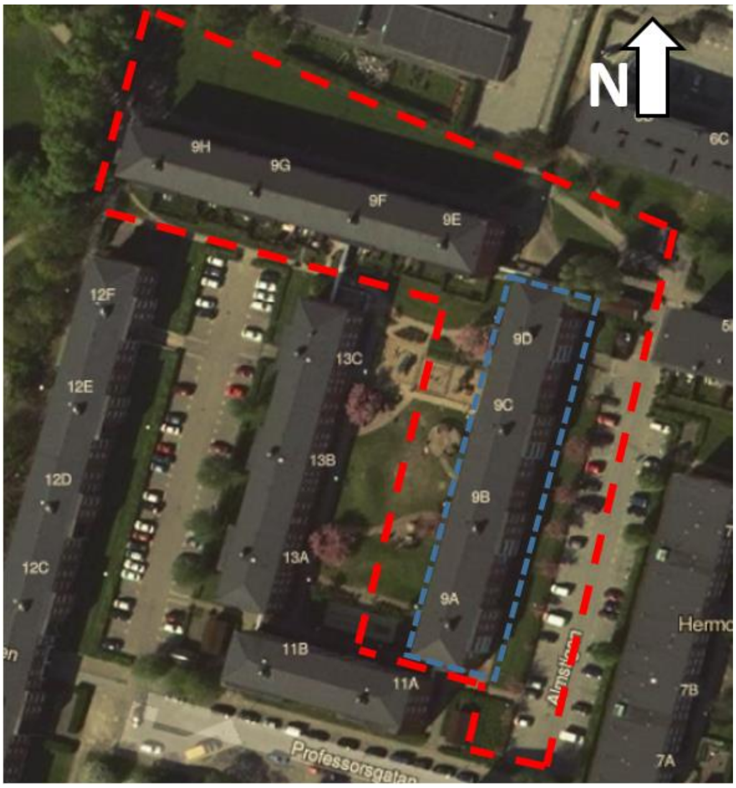


Figure 4.1. Top view of the approximate property designation of Professorn 11 highlighted in red and the studied reference building highlighted in blue. (Hitta.se, 2016)

The studied reference building has three floors above ground and one floor below ground. The floor below ground mainly serves as storage space and laundry area for the tenants in the building. The reference building accommodates, in total, 36 apartments, 4 stairwells, 2 laundry rooms and 2 drying rooms. The total floor area is approximately 4326 m^2 including both heated and unheated floor areas, which account for 2949 m^2 and 1377 m^2 respectively and the caretaker of the building estimates that there are between 90 and 110 tenants in the building. Furthermore, a close collaboration with the property owner *Stena Fastigheter* have been kept throughout the whole study. Hence, all the required technical details regarding the measured energy use of the building, architectural drawings, the renovation measures that have been carried out etc. was provided by *Stena Fastigheter*. However, the majority of the constructional drawings of the building was gathered from Malmö city archives. The building is characterized by its brick facade and its low-sloped wooden roof and the construction technique used for the reference building are typical for the types of buildings in Sweden known as *Lamellhus,* which were extensively constructed during the 50s and 60s.

The typical construction of a *Lamellhus* is characterized by a load bearing masonry construction and a wooden roof with an unconditioned attic which is separated from the heated zones below. (Andersson, 1986)

A panoramic view of the west side of the studied reference building is shown in Figure 4.2 and all four orientations of the building is presented as façade drawings in Figure 4.3.

Figure 4.2. Panoramic view of the west side of the studied reference building.

Figure 4.3. Façade drawings of the four orientations of the studied reference building. (Wall, 1997)

The facade drawings presented in Figure 4.3 represents how the case study building looks like today. However, the building did not always look like that. During the year of 1997 the building went through a renovation of the balconies where all the existing balconies were glazed-in. Nevertheless, the current balcony slabs of the building have not been changed or replaced since the construction of the building. Furthermore, the balcony slabs are all intersected with the external wall, which gives a significant disadvantage when considering the thermal bridges effect compared to a disjointed structure.

The apartments in the building consists of one-, two- and three bedroom apartments where each apartment has its own balcony facing either south, west or east. Furthermore, all floor plans above ground have the same layout. The detailed floor plans are presented in Appendix A.

4.1 Building Components

The overall energy performance of the reference building is strongly depended on the heat transmittance (U-value) of the building components such as windows, roofs, floors, walls etc. However, the infiltration rates have also a significant influence of the energy performance in the reference building. In the next sub-chapter the features and properties of the different building components in the reference building are described.

The heat transfer coefficients, U-values, of the different building components in the reference building were calculated according to both the SS-EN ISO 13789 standard and the calculation method described in BBR (SIS (a), 2007). Furthermore, the thermal conductivity values, λ, for all the different materials of the building components have been chosen according to the ISO 10456:2007 standard. (SIS, 2009)

External Wall

The external walls above the ground level of the reference building consists of a load bearing masonry construction. The wall is made up by three different layers; two layers of solid brick masonry which are separated by a cavity filled with mineral wool insulation. The total width of the external wall is 340 mm and the thicknesses of the three layers are presented in Figure 4.4. Furthermore, the overall heat transfer coefficient, U-value, of the external wall was calculated to approximately 0.38 W/($m^2 \cdot K$). Overall, the external wall is in a good condition. However, traces of frost damages are noticeable on some specific areas on the façade which mainly reduces the building's aesthetics from the outside.

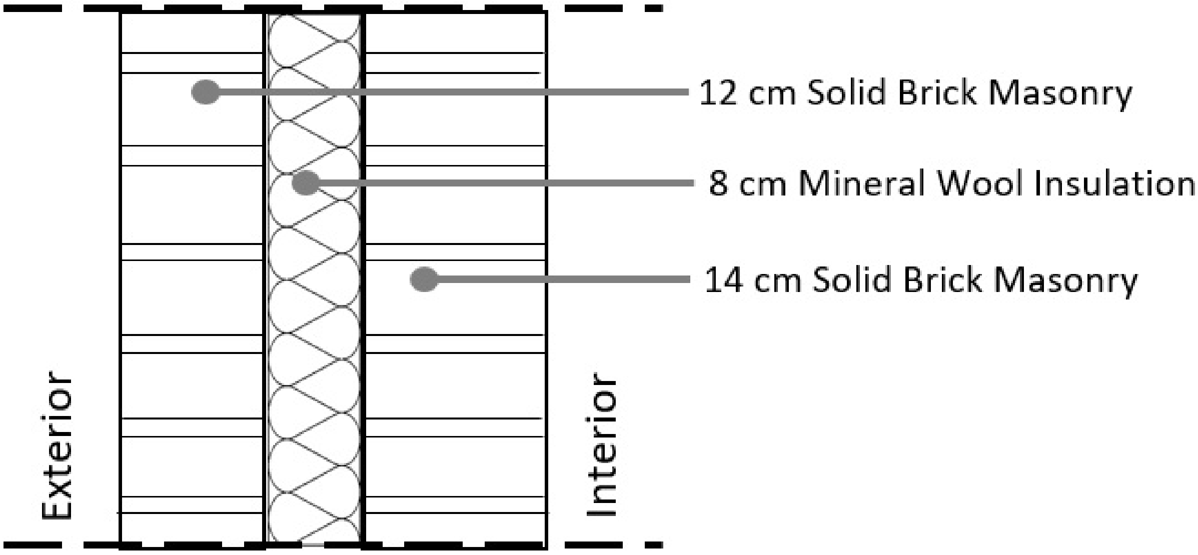
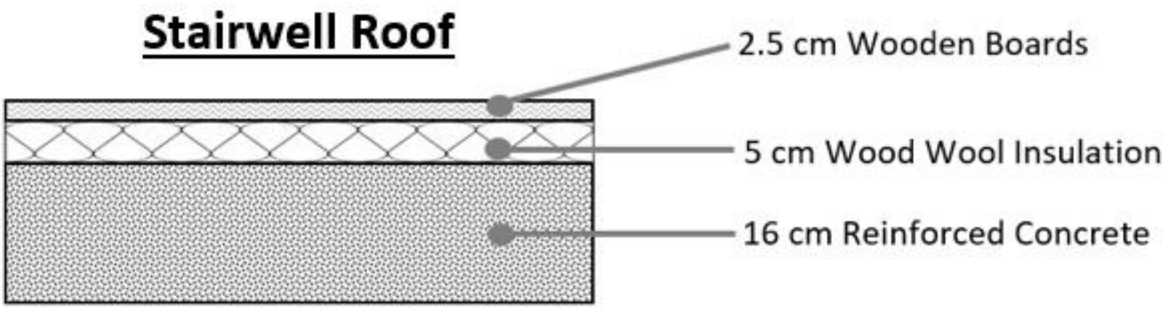


Figure 4.4. Construction details of the external wall of the reference building.

Roof

The low-sloped roof connected to the top floor is mainly constructed of pressure impregnated wood. The roof consists of low-sloped wooden rafters with horizontally placed tongue and groove boards covered with an underlay board and a bituminous felt. The rafters are held up and stabilized by multiple joists which are steel anchored in the attic floor. The attic floor consists of 16 cm of reinforced concrete which is insulated upwards by 12 cm of mineral wool insulation. The insulation installed in the attic makes the attic a non-conditioned space which reduces the heat losses from the heated zones below. However, the steel anchored joists creates a potential thermal bridge in the attic floor. Furthermore, the stairwell roof in the reference building consists of 16 cm of reinforced concrete and 2.5 cm wooden boards separated by 5 cm of mineral wool insulation. The structural details of the two different roofs installed in the building are presented in Figure 4.5.



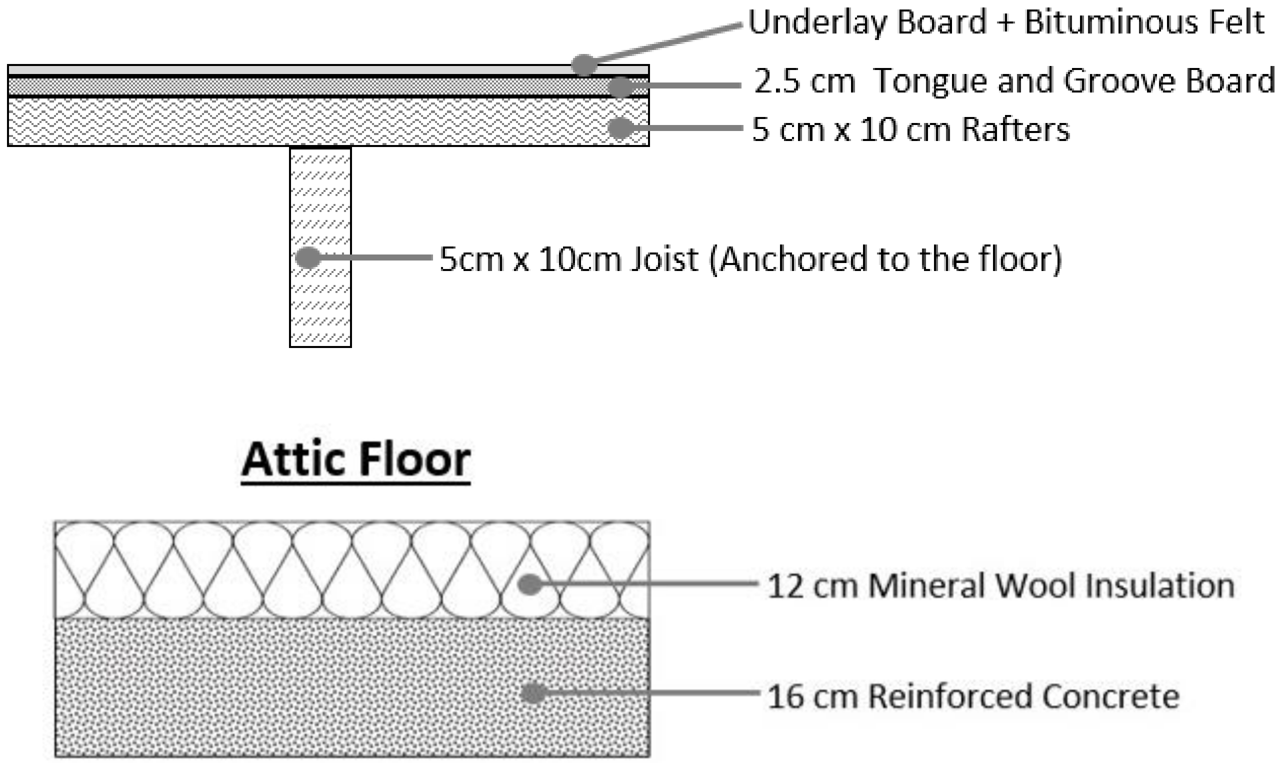


Figure 4.5. Construction details of the roof structures.

Basement wall and ceiling

The basement ceiling in the studied reference building consists of 160 mm of reinforced concrete which is insulated downwards with 70 mm of wood wool insulation. The load bearing basement walls consists of 280 mm of reinforced concrete with 70 mm of wood wool insulation which is placed on the interior side of the wall. The structural details of the basement walls and ceilings are presented in Figure 4.6. The ground slab consists of 320 mm of un-insulated reinforced concrete. Thus, the lack of insulation materials in the ground slab makes the thermal losses towards the ground beneath the slab rather high.

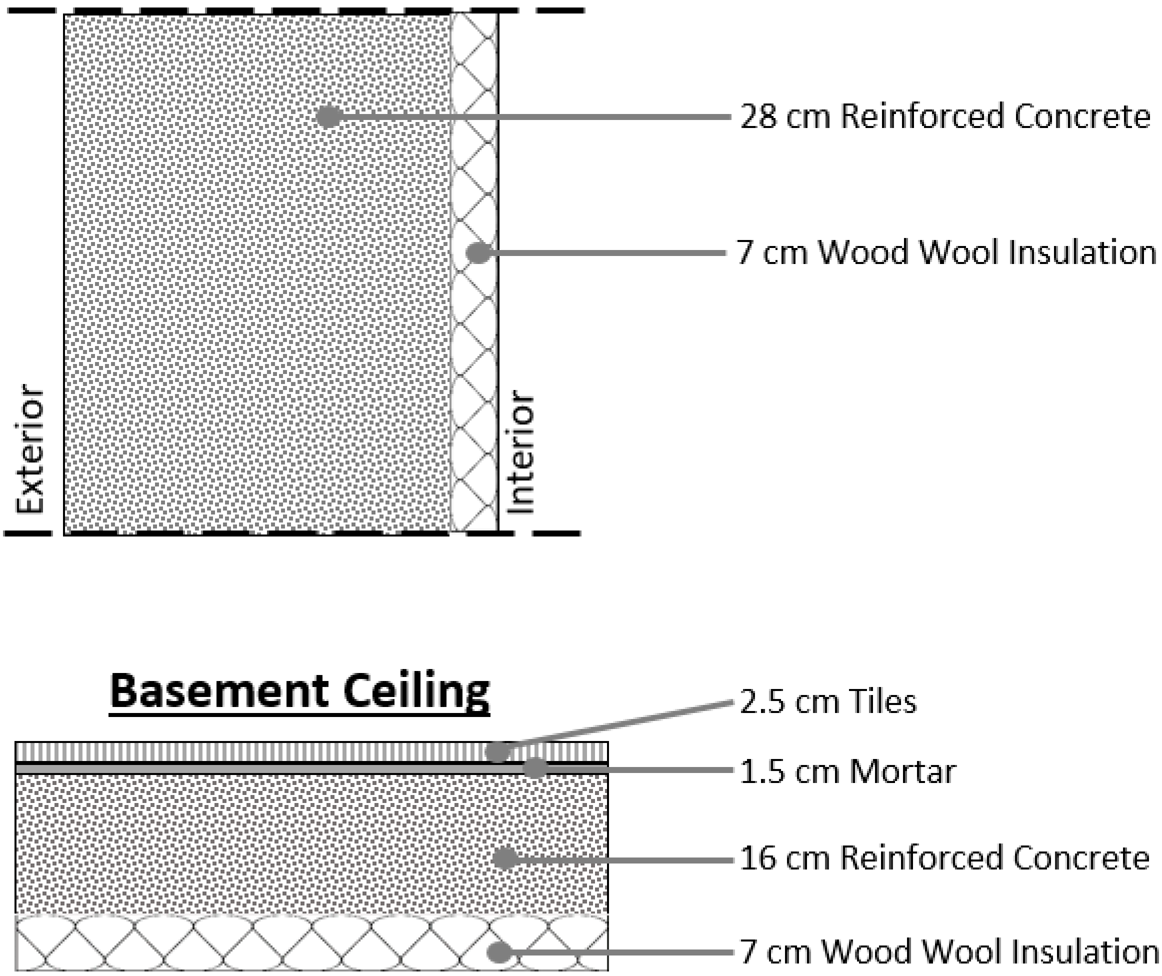


Figure 4.6. Construction details of the basement walls and ceilings.

Windows

The existing windows in the studied reference building were installed during the construction of the building in year 1965. The only changes made regarding the glazed building components was carried out in 1997 when the balconies were glazed-in. All the windows installed on the building envelope are double glazed windows with white painted wooden frames. Furthermore, the installed windows are in a rather poor condition from an architectural perspective since much of the paint on the majority of the wooden window frames have flaked off and some windows even have small cracks on the exterior pane (See Figure 4.7).

There are six different sizes of the windows installed that varies from 0.64 m^2 to 1.88 m^2 in total window area including the window frame. The thermal performance of the windows are particularly determined by the g-value and the U-value of the windows. The g-value, also known as the solar heat gain coefficient, of a window describes the solar heat transmittance through the transparent and translucent materials of the window. A high g-value indicates that the heat transmittance through the window is high (Autodesk, 2015). However, there are no information available on the g-values and U-values for the specific windows installed in the reference building. Thus, an estimation had to be made regarding the thermal properties of the installed windows. An assumed U-value and g-value of all the installed windows, including window frames, on the building envelope was set to 2.8

W/($m^2 \cdot$ K) and 0.76, respectively. The chosen U-value for the installed windows was based on the measurements performed in a study on similar windows conducted by the *Swedish National Testing Institute* in 1981. (Swedish National Testing Institute and Nordtest, 1981)

Figure 4.7. Photo of a window installed in the basement of the studied reference building.

Internal floors, walls and ceilings

The internal walls, ceilings and floors that separates the different apartments in the building do not contribute to the thermal losses that occur between the heated zones and the outside. However, they were all accounted for in the simulation model of the reference building since they contribute to the overall thermal mass in the building.

The overall heat transfer coefficients for the main building components on the building envelope of the studied reference building are summarized in Table 4.1. The thermal conductivity and specific heat values of all the materials on the building envelope were chosen according to the ISO 10456:2007 standard. (SIS, 2009)

Table 4.1. Overall heat transfer coefficients for the building envelope elements.

Building Component	**U-value [W/m^{2}K]**
External Wall	0.38
Stairwell Roof	0.65
Roof Construction	0.28
Basement Construction	0.32
Ground Slab	3.28
Windows	2.80

4.2 Facility Equipment

The facility equipment in a building can be a major contributing factor to the overall energy consumption in the building. Facility electricity refers to the electricity needed for the operation of a property as well as services provided in the common areas of the building. There is a big savings potential in many buildings in Sweden regarding the facility electricity. Savings can be made by controlling the equipment so that it is only used when needed or by replacing old appliances and equipment to more energy efficient products.

In the studied reference building there are, as mentioned before, two laundry rooms and two drying rooms in the basement of the building. The machines installed in these rooms are essentially products produced by the Swedish home appliance manufacturer *Electrolux.* Furthermore, a complete list of all the specific equipment installed in the laundry- and drying rooms was provided by the caretaker of the studied reference building who is also an employee at Stena Fastigheter. The provided list also included the current booking schedule for the laundry- and drying rooms of the building. Hence, these rooms are available for booking every day between 8am to 8pm for the tenants in the building. All the equipment installed in the laundry- and drying rooms of the building and their required power input during operation is presented in Table 4.2.

Table 4.2. Installed equipment in the laundry- and drying rooms of the reference building.

	Laundry Room 1	**Laundry Room 2**	**Drying Room 1**	**Drying Room 2**
Washing Machines				
- Amount installed	2	2	-	-
- Manufacturer	Electrolux	Electrolux	-	-
- Model	W365HLE	W365HLE	-	-
- Engine Power Input (Nominal Load)	550W [1]	550W [1]	-	-
Drying Machines				
- Amount installed	1	1	1	1
- Manufacturer	Electrolux	Electrolux	Electrolux	Electrolux
- Model	T3190	T3190	HT 400 E	HT 400 E
- Engine Power Input (Nominal Load)	130W [2]	130W [2]	140W [3]	140W [3]
References: *1. (Manuall, 2017) 2. (SBC, 2015) 3. (Electrolux, 2014)*				

4.3 Building Services Engineering

The studied reference building is heated by district heating distributed by *E.ON* which is the main energy supplier in Malmö. The two buildings on the property have a shared substation where the district heating meter is placed. Thus, the energy meter shows the total energy consumption for both buildings on the property. The space heating of the apartments is provided by the means of radiators. The domestic hot water in the studied reference building is also heated by district heating from *E.ON*. Thus, the heat provided to the building including both the space heating and domestic hot water have a *COP* of 1. The abbreviation COP is short for *coefficient of performance* which is a ratio between the useful heating or cooling provided per energy input. In this case, a COP value of 1 indicates that the bought energy from the district heating distributer is equal to the useful heating provided to the building. (Power Knot, 2009)

4.4 Ventilation

The ventilation system installed in the studied reference building is a mechanical exhaust air ventilation system combined with natural supply air ventilation. Each apartment has exhaust air ventilation valves installed in the bathroom and the kitchen. The supply air valves are installed in the separating wall between the living room and the glazed-in balcony as well as in the bedroom for each apartment in the building. This type of combined ventilation system generates a negative pressure in the building which is beneficial from a moisture safety point of view. Furthermore, the ventilation fans are placed on the roof of the reference building and they are all connected, via a pipe system, to all kitchens and bathrooms in the building. The exhaust airflows were difficult to determine since there was no accurate data on the specific airflows of the ventilation system in the latest mandatory ventilation control (Swedish: Obligatorisk Ventilations Kontroll) that was conducted in the building. Thus, the exhaust airflow in the building had to be assumed and was therefore given a value of 0.35 $L/(s \cdot m^2)$ which is the lowest acceptable value of the exhaust airflow according to requirements in Boverkets Byggregler (Boverket, 2016). Furthermore, the window opening rate in the building has not been accounted for in this study because it is difficult to estimate since it completely relies on the habits of the tenants in the building. Thus, this effect can only be properly determined through a thorough sensitive analysis.

Air tightness

There is a lot of lacking information on the construction details and infiltration rates of the studied reference building. There are no blower door test results with specific air exchange rates available for the studied reference building. Thus, at first, the air exchange rate was considered a missing value. However, the air infiltration value is of great importance when determining the overall energy performance of the studied building. Later on, a model calibration procedure was conducted on the energy simulation model. Different values of the total air exchange rate was implemented in the energy simulation model until the simulation results of the energy consumption gave realistic results compared to the measured energy use in the building. The same model calibration procedure in order to estimate the air exchange rate was used in the study "Holistic method for energy renovation of buildings: focus on users involvement" written and conducted by Carsten Rode et al. Thus, the obtained results of the air exchange rate from the calibration procedure was considered reasonable. (Rode C et al, 2013)

The resulting air exchange rate of the model calibration was 1.5 ACH at a pressure difference of 50 Pascal. This infiltration value is equivalent to an airtightness of approximately 1.05 L/m^2s for the heated zones in the building. Furthermore, the obtained value from the calibration corresponds to many new building codes in Northern Europe that require an air exchange rate of 0.6-1.5 ACH at 50 Pascal pressure difference for buildings with mechanical exhaust ventilation. (International Energy Agency, 2013)

4.5 Measured Energy Use

The overall energy performance of the studied reference building was determined according to the measured yearly values of the energy use. The measured energy use data available includes specific data on the facility electricity and the overall heating need of the building. However, the measured energy use for both domestic hot water and heating zone is presented as a common value in kilowatt-hours. This means that there are no precise data available on the yearly energy use of neither the domestic hot water nor the zone heating. Only a common measured value in kilowatt-hours for both the DHW and heating zone is available. Furthermore, the sub-station placed on the property measures the energy use for both the buildings on the property. Thus, it is difficult to precisely determine the measured energy use for only the studied reference building. However, an estimation was made that both buildings on the property consumes the same yearly amount of energy in kilo-watthours per square meter. This estimation is fairly reasonable since both the buildings on the property are constructed during the same time period and with the same constructional details. The available data on the measured energy use of the two buildings was provided by Stena Fastigheter and was measured during the year of 2015. Furthermore, the measured energy use was degree-day corrected to a year with normal weather conditions in Malmö. This correction was carried out since the energy use was measured exclusively for the year of 2015. A degree-day correction factor of 1.17 was used for the measured energy (Malmö Stad (a), 2017). This correction factor indicates that the average temperature in 2015 in Malmö was higher compared to a normal year. The measured energy use for the studied reference building, with the criteria's mentioned above, is presented in Table 4.3.

Table 4.3. Degree-day corrected measured energy use for the studied reference building.

Measured Energy	**Total Yearly Energy Use For A_{TEMP}**	
Facility Electricity	41.3 MWh	14 kWh/A_{TEMP}·Year
Total Heating (DHW + Zone Heating)	460 MWh	156 kWh/A_{TEMP}·Year

5. Methods and Tools

The following chapter presents the complete methods used in this study including all assumptions made throughout the project. This chapter also includes a description of all the tools employed in order to assess the impact of energy-related renovation measures on the overall energy performance of the studied building.

5.1 Software employed

IDA ICE 4.7.1

IDA ICE is an extensive dynamic energy simulation software developed by the Swedish company EQUA which was used for all the conducted energy simulations of the studied reference building. The software was chosen because of its ability to execute detailed energy simulations for multi-zone buildings. IDA ICE is a modelling software that provides a range of performance data such e.g. as energy consumption, thermal comfort, daylight luminance, internal heat gains and ventilation conditions of the studied building model. The software has a simple interface which makes both the navigation and modelling work in the software rather easy. IDA ICE also has a rich template library which includes different types of occupancy schedules, activities, construction details and HVAC systems which allows the user to quickly load data into the building model. (EQUA, 2016; Building Energy Software Tools, 2015)

HEAT2

HEAT2 is a software that can be used to calculate the two-dimensional temperature distribution, surface temperatures and heat flows in different building components and structures. The software is able to implement steady state and transient calculations. The studied model can either be drawn directly in the software or exported from a number of different software. HEAT2 contains a materials library with over 200 different building materials where the material properties can be supplemented and adjusted for each individual simulation. In this project, HEAT2 was used for assessing the linear thermal bridges of the different studied building components on the building envelope. The calculation method used for the calculations of the linear thermal bridges in HEAT2 is in accordance with the EN ISO 10211 standard. (Building Physics, 2013)

Eco-Bat 4.0

Eco-bat is a user-friendly simulation tool that allows the user to quickly model a building and then perform a life cycle assessment analysis of the building. The software foresees by default an evaluation of the studied buildings environmental impact. The default environmental evaluation is based on the methodology developed within Annex 56. Thus, it enables a direct comparison of the environmental impacts between different energy-related renovation measures. Hence, Eco-Bat 4.0 was used for all conducted LCA-analyzes in this project. (Eco-bat, 2016)

Wikells Sektionsdata 4.2

Wikells Sektionsdata 4.2 is a software that allows the user to calculate the costs for different building materials, components, services as well as labor costs. The software provides an extensive template library which includes e.g. current Swedish prices for different building components and materials. Furthermore, the software continuously updates the prices in the template library according to the current average prices available on the Swedish market. Thus, the software was used to determining the accurate investment costs related to the different types of renovation measures studied in this project. (Wikells, 2017)

5.2 Base Case Model and Input Data

In order to be able to conduct the energy simulations of the reference building a 3D model of the studied building and its surroundings were modelled in IDA ICE. The surrounding buildings were also included in the 3D model in order to take into account the shading effects on the studied reference building. The parameters assigned for the thermal performance evaluation of the studied building are listed and explained below. Figure 5.1 below shows the 3D model of the building from a southwest orientated view with the surrounding elements.

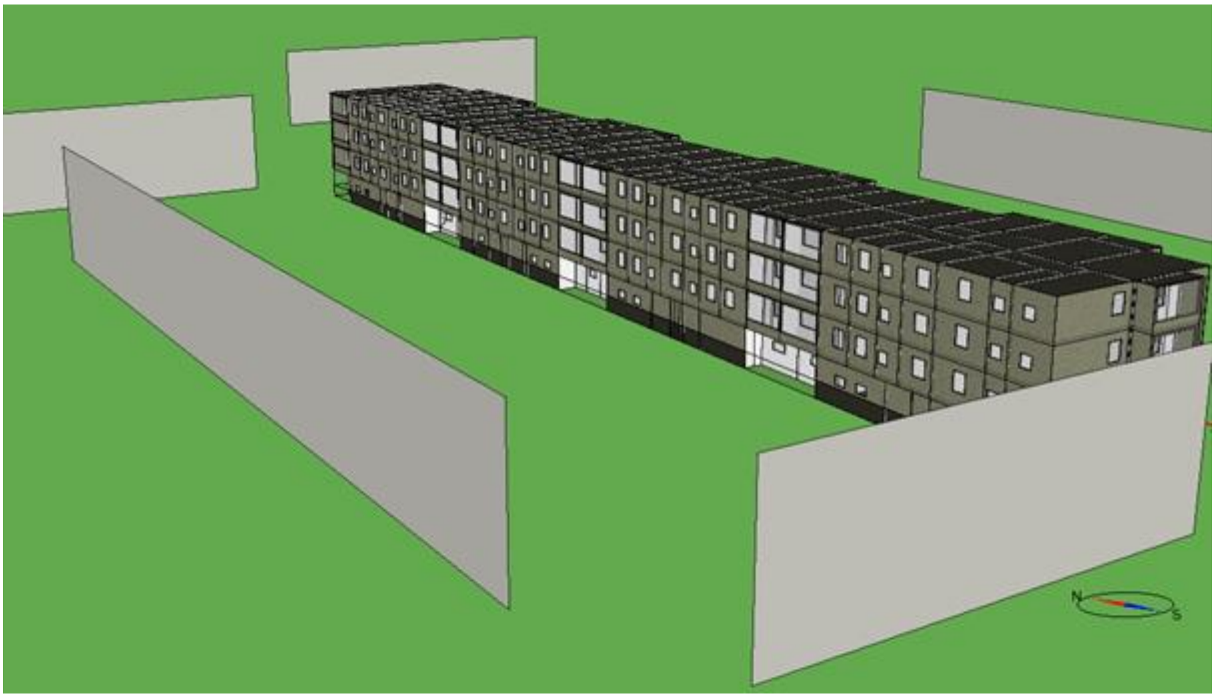


Figure 5.1. The IDA ICE geometrical model of the studied reference building and the surroundings.

Geometrical Properties

All the geometrical properties implemented in the 3D model was gathered from the original architectural drawings of the building. The thermal properties of each building element were assigned according to the values presented in the previous chapter *"Description of case study building".* The model was simplified in order to shorten the simulation time. However, the final IDA ICE model of the building contained 241 studied zones with varying thermal properties, internal gains and occupancy schedules. The three floors above ground level comprises 234 modelled zones in total, 78 zones per floor, corresponding to the four stairwells and the residential zones. The residential zones were divided into individual zones for the kitchens, hallways, living rooms, bathrooms and bedrooms (See Figure 5.2). The attic was modelled as one single unconditioned zone in IDA ICE. The basement comprises 6 different zones where 5 of the zones represents the laundry- and drying rooms and the remaining zone in the basement represents the storage areas and the corridors in the basement (See Figure 5.3). Furthermore, all the structural partitioning walls inside the residential zones were also included in the model in order to account for the internal thermal mass.

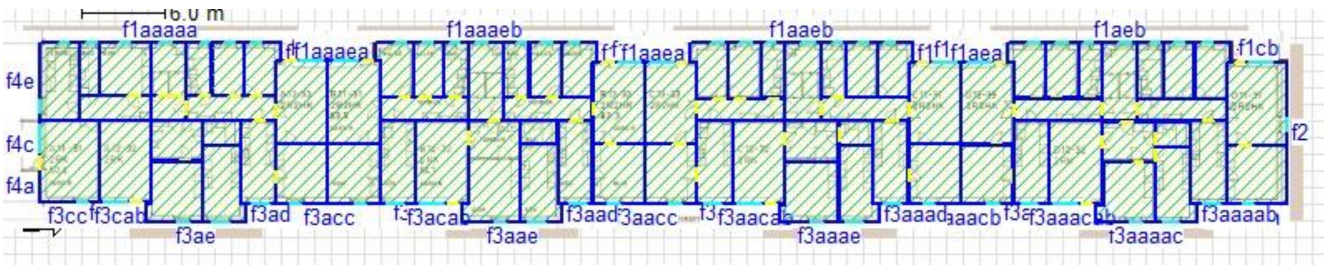


Figure 5.2. Zone distribution in IDA ICE for the heated zones on the first, second and third floor.

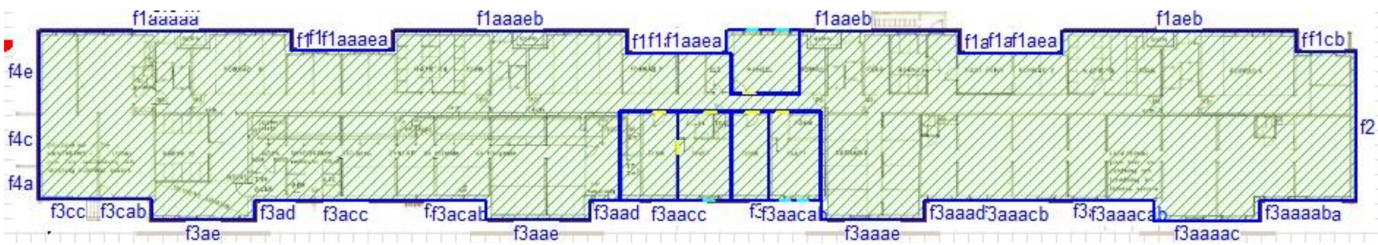


Figure 5.3. Zone distribution in IDA ICE for the unconditioned basement floor.

Environmental Properties

The building orientation was defined in IDA ICE by orientating the geometrical model according to the North indicator presented on the architectural drawings. The weather data for the studied reference building was set up by choosing a local weather file for Malmö in IDA ICE. The software uses hourly weather data to define external conditions during the simulations. The weather file that was chosen in IDA ICE contains hourly data of the external solar radiation, temperature, atmospheric conditions etc. for the city of Malmö. Furthermore, the external dimensions of the surrounding buildings were gathered from several architectural drawings obtained from the municipality of Malmö. The external dimensions of the surrounding buildings were then implemented in the IDA ICE model as flat vertical surfaces (See Figure 5.1).

Internal Thermal Loads

The internal thermal loads is a term used to describe heat generated from people, light sources and equipment in a building. Light sources and most household equipment generates sensible heat, while the metabolic heat generated by people are a combination of both latent and sensible heat. Thus, the internal thermal loads are important to determine before assessing the overall heating need of a building since they generate added heat to the internal areas of the building.

IDA ICE subdivides the internal thermal loads into five main categories; facility- and tenant lighting, facility- and tenant equipment and occupancy schedules. All five categories of the internal thermal loads have been taken into account in the IDA ICE model. Individual schedules regarding the studied internal thermal loads were developed in order to ensure that the building model in IDA ICE is as close to the reality as possible. The schedules were developed by the author of this report and they were based on the recommendations set by SVEBY and IDA ICE as well as the actual reservation schedules of the laundry- and drying rooms in the building. Furthermore, SVEBY recommends an occupancy time of 14 hours per day for each apartment and a yearly energy consumption for the household electricity of 30 kWh/A_{TEMP} (SVEBY, 2012). However, it is difficult to determine the exact energy consumption in Watts per square meter for both the interior lighting and tenant equipment. Thus, an assumption of these values had to be made. The tenant lighting consumption was assumed a value of 250 lux/m^2 with an installed power of 3.4 W/m^2. These values corresponds to the values presented in the IDA ICA guidelines for interior lighting in Swedish households. The facility lighting was also set to 250 lux/m^2 with an installed power of 3.4 W/m^2. However, the facility lighting was set to a much lower intensity compared to the tenant lighting. The reason for the different input of the lighting intensity is because all the facility light sources are time controlled with sensors that automatically switches off the light after 10 minutes. The internal gains from the household equipment was set to an assumed value of 4.0 W/m^2. The assumed value is based on the SVEBY recommendations that the yearly energy consumption is higher for the household equipment compared to the lighting (SVEBY, 2012). Thus, the household equipment will generate more heat compared to the lighting installed in the apartments. Furthermore, the power input and operation hours for the facility equipment was based on the data received from the janitor (Celind, 2017) regarding the installed laundry- and drying machines and the current reservation schedule of the laundry rooms (See Subchapter *4.2 Facility Equipment*). However, the operation schedule for the laundry- and drying machines was assumed an intensity rate of 75% since the machines are not constantly running during all reservation hours throughout the year. Furthermore, the installed air handling unit is also contributing to the overall facility electricity use. The operational energy use for the ventilation system is, however, automatically calculated by IDA ICE based on e.g. the air flow rates and the specific fan power of the ventilation fans. This will be explained further in the subchapter *Ventilation System Measures*.

Moreover, two different patterns were assumed for the occupancy schedules to differentiate between weekdays and weekends. This distinction was made since it is reasonable to expect that most of the tenants are not home during the working days within working hours while being home between the same hours on the weekends. It was also assumed that not all the tenants spend their entire weekend in their apartment. Thus, the tenant appliances operation- and lighting schedules are depended on the occupancy schedules. Different summer and winter schedules was not considered for neither the lighting- nor the equipment schedules since this study do not focus on daylight simulations. However, different seasonal patterns should be taken into consideration for a greater accuracy. The different occupancy and operation schedules implemented in the IDA ICE model are presented in Figure 5.4 to Figure 5.7 and the internal gains values are presented in Table 5.1.

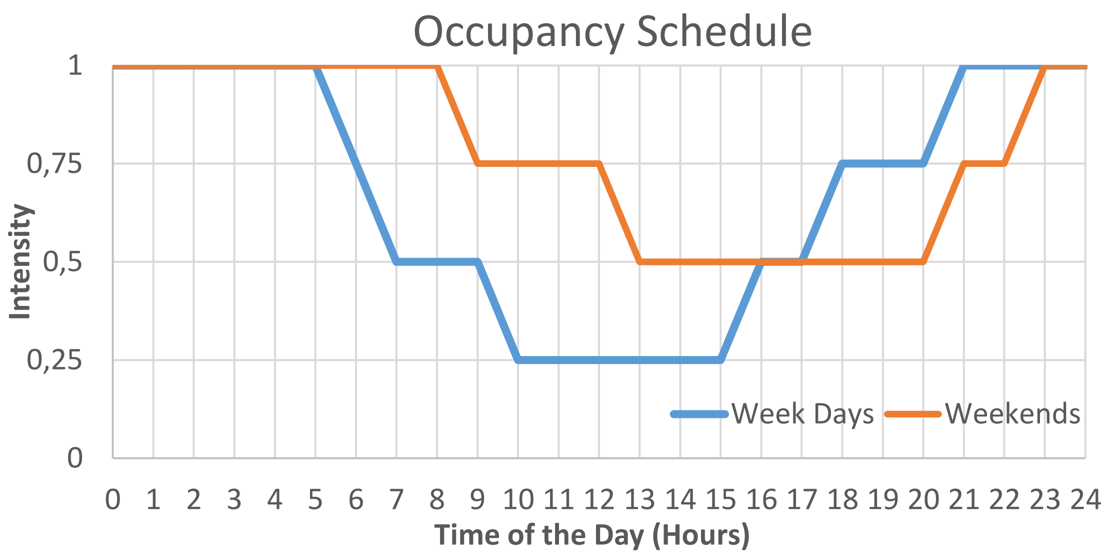


Figure 5.4. Defined occupancy schedule.

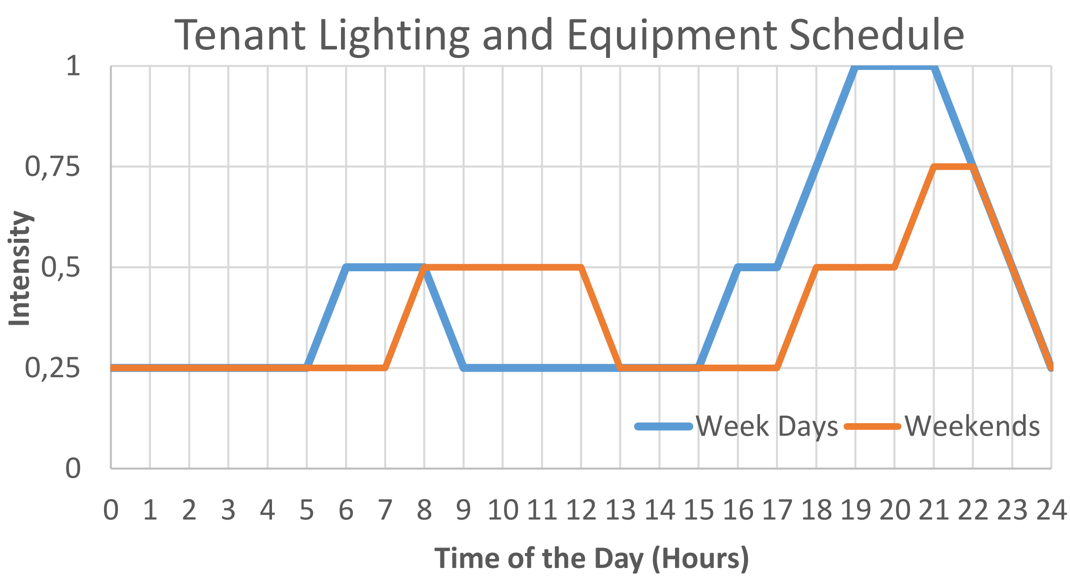


Figure 5.5. Defined tenant lighting and equipment schedule.

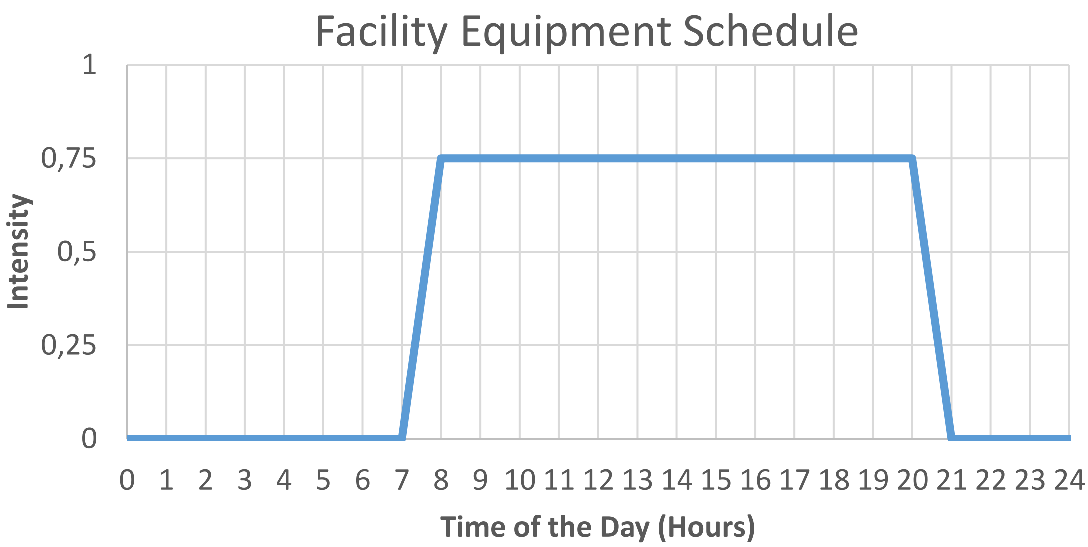


Figure 5.6. Defined facility equipment schedule.

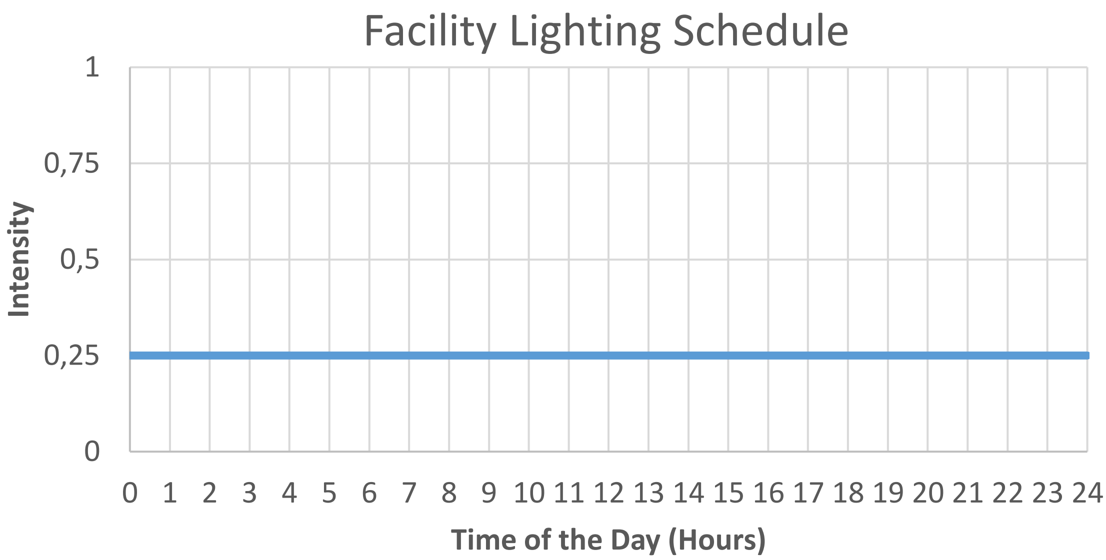


Figure 5.7. Defined facility lighting schedule.

Table 5.1. Internal thermal gains values implemented in the IDA ICE model.

Internal Thermal Load Categories	Source and Input Value
Internal Gains from the Tenants	**Density:** 0.034 tenants/A_{TEMP} (100 tenants in total, based on the janitors' estimation of current amount of tenants living in the building.) **Heat Generated per Person:** 80 W [1] **Metabolic Factor:** 1.0 [1]
Facility Lighting	250 lux/m^2 with an installed power of 3.4 W/m^2 (According to IDA ICE guidelines for interior lighting in Sweden)
Facility Equipment	According to the Power Input values presented in Table 4.2
Tenant Lighting	250 lux/m^2 with an installed power of 3.4 W/m^2 (According to IDA ICE guidelines for interior lighting in Sweden)
Tenant Equipment	Assumed internal thermal gains of 4.0 W/m^2
References: 1. (SVEBY, 2012)	

Venting and Infiltration Rates

The venting and infiltration rates were regarded as missing variables, as described in the previous chapter. The venting and infiltration values were therefore obtained after a model calibration procedure which is explained in the previous chapter *Description of Case Study Building.*

Heating and Domestic Hot Water Systems

The heating set-point temperature was set to 21°C for all heated zones in the building. The heated zones includes all apartments and all stairwells above ground level in the building. The heating set-point temperature was chosen according to the SVEBY recommendations of the minimum indoor air temperature for multi-family apartment buildings in Sweden. The heating set-point temperature is, however, an assumed value since the landlord, *Stena Fastigheter*, have no building automation system installed for the studied reference building. Thus, the actual set-point temperature might differ between the individual apartments in the building. However, all heated zones in the IDA ICE model was given a heating set-point temperature of 21°C with no heating setback in order to simplify the energy simulations. The basement floor and the attic spaces were regarded as unheated zones. Thus, their indoor temperatures were automatically calculated by the energy simulation software.

The default settings in IDA ICE regarding the delivered temperature and the main supply temperature of the domestic hot water was used for the energy simulations. The default temperature values of the domestic hot water in IDA ICE were considered reasonable since they are within the safety margin for potential legionella growth (Boverket, 2000). The DHW consumption rate was set to 60 liters per tenant and day. This value corresponds to the average consumption rate in multi-family apartment buildings in Sweden according to *Energimyndigheten* (Energimyndigheten, 2012). The values of the domestic hot water implemented in the IDA ICE model are presented in Table 5.2.

Table 5.2. Domestic hot water values implemented in the IDA ICE model.

Input Data	Value
Delivered Temperature	55 ℃
Main Supply Temperature	5 ℃
Consumption Rate	60 Liters/tenant and day [1]
References: 1. (Energimyndigheten, 2012)	

5.3 Thermal Bridges Analysis

A thermal bridge can be defined as a specific area of the building envelope which has different heat conduction properties compared to its surrounding and which are not accounted for in the overall U-value calculation of that specific area of the building envelope. In other words, the thermal bridges should be added to the energy calculation in order to take into account all the losses or reduced energy flows that are not included in the U-value calculations. This applies to simulations of the expected energy performance of buildings as well as the dimensioning of heating systems. Significant thermal bridges in buildings will often result in noticeable effects on the indoor environment since the thermal bridges causes low surface temperatures in the building. Thus, the thermal bridges will also affect the operative temperature in the building. (Schöck Isokorb, 2015; Allen E & Iano J, 2008)

Thermal bridges are divided into linear (Ψ, psi) and point (χ, chi) thermal bridges. A linear thermal bridge is defined by a homogeneous heat flow per length unit, e.g. the connection between the joists and the external wall. A point-shaped thermal bridge appear intermittently in a building e.g. at continuous fixings of the building. However, the point-shaped thermal bridges are often neglected in energy calculations since the heat flow is often very small in relation to other losses through the building envelope. Furthermore, in this study the linear transmittance has been used to describe the effects of the thermal bridges and all point-shaped thermal bridges have been neglected. (Schöck Isokorb, 2015; Allen E & Iano J, 2008)

The linear thermal bridges was calculated by applying the calculation method described in the EN ISO 10211-2 standard. The EN ISO 10211-2 standard introduces the coefficient, L_{2D}, known as the thermal coupling coefficient [W/m·K]. The thermal coupling coefficient, L_{2D}, is obtained by the ratio between the total heat flow, $\sum Q$, and the temperature difference between the indoor temperature and the outdoor temperature, ΔT, multiplied by the total length of the studied building element, L. The calculation of the thermal coupling coefficient, L_{2D}, is described in Equation (1). (SIS (b), 2007)

$$L_{2D} = \frac{\sum Q}{L \cdot \Delta T} \tag{1}$$

Furthermore, the linear thermal bridge, Ψ, is calculated by subtracting the 1-dimensional heat flows through the studied building element from the resulting value of the thermal coupling coefficient, L_{2D}. This relation is described by Equation (2) and Figure 5.8. (SIS (b), 2007)

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i \tag{2}$$

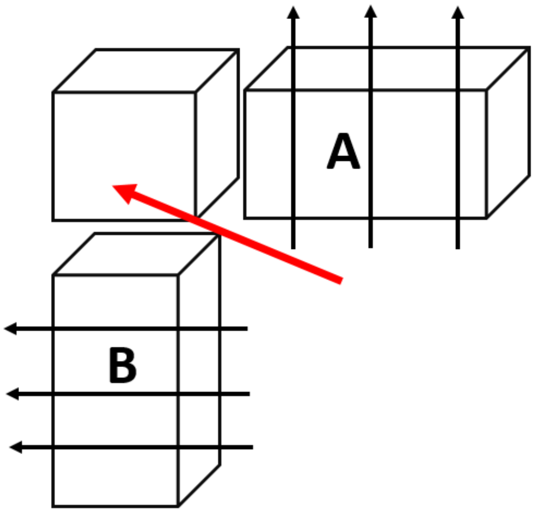


Figure 5.8. Scheme of the linear thermal bridge due to shape variations of the building components.

A junction on the building envelope similar to the one described in Figure 5.8 obtains the following calculation of the linear thermal bridge (according to the EN ISO 10211-2 standard) (SIS (b), 2007):

$$\Psi = L_{2D} - U_A \cdot L_A - U_B \cdot L_B \tag{3}$$

Furthermore, the steady-state heat transfer software HEAT2 (version 9.04) was used to evaluate all the thermal bridges for the studied building elements. All studied building elements where modelled in HEAT2 and the indoor- and outdoor temperatures were defined. The resulting values provided by the software were; U_i [W/m^{2}K], L_i [m] and $\sum Q$ [W]. The indoor temperature and the outdoor temperature was set to 21 °C and 0 °C respectively for all studied building elements in HEAT2. Furthermore, the thermal coupling coefficients, L_{2D}, and the linear thermal bridges, Ψ, were calculated manually based on the resulting values obtained from the HEAT2 simulations. The distribution of the studied thermal bridges on the building envelope are presented in Figure 5.9.

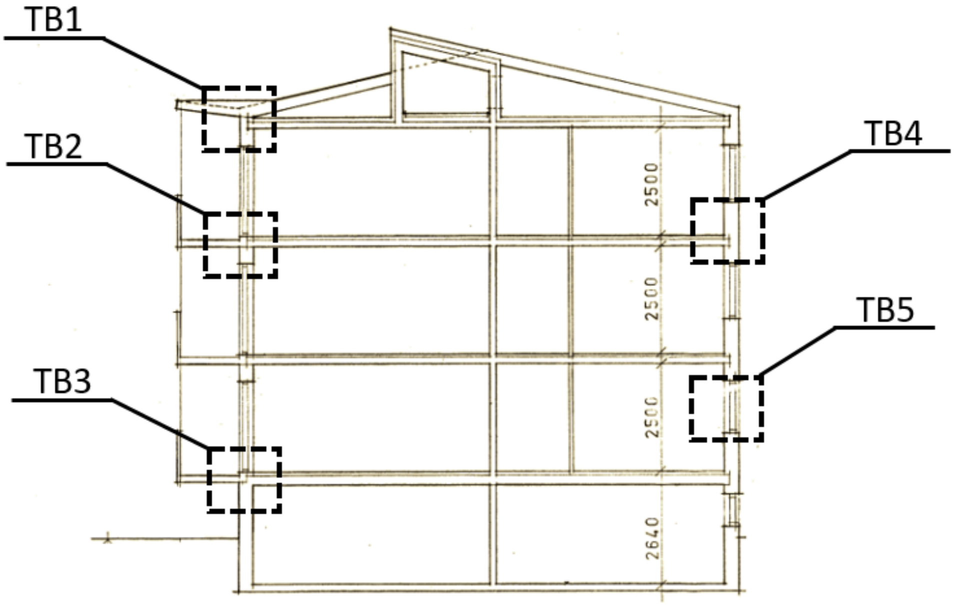


Figure 5.9. The distribution of the junctions on the building envelope where the linear thermal bridges where studied. (Jansson & Persson, 1962)

Furthermore, all resulting values of the calculated thermal bridges, Ψ, where directly implemented in the energy simulation models in IDA ICE, including both the reference case as well as for all studied cases where renovation measures were implemented in the energy model. All the resulting values from the HEAT2 simulations as well as the calculations of the linear thermal bridges for the reference building without improvements are presented in Appendix B. However, the resulting values of the thermal bridges for the reference building are also summarized in Table 5.3. Moreover, the resulting values of the thermal bridges for the cases where renovation measures were implemented on the building envelope are presented in detail in Appendix B.

Table 5.3. The resulting linear thermal bridges for the reference building without any improvements.

Thermal Bridge	Junction	Heat transfer	L_{2D} [W/m·K]	Ψ [W/m·K]
TB1	External Wall and Roof	Heated Zone to Exterior	1.198	0.443
TB2	External Wall and Balcony	Heated Zone to Exterior	1.756	0.820
TB3	External Wall and Basement Ceiling	Heated Zone to Exterior	1.160	0.270
		Heated Zone to Unheated Zone	0.925	0,030
		Unheated Zone to Exterior	0.938	- 0.007
TB4	External Wall and Floor	Heated Zone to Exterior	0.900	0.090
TB5	External Wall and Window	Heated Zone to Exterior	3.74	0.256

5.4 Renovation measures for energy savings

This chapter delineates all the energy saving strategies that were investigated and whose approach were assessed by following the Annex 56 approach described earlier. The investigated renovation strategies do not include changes of neither the heating system and environmental properties nor the internal thermal gains. Instead, the renovation measures have been categorized into three main categories; the building envelope, the ventilation system and the domestic hot water which are explained in detail below. The main objective of the studied renovation measures was to reduce the specific energy use in the building to at least the same level as the requirements for newly constructed buildings in southern Sweden. Thus, the suggested heat transfer coefficient values presented in Boverkets Byggregler for different building components was used as a guideline when the different renovation measures were investigated.

5.4.1 Building envelope measures

The building envelope measures analyzed within this study included exclusively measures were additional insulation was added to the building envelope as well as replacement of the existing windows with high performing low-e windows. The changing quantity of the linear thermal bridges as well as the overall airtightness in the building as a direct result of the implemented renovation measures have also been accounted for. Furthermore, a literature study of different *Environmental Product Declarations* (EPDs) as well as purchasing prices for different insulation materials was also carried out. The literature study was conducted in order to find cost-effective and environmentally friendly insulation materials. Thus, the chosen insulation materials for the renovation measures were based on the information gathered from the EPDs and the purchasing prices.

External Walls Solutions

The studied renovation measures of the external walls included measures of added insulation to the façade of the reference building. The option of insulating the external walls internally was never considered since such a measure will result in a smaller living area inside the building as well as a negative change of the moisture movement within the walls. However, the ability to increase the depth of the walls externally is limited since there is a risk that the glazed-in balconies will disappear into the walls which will reduce the overall daylight performance of the building as well as change the aesthetics of the building for the worse. Moreover, the eaves of the building are relatively short which also limits the ability to insulate the walls externally. Thus, a high performing insulation material with a very low thermal conductivity was necessary to implement in order to reduce the overall thermal transmittance of the external walls without adding to much depth to walls. A literature study of different insulation materials such as vacuum insulated panels, extruded polystyrene foam, thermoset phenolic boards and high performance foil faced panels was therefore conducted in order to find the most appropriate insulation material for the external walls. Furthermore, the chosen insulation material, based on the literature study, was a high performing and fiber-free thermoset phenolic board produced by the British company *Kingspan* called *Kooltherm K5*. The Kooltherm K5 insulation board has a thermal conductivity value of between 0.020 and 0.023 W/m·K depending on the thickness of the board. The board is mainly used for external insulation on existing masonry walls and lightweight polymer modified renders. The installation is carried out manually and the board shall always be anchored with screws and plugs in the existing facade. The Kooltherm K5 is also evaluated by Byggvarubedömningen and SundaHus. Two thickness of the insulation boards were used for the studied renovation measure of the external walls, 80 mm respectively 100 mm.

Furthermore, plaster was used as a façade material after the installation of the Kooltherm K5 insulation. The installation of the plaster façade was carried out by adding a thin protecting wire lath to the external surface of the insulation boards on which several layers of plastering mortar was added (See Figure 5.10). The renovation measures will only add approximately 100 or 120 mm of additional depth to the existing external walls depending on the thickness of the insulation boards, while significantly improve the thermal properties of the walls (See Table 5.4). However, the plaster façade will completely change the aesthetics of the building. (Kingspan, 2016)

Figure 5.10. Illustration of the different layers included in the renovation measure of the external walls. (Kingspan, 2016)

Furthermore, the Kooltherm K5 insulation material is highly moisture resistant and has diffusion resistance to moisture of approximately μ = 35 (Kingspan, 2016). However, it is important that a qualitative moisture safety analysis is performed for the external wall construction before the implementation of the Kooltherm K5 insulation board in order to ensure that the renovation measure will result in a moisture safe construction after the implementation.

Table 5.4. Overall heat transfer coefficients of the modified external walls.

Additional Insulation Thickness [mm]	U-value of the External Walls [W/m^2·K]
None	0.38
80mm (Kooltherm K5)	0.15
100mm (Kooltherm K5)	0.13
Boverket's Recommendation	0.18 [1]
References: 1. (Boverket, 2016)	

Roof and Attic Solutions

The attic floor is often one of the easiest areas to apply additional thermal insulation because of its easy accessibility and ample space for the installation of thermal insulation. The existing 120 millimeters of mineral wool insulation was removed from the attic floor and replaced by stone wool insulation boards called *Hardrock ElementBatts* which are manufactured by the Scandinavian company *ROCKWOOL*. The chosen insulation boards have a thermal conductivity of approximately 0.035 W/m·K and they are both moisture and water repellent as well as non-combustible which are ideal insulation properties for the attic space. The Hardrock ElementBatts insulation boards were chosen since the boards are locally manufactured (Vamdrup, Denmark) and have a rather low environmental impact during the manufacturing process. Furthermore, two different insulation thickness were analyzed, 300mm and 400mm. However, there are not enough space for the thick insulation boards at the edges of the attic floor because of the low sloped roof. Thus, the insulation boards have to be angularly cut off at the edges of the attic floor. (Rockwool, 2013; Rockwool (a), 2017)

Furthermore, the only changes implemented for the roof construction was the replacement of the existing bituminous felt with a new waterproofing bituminous layer. This measure has no impact on the overall thermal properties of the roof. Thus, the overall heat transfer coefficient for the existing roof was used throughout all studied renovation measures.

Table 5.5. Overall heat transfer coefficients of the modified attic floor.

Additional Insulation Thickness [mm]	**U-value of the Attic Floor [W/m^2·K]**
None	0.28
300mm (HardRock ElementBatts)	0.11
400mm (HardRock ElementBatts)	0.08
Boverket's Recommendation	0.13 [1]
References: 1. (Boverket, 2016)	

Basement Solutions

The existing wood wool insulation on the internal side of the basement walls and ceiling was kept. However, a 100 millimeter drainage insulation board from the manufacturer ROCKWOOL was added to the external side of the basement walls in order to improve the thermal properties of the basement walls. The overall heat transfer coefficient of the drainage insulation board is approximately 0.16 W/m^2·K for a 100mm thick insulation board. Furthermore, the externally added insulation was also implemented in order to increase the temperature on the interior side of the basement walls which minimizes the risk of condensation and mold growth since the walls becomes drier. This measure is, however, a quite time consuming and expensive measure. Thus, it should preferably be carried out in conjunction with the replacement of the drainage system of the building. (Rockwool (b), 2017)

Table 5.6. Overall heat transfer coefficients of the modified basement walls.

Additional Insulation Thickness [mm]	U-value of the Basement Wall [W/m²·K]
None	0.32
100mm (Rockwool Drainage Insulation)	0.18
Boverket's Recommendation	-

Window Solutions

The existing windows installed in the reference building are in a rather poor condition, as mentioned in the chapter *Description of case study building*. Both the thermal properties as well as the overall aesthetics of the windows are far from preferable. Thus, it is crucial to replace all the existing windows with new low energy windows in order to improve the overall energy performance of the building. A renovation measure was therefore conducted were all existing windows were replaced by new low energy windows from the Swedish manufacturer *Elitfönster.* The new implemented windows had a low emissivity coating and the gaps between the panes are filled with Argon gas. The U-value and g-value of the new installed windows were 1.0 W/m²·K and 0.48, respectively. The window frames were made of wood and cladded externally with aluminum. The new windows were installed on the same position as the existing windows which is on the exterior brick layer. The installation procedure should be carried out carefully in order to ensure an airtight construction. (Elitfönster, 2017)

Furthermore, the window replacements were supposed to be carried out simultaneously with the renovation measures regarding the external walls in order to only account for the scaffolding costs once in the renovation project. Besides, it was considered that if these measures were carried out simultaneously the building airtightness will be further improved to 0.6 ACH at 50 Pa, approximately 0.3 L/(s·m²), due to the better sealing and fastening. It should, however, be mentioned that window replacement is generally not a cost-efficient renovation measure due to the high investment costs related to the measure (IEA Annex 56, 2014). Nevertheless, it was considered necessary to replace all the existing windows on the studied reference building in order to improve the overall energy performance and aesthetics of the building. Thus, the window replacement measure was implemented in the majority of all studied combined renovation measures.

Combined Solutions

The combined renovation solutions considered within this study refers to the packages of building envelope measures carried out simultaneously in order to improve the energy performance of the building as much as possible. Thus, the combined solutions are a combination of benefits resulting from different single renovation measures. There two different methods that could be used in order to assess the combined effect of more than one renovation measure, either adding all the single measures together or perform a different simulation where all the studied measures are included. The first method is faster but it will however result in a risk of overestimating the overall energy savings. Thus, the second method was used for the combined solutions in order to obtain more reliable results. However, simulations of all single renovation measures were performed individually for each measure in order to find out which single measure that has the greatest impact on the overall energy use in the reference building. Furthermore, the cost of the combined solutions are not merely the linear summary of the costs for the individual measures. Usually the cost is less for the combined solutions due to the volume of work is compressed. Nevertheless, this effect was not considered in this study except for the scaffolding cost. The single renovation measures as well as the combined solutions are presented in Table 5.7 and Table 5.8 below. The combined renovation solutions are essentially a combination of the single renovation measures mentioned in the previous sub-chapters.

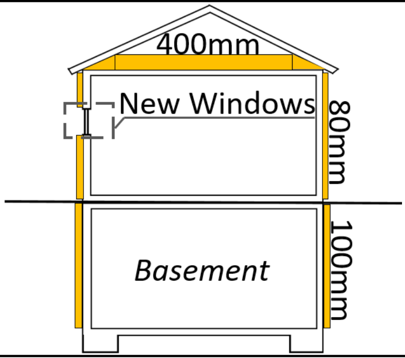
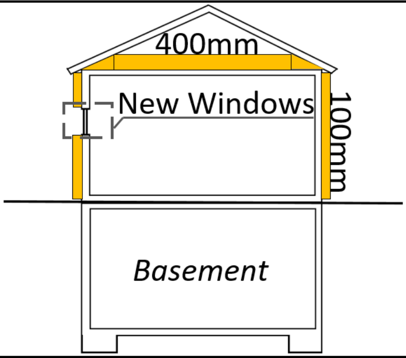
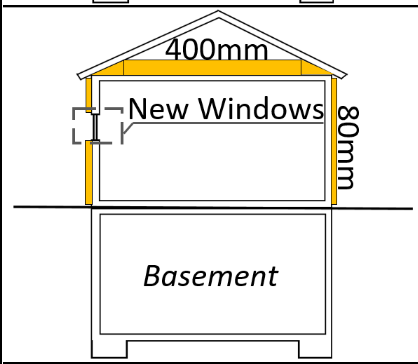
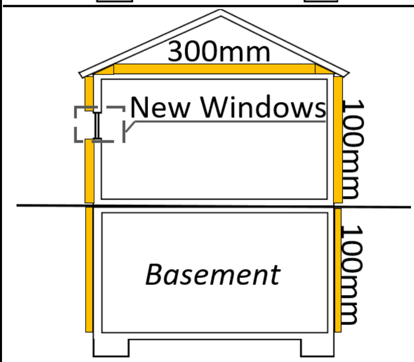
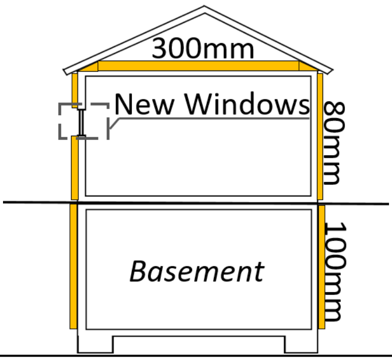
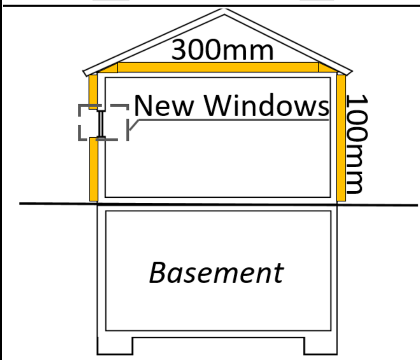
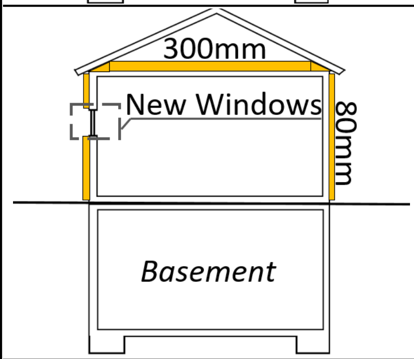
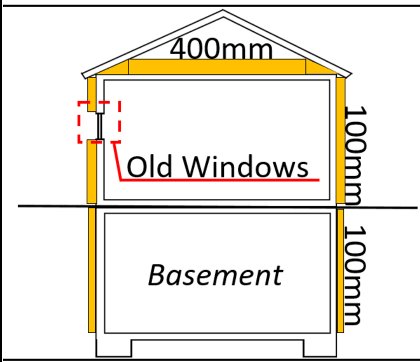
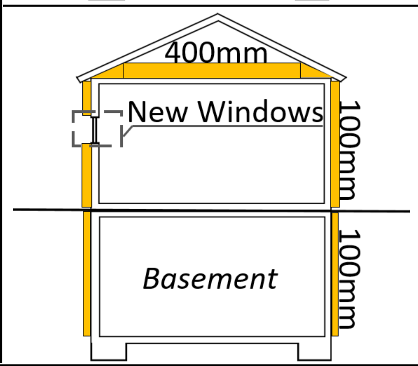
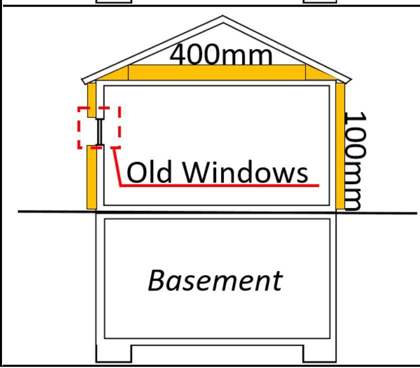
Table 5.7. List of considered single renovation measures on the building envelope.

Code of measure	External Walls	Roof / Attic	Windows	Basement Walls
REF	No Additionally Added Insulation	No Additionally Added Insulation	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM1	80mm of Kooltherm K5 insulation (Exterior Side)	No Additionally Added Insulation	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM2	100mm of Kooltherm K5 insulation (Exterior Side)	No Additionally Added Insulation	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM3	No Additionally Added Insulation	300mm of added Rockwool Insulation to the attic floor	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM4	No Additionally Added Insulation	400mm of added Rockwool Insulation to the attic floor	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM5	No Additionally Added Insulation	No Additionally Added Insulation	New 3-pane argon filled low-e windows (U-value: 1.0 $W/m^2 \cdot K$)	No Additionally Added Insulation
SM6	No Additionally Added Insulation	No Additionally Added Insulation	Old 2-pane windows (U-value: 2.8 $W/m^2 \cdot K$)	100mm of added insulation on the basement ceiling and wall

Table 5.8. List of considered combined renovation measures on the building envelope.

Code of measure	External Walls	Roof / Attic	Windows	Basement Walls
REF	No Additionally Added Insulation	No Additionally Added Insulation	Old 2-pane windows (U-value: 2.8 W/m^2·K)	No Additionally Added Insulation
HM1	80mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	100mm of added insulation on the basement ceiling and wall
HM2	80mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	No Additionally Added Insulation
HM3	80mm of externally added Kooltherm insulation	300mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	100mm of added insulation on the basement ceiling and wall
HM4	80mm of externally added Kooltherm insulation	300mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	No Additionally Added Insulation
HM5	100mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	100mm of added insulation on the basement ceiling and wall
HM6	100mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	No Additionally Added Insulation
HM7	100mm of externally added Kooltherm insulation	300mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	100mm of added insulation on the basement ceiling and wall
HM8	100mm of externally added Kooltherm insulation	300mm of added Rockwool Insulation to the attic floor	New 3-pane argon filled low-e windows (U-value: 1.0 W/m^2·K)	No Additionally Added Insulation
HM9	100mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	Old 2-pane windows (U-value: 2.8 W/m^2·K)	100mm of added insulation on the basement ceiling and wall
HM10	100mm of externally added Kooltherm insulation	400mm of added Rockwool Insulation to the attic floor	Old 2-pane windows (U-value: 2.8 W/m^2·K)	No Additionally Added Insulation

Table 5.9. Illustrations of the studied combined renovation measures on the building envelope.

Code Of Measure	Illustration of the Combined Renovation Measures	Code Of Measure	Illustration of the Combined Renovation Measures
HM1		**HM6**	
HM2		**HM7**	
HM3		**HM8**	
HM4		**HM9**	
HM5		**HM10**	

5.5 Ventilation System Measures

In order to improve the ventilation system in the building a balanced mechanical ventilation system with heat recovery was considered as a possible renovation measure. The existing ventilation system in the building is a mechanical exhaust air system with a constant air volume rate. This means that the installed ventilation fans in the building only provides constant exhaust air flow rates in the building and therefore lacks the necessary components needed for a balanced mechanical ventilation system. Thus, in order to implement a balanced mechanical ventilation system in the building a new air handling unit with all the required components had to be installed. The required components for a balanced mechanical ventilation system with heat recovery include e.g. heating- and cooling coils, a heat exchanger, supply air fans, humidifier etc. However, only the sizing of the AHU was determined. The size of the air handling unit was considered essential to determine in order to properly estimate the investment cost of the new ventilation system. However, the specific fan power of the ventilation fans for both the existing ventilation system and the proposed ventilation system were assumed according to the ASHRAE 90.1 standard (See Table 5.10). The ASHRAE 90.1 standard is used as a reference standard in IDA ICE for the default settings of various types of ventilation systems.

Furthermore, the balanced mechanical ventilation system was equipped with a rotary air-to-air heat exchanger, which extracts heat from the exhaust air, which would otherwise be rejected as waste, to pre-heat the incoming air which results in saved energy. A fan efficiency of 70% for both the supply and the exhaust air fans was adopted, which corresponds to the default settings in IDA ICE. The supply air dry-bulb temperature was set to a constant value of 18°C which is the default settings in IDA ICE for a temperature controlled VAV-system. Moreover, despite the fact that a rotary heat exchanger can have an efficiency of up to 85% (SEAI, 2009), an efficiency of 70% was assumed in order to account for the losses in terms of electricity that may be needed for defrosting the system during severe winters.

The sizing of the AHU was carried out by calculating the dimensioning air flow rate required for the ventilation fans. According to the Swedish building regulations, the minimum supply air flow rate in a residential building shall at least correspond to 0.35 liters/second per m^2 (Boverket, 2016). Furthermore, the ventilated zones includes all heated zones in the building. The unheated zones is however ventilated by the means of window opening and air infiltration. The supply air flow rate was set to 95% of the exhaust air flow rate in order to continuously maintain a negative pressure in the building. Hence, the selection of the air handling unit was based on the exhaust air flow rate. The chosen air velocity rate for the air handling unit was set to 2.5 meters/second, which is a commonly used air velocity rate used in residential buildings. The air handling unit was selected from a product catalog of air handling units provided by the Swedish company *FläktWoods* based on the dimensioning air flow rate and the chosen air velocity (See Appendix C). The purchasing costs of the air handling unit was provided by *André Bond,* sales person at *FläktWoods* based on the calculated dimensioning air flow rates and the chosen AHU of the ventilation system (Bond, 2017). The complete calculation of the dimensioning air flow rates of the ventilation fans as well as the selection of the air handling unit is described further in Appendix C.

The proposed ventilation system is a temperature controlled system with variable air volume. This means that the air flow rates are adjusted depending on the current temperature and set-point temperature in the ventilated zones in the building. Furthermore, along with the installation of the balanced mechanical ventilation system follows the installation of new supply air ducts. Thus, there have to be enough available space in the building for the installation of the duct system. However, only the vertical connection of the new supply air ducts were considered in this assessment. The vertical supply air ducts were assumed to be installed in the four existing ventilation shafts on the roof, were the existing exhaust air fans are located, and connected to the new air handling unit which is assumed to be placed centrally between the ventilation shafts on the roof (See Figure A3 in Appendix A). Moreover, no reduction of the living area have been taken into account in the assessment due to the installation of the horizontal ducts.

All ventilation measures were applied along with the combined renovation measures of the building envelope, since the balanced mechanical system requires a high airtightness and good thermal properties of the building envelope in order to work efficiently. The annual energy required for the operation of the ventilation fans and the heating and cooling coils was added to the overall annual energy use of the facility equipment in the building.

Furthermore, no calculations of the pressure drops in the different components and ducts have been conducted neither for the existing ventilation system nor the proposed balanced mechanical ventilation system. Thus, the default values in IDA ICE were used for the determination of the pressure drops for all the components and ducts in both systems. Moreover, all the prices related to the installation process of the proposed ventilation system was assessed by using Wikells calculation software. Table 5.10 below presents all the input values in IDA ICE for both the existing and the proposed ventilation system.

Table 5.10. Input data used for the assessment of both the existing and proposed ventilation system.

Input Category	Input Data
Existing CAV System	
- Exhaust air flow rate	0.35 L/s·m^2
- Specific Fan Power	0.5 kW/(m^3/s) (Default input value in IDA ICE)
- Fan Efficiency	70 % (Default input value in IDA ICE)
Balanced Mechanical VAV System	
- Product Name of the AHU	FläktWoods EQ Master (See Appendix C)
- AHU size (Height x Width)	776mm x 1400mm (Size 18 of FläktWoods EQ Master. See Appendix C)
- Purchasing Price of the AHU	122 400 SEK [1] (Including VAT)
- Supply Air Temperature	18 °C (Default input value in IDA ICE)
- Efficiency of the Heat Exchanger	70 % (Assumed value)
- Supply air flow rates	0.35 – 0.45 L/s·m^2 (See Appendix C)
- Exhaust air flow rates	0.35 – 0.48 L/s·m^2 (See Appendix C)
- Specific Fan Power	1.6 kW/(m^3/s) (Default input value in IDA ICE)
- Fan Efficiency	70 % (Default input value in IDA ICE)
References: 1. (Bond, 2017)	

5.6 Domestic hot water measures

In order to reduce the domestic hot water use in the studied reference building an individual metering and price charging system of the domestic hot water, abbreviated as IMD, was considered as a possible renovation measure. An individual metering and price charging system of the domestic hot water is a system that measures the tenants' monthly tap water consumption whereupon the tenants then individually gets charged a fee for their monthly consumption at the end of each month. Currently the costs for space heating and domestic hot and cold water are included in the monthly housing rent in the studied reference building. However, by introducing IMD to the building will lead to that the housing rent will be divided into one fixed part and one variable part (SABO, 2015). Usually, the fixed part of the housing rent will then be lowered with the corresponding average monthly cost of the domestic hot water (See Figure 5.11). Nevertheless, a study conducted by *Energimyndigheten* shows that the savings potential when implementing individual metering and price charging of the domestic hot water is usually between 25 and 35 % of the total domestic hot water consumption (Energimyndigheten, 2003). Additionally, implementing an IMD system for the domestic hot water will create a positive co-benefit for the tenants in the building since the system allows the tenants to have a greater opportunity to influence their housing costs (SABO, 2015). However, the investment costs related to the installation of the IMD are often relatively high. The installation costs usually varies between 4000 – 10000 SEK per apartment, including VAT, depending on the specific location and design of the installed tap water pipes in the building and on the chosen measurement system (Energimyndigheten, 2003). An advanced water meter with a display and wireless internet connection that measures the domestic hot water consumption instantaneously and transfers the data to an Internet domain is the more expensive option. While a water meter without a display and without instantaneous measurement of the domestic hot water consumption is the cheaper alternative. Thus, the economic viability of the investment of the IMD is dependent on the chosen measurement system, the price growth rate of the local district heating and the price level of the fixed part of the monthly housing rent after the installation of the IMD. (Energimyndigheten, 2003).

Figure 5.11. Monthly housing rent before and after the implementation of the IMD system.

Moreover, an advanced water meter with a display and wireless internet connection was chosen for the studied renovation measure of implementing IMD to the domestic hot water in the reference building. The chosen water meter allows the tenants to get an overview of their consumption rate in real time while the landlord will also receive the consumption rate for each tenant in the building to a specific internet domain. The expected reduction of the domestic hot water consumption in the reference building was assumed a value of 35% after the installation of the IMD. This value corresponds to the reduction values presented in the report *Individuell Värmemätning I Svenska Flerbostadshus* conducted by *Energimyndigheten* for similar types of buildings in Sweden where IMD have been implemented (Energimyndigheten, 2003). However, the expected reduction of the DHW consumption is only an estimation. Thus, the actual reduction can only be properly determined by measurements of the DHW after the IMD has been installed in the building (Energimyndigheten, 2003). Furthermore, the location and design of the installed tap water pipes in the studied reference building is unknown. The unknown location and design of the tap water pipes made it difficult to determine how many mechanical water meters that were necessary to install in each apartment. Thus, the installation costs of the IMD were estimated. The total investment cost, including the installation cost, of the IMD were assumed a value of 8500 SEK per apartment, including VAT. Furthermore, the suggested IMD system of the domestic hot water was applied along with the combined renovation measures of the building envelope and the ventilation system in order to evaluate the combined effect on the total specific energy use in the reference building. Table 5.11 below presents all the input values used for the implementation of the IMD in the studied reference building.

Table 5.11. Input data used for the assessment of the IMD system of the domestic hot water.

Input Category	**Input Data**
Chosen Type of Water Meter	Advanced Water Meter With a Display and Internet Connection
Lifespan of the Water Meter	20 years (Assumed value)
Estimated Reduction of the DHW Consumption	35 % [1]
Total Investment Cost Including Installation	8500 SEK/Apartment (Including VAT) [1]
References: 1. (Energimyndigheten, 2003)	

5.7 Life Cycle Cost Assessment

The cost assessment of this project was performed by including real costs (the inflation was accounted for) by using real interest rates. In order to find a representative real interest rate for the life cycle cost assessments, data of the average mortgage rates from the Swedish bank *SEB* was gathered between the years of 2002 to 2016 (SEB, 2017). The mortgage rate is, however, a nominal interest rate, which means that it does not account for the inflation. Thus, it can not be used to provide accurate measures of the financial returns. Data was therefore gathered from the *Swedish Central Bureau of Statistics* of the Swedish inflation rates between the same time period in order to convert the mortgage rates into real interest rates (Statistiska Centralbyrån (a), 2017). This conversion was performed by subtracting the varying inflation rates from the varying mortgage rates during the studied time period. This procedure resulted in an average real interest rate of approximately 3.19% between the years of 2002 and 2016. This real interest rate value was implemented in all life cycle cost assessments conducted in this project. It should however be mentioned that the investors of major renovation projects receives, in general, more favorable interest rates from the Swedish banks compared to the standard mortgage rates. These interest rates are however never published by the banks. Thus, the trend of SEB's mortgage rates and the inflation rates for the past 15 years were used to determine a representative value of the real interest rate used in this project. The comparison between the mortgage rates from SEB and the corresponding real interest rates between the years of 2002 and 2016 are presented in Figure 5.12.

Moreover, Annex 56 suggests a studied reference period of 60 years for the life cycle cost assessments (IEA Annex 56, 2014). However, two different studied time periods of 30 and 60 years have been conducted for all life cycle cost assessments in this project. The two different studied time periods were considered in order to highlight how the length of the time period will influence the results of the life cycle cost assessments. Furthermore, the life cycle cost assessments conducted in this study focuses only on the private perspective since this perspective is considered more interesting for practical purposes. The private perspective refers to the perspective of the investors and property owners.

The cost assessment conducted in this study is based on a life-cycle approach, as indicated in Annex 56 (IEA Annex 56, 2014). It comprises all costs that are considered relevant such as e.g. initial investment costs for the renovation measures (which includes overhead costs, planning costs, professional fees, labor expenses, taxes and other project contingencies), energy costs and other operational costs (which includes maintenance and operational costs throughout the life span of the building elements) and disposal costs for replaced building elements. However, all costs that occur during the studied time period for all renovation measures such as maintenance costs for the radiators, lighting system, domestic hot water pipes, drainage system and common appliances in the building were not taken into account in the life cycle cost assessments conducted in this project. Regarding the “anyway” renovation scenario, only the scaffolding costs related to the building envelope modifications were taken into consideration.

All the investment costs related to the renovation measures are based on the work tariff in Sweden as well as purchasing prices from the manufacturers’ and resellers websites. The maintenance cost for each building element were obtained by dividing the investment cost of the building element by the corresponding lifetime as done in the LCC analysis for the case study “Backa Röd” which is a part of the IEA EBC Annex 56 project (Blomsterberg & Nilsson, 2014). All the investment cost related to the studied renovation measures are presented in detail in Appendix D.

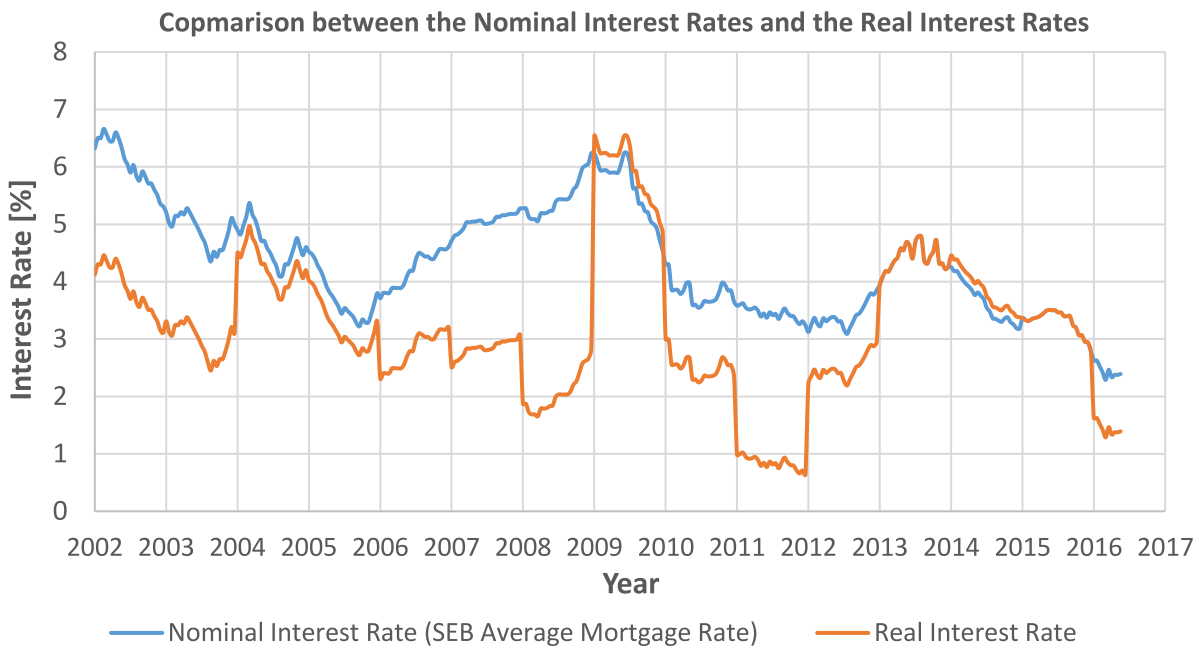


Figure 5.12. Comparison between SEB's average mortgage rates and the real interest rates between the years of 2002 and 2016.

LCC Method

As previously mentioned, the cost calculations of the renovation measures were performed dynamically. This means that all future costs and benefits have to be discounted. In order to perform such a cost calculation the annuity method was employed. (IEA Annex 56, 2014)

The annuity method converts investment costs into average annualized, yielding constant annual costs during the lifespan of the investment considered. The operational costs, annual energy costs and maintenance costs are then added to the yearly annuity costs of the initial investment. This results in a constant annual global cost during the studied evaluation period. The formula used in order to convert the investment cost of the renovation measures into annual annuity costs is described in Equation (4) below. (IEA Annex 56, 2014)

$$a = \frac{i \cdot (1+i)^t}{(1+i)^t - 1} \tag{4}$$

Where:

a – is the annuity for constant real costs;
t – is the time period of the cost evaluation;
i – is the real interest rate.

If the energy prices or the costs related to the renovation measure are increasing, it is necessary to calculate an average energy price or cost value, which dynamically takes into account the price growth rates for the studied evaluation period. This can be accomplished by calculating an average adjustment factor, *m*, which has to be multiplied with the energy prices or the annual costs related to the renovation measures at the beginning of the studied evaluation period. The formula used to calculate the medium adjustment factor is described in Equation (5) below. (IEA Annex 56, 2014)

$$m = \frac{(1+\frac{i-r}{1+r})^{t}-1}{\left(\frac{i-r}{1+r}\right)\cdot(1+\frac{i-r}{1+r})^{t}} \cdot a \quad (5)$$

Where:

m – is the average adjustment factor;
r – is the annual price growth rate of the energy prices;
t – is the time period of the cost evaluation;
a – is the annuity for constant real costs;
i – is the real interest rate.

If the annuity method is used to determine the life cycle costs, it is not necessary to determine the residual values at the end of the calculation period for whose lifetime is longer than the assumed cost evaluation period. Thus, the annuity method assumes that the building elements are replaced at the end of their element-specific service life. (IEA Annex 56, 2014)

5.7.1 Energy prices and price growth rates

When determining the life cycle costs of a renovation measure it is necessary to take into account the impact of the fixed costs, the varying costs throughout the evaluation period and the annual price growth rates of the energy prices. However, it is difficult to determine a fixed annual price growth rate of the energy prices since it varies from year to year. Thus, in order to make a reasonable estimation of the future annual price growth rates one has to look back in time and study the trend of the energy prices from previous years. This method was used in this project in order to make an estimation of the future annual price growth rates of the energy prices.

Moreover, it was also assumed that the studied renovation measures were supposed to be carried out during the current year. Thus, the most recent average energy prices have been used in all life cycle cost assessments conducted in this project.

District Heating

An assumed district heating price of 0.85 SEK/kWh was used for all the life cycle cost assessments conducted in this project. This value refers to the 2016 average price of district heating, including VAT, supplied by the company E.ON to multi-dwelling buildings in Malmö. (Energiföretagen, 2016)

The annual price growth rate was assessed by studying the trend of the price growth rates from previous years and then finding a pattern in the development. The district heating prices from previous years were gathered from the *Swedish Central Bureau of Statistics* which provides statistics of monthly average prices for each year between 2006 and 2016 (Statistiska Centralbyrån (b), 2016). However, the district heating prices decreases significantly during the summer season since the demand is lower (See Figure 5.13). Nevertheless, the prices considered in the assessment refer to the months of October to March since the considered renovation measures have only a direct impact on the space heating consumption, which is mainly acquired during the cold season. Finally, the annual price growth rate of the district heating could be determined by linearly interpolating the energy prices from October to March between the years of 2006 to 2016. This resulted in an annual price growth rate of 2.0 %. Figure 5.14 below illustrates the trend of the energy prices during the cold season.

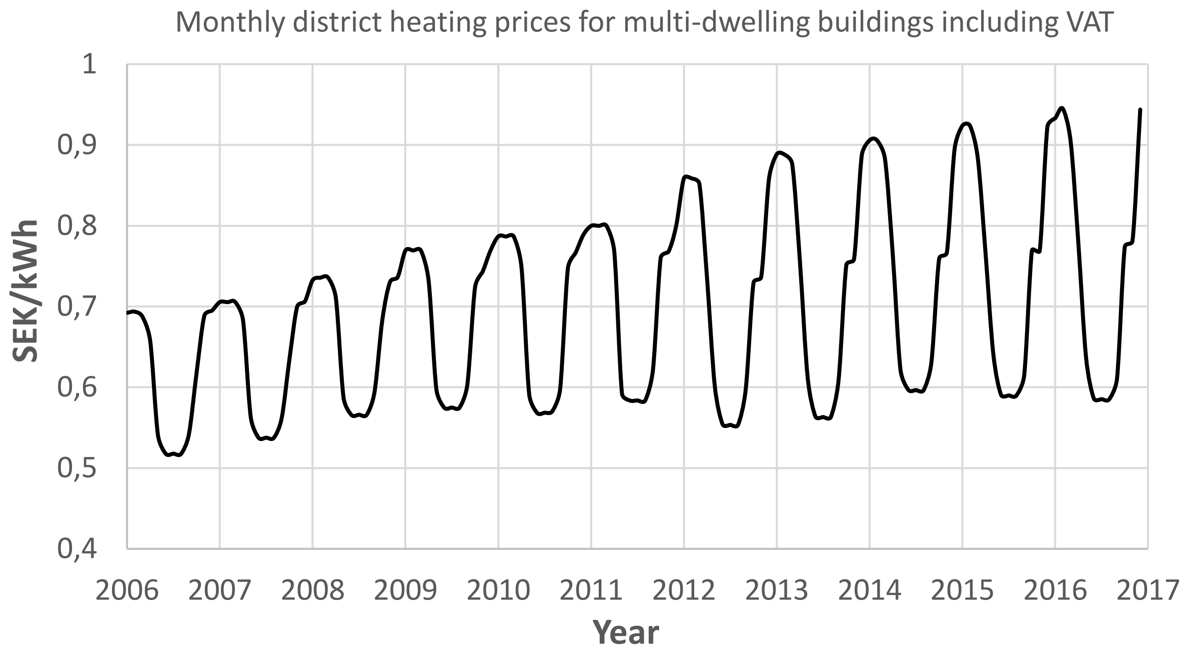


Figure 5.13. Price fluctuation of the district heating prices in Sweden between 2006 and 2016.

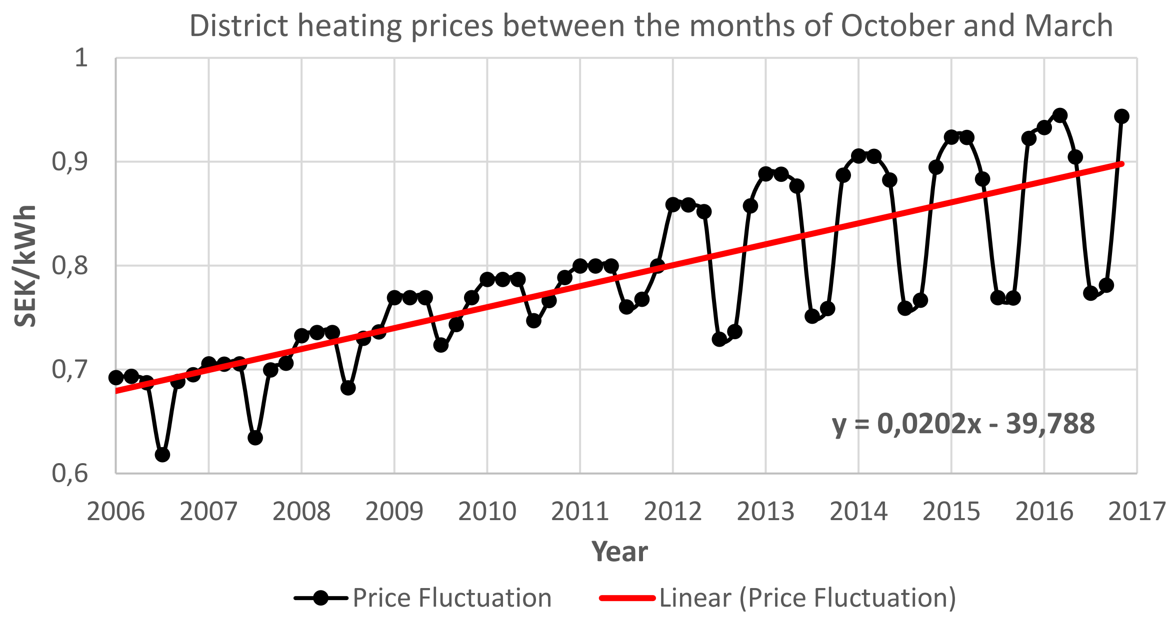


Figure 5.14. Linear interpolation of the district heating prices between the months of October and March.

Electricity

The price for household electricity in Sweden consists of one fixed part and one variable part. The fixed part consists of fixed fees paid to the grid and the electricity supplier while the variable ones depends on five different things; the spot prices, energy taxes, transfer fees, certificate fees and value-added taxes. An assumed electricity price of 0.88 SEK/kWh, including both variable fees and fixed fees, was used for all life cycle cost assessments conducted within this project. This value refers to the 2016 average Swedish electricity prices, including 25% VAT, for industrial customers whom consumes between 20 and 500 mega-watthours annually (Statistiska Centralbyrån (b), 2016).

The annual price growth rate of the electricity was assessed by using the same method as for the estimation of the price growth rate of the district heating, see the previous sub-chapter. The industrial electricity prices from previous years were gathered from the *Swedish Central Bureau of Statistics* which provides statistics of average total electricity prices for each year between 1997 and 2016 (Statistiska Centralbyrån (b), 2016; Statistiska Centralbyrån (c), 2007). The gathered electricity prices from The Central Bureau of Statistics represent average prices for industrial customers with an annual consumption rate of between 20 and 500 mega-watthours. Furthermore, the annual price growth rate of the electricity prices, including both fixed fees and variable fees, could be determined by linearly interpolating the prices between the years of 1997 and 2016. This resulted in an annual price growth rate of 1.7 %. Figure 5.15 below illustrates the trend of the electricity prices for industrial customers in Sweden for the past 19 years.

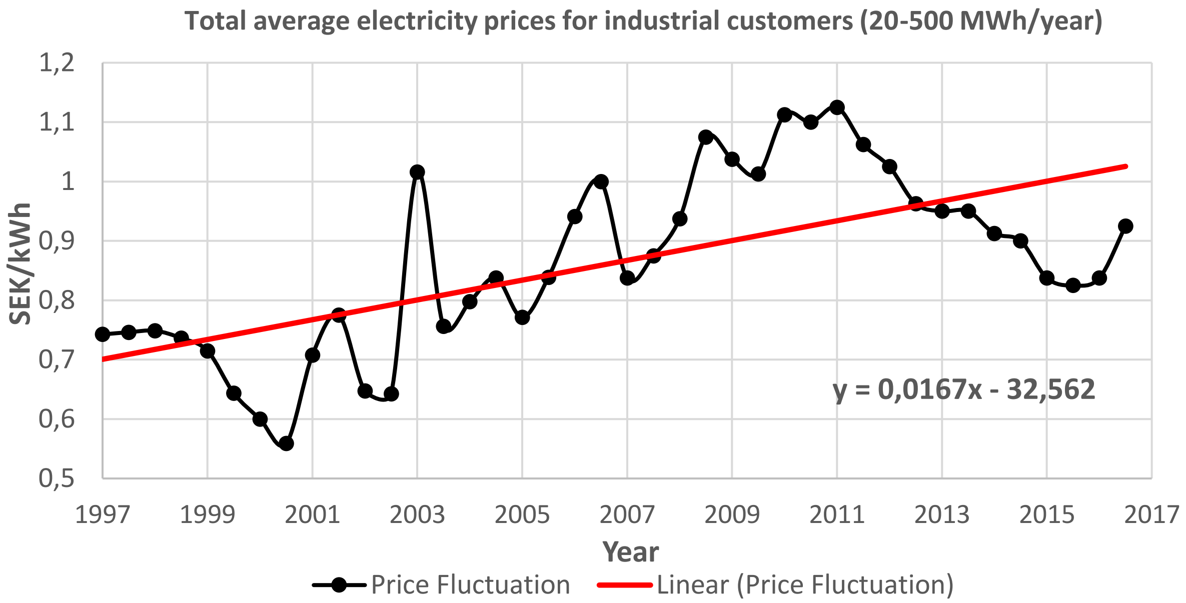


Figure 5.15. Linear interpolation of the electricity prices between the years of 1997 and 2016.

5.7.2 Legal aids that might affect the cost-effectiveness of the renovation measures

There is an opportunity for the private investors in Sweden to increase the cost-effectiveness of a renovation project by applying for a number of legal aids. However, in this project only two different legal possibilities have been briefly analyzed. These possibilities include financial support through governmental subventions and an increased monthly housing rent after the renovation project has been conducted. These legal aids are, however, highly uncertain for the private investors to rely upon since there is always a possibility that the application for the governmental subventions is denied and that the tenant association (Swedish: Hyresgästföreningen) appeal against the proposed increase of the monthly housing rent. For this reason, the legal aids were not directly included in the life cycle cost analysis conducted in this project. Instead, these legal possibilities potential effect on the overall cost-effectiveness of the studied renovation measures have been discussed separately in the *Discussion and Conclusions* chapter of this report.

5.8 Life Cycle Impact Assessment

The life cycle impact assessment was performed in order to compare the environmental impacts of energy-related renovation measures as specified in Annex 56. The life cycle impact assessment required that both the primary energy use and the carbon emissions related to renovation measures were assessed. The analysis was conducted in the software Eco-bat 4.0. The software includes both the evaluation of consumed and embodied energy (manufacturing, transportation, replacement and waste treatment) for all materials used for the studied renovation measures. The transportation distance of the materials was only calculated individually for the insulation materials while the remaining materials were set to the default transportation distance in Eco-bat 4.0. The environmental impacts of the renovation measures were calculated on the basis of the following parameters: *Total Primary Energy (TPE)* in kWh/(A_{TEMP}· year) and *Global Warming Potential (GWP)* in $kgCO_2eq$ /A_{TEMP}· year). Furthermore, the district heating consumption in the reference building is also a contributor to the overall environmental impact of the building. The local district heating provided by the company *E.ON* consists of different production units, which together entails the following impact parameters: Primary energy factor for district heating = 0.44, percentage of fossil fuels = 38.18 %, percentage of renewable fuel = 1.95%, percentage of recycled fuel = 59.26% and GWP= 0.140 $kgCO_2eq$/kWh (E.ON, 2016). The primary energy factor used for the facility electricity was set to 2.6, which corresponds to the recommended value in Annex 56 for Swedish low voltage electricity (IEA Annex 56, 2014). These parameters were implemented into Eco-bat in order to make the life cycle impact assessments as realistic as possible. However, the district heating distribution losses were not considered in the assessments since these losses are rather difficult to determine. A detailed presentation of the implemented input data in Eco-bat 4.0 and the detailed results of the life cycle impact assessment is presented in Appendix E. Moreover, the total primary energy use (TPE) is calculated in the Eco-bat software according to Equation (6), (7) and (8) below.

$$PE\ (District\ Heating) = Primary\ Energy\ Factor\ \cdot E_{District\ Heating} = 0.44 \cdot E_{District\ Heating} \quad (6)$$

$$PE\ (Fac.Electricity) = Primary\ Energy\ Factor\ \cdot E_{Fac.\ Electricity} = 2.6 \cdot E_{Fac.\ Electricity} \quad (7)$$

$$TPE = PE_{Fac.Electricity} + PE_{District\ heating} + PE_{Materials} + PE_{Transportation} + PE_{BITS} \quad (8)$$

Furthermore, the primary energy use for the materials manufacturing and installation, the transportation of the building materials and the building integrated technical systems (BITS) were calculated according to the default settings in Eco-bat 4.0 for each studied building material within this project. Additionally, the results obtained from the environmental impact assessments of the studied renovation measures were also plotted together with the annual life cycle costs of the measures. This evaluation was performed in order to visually present the sustainability of the different renovation measures.

5.9 Co-benefits

Several of the studied renovation measures in this project did also result in benefits that are not directly related to the economic aspect. These benefits are often referred to as the co-benefits. Although the co-benefits are not directly related to the economic aspect, they can still be observed in both the macroeconomic and private perspective. However, only the private perspective was considered within this study. The private perspective of the co-benefits takes into account the concerns of the investors, promoters, owners and users of the building and primarily focuses on the financial aspects that are considered relevant for these stakeholders. The reduction of the global cost of the renovation work and adding maximum value to the building are two examples of co-benefits relevant for the stakeholders included in the private perspective. (IEA EBC, 2015)

Furthermore, a matrix of co-benefits related to renovation measures provided by the *International Energy Agency* was used in order to integrate the resulting co-benefits from the studied renovation measures in the overall assessment (IEA EBC, 2015). The most relevant information from the co-benefits matrix, concerning this specific study, were gathered and compiled into a matrix (See Table 5.12). Nevertheless, the compiled co-benefits were not monetized since the results were considered too approximate because of the current lack of reliable studies and documentations within this topic. This overview was therefore consulted in order to establish the co-benefits that arises from the renovation measures considered in this project.

Table 5.12. Relationship between the co-benefits and the studied renovation measures.

Co-benefits	Thermal Comfort	Building Physics	Reduced Exposure to Energy Price Fluctuations	Architectural Integration	External Noise	Internal Noise	Pride/Prestige
External Façade Insulation	+++	++	++	- -	++	-	++
Attic floor Insulation	+++	+	++		++	-	+
Basement Ceiling and Walls Insulation	+++		++			+	+
Window Replacement	+++	+	+	+	+++	-	+
MVHR Ventilation	++	+	+			- -	+
Efficient DHW System			++				+

Table 5.12 above shows the relationship between the co-benefits and the studied renovation measures (the sign “+” signals for positive co-benefits and “–“ for negative co-benefits). Their relevance is also indicated by the number of signals and color tonality (green for positive and brown for negative)

6. Results

This chapter presents the results of the conducted research work. The results presented in this chapter are sorted according to the methodology order described in the previous chapter. In order to limit the extent of the report, some results are presented in detail in the appendix section.

6.1 Energy Consumption

In this sub-chapter, the simulation results obtained from the IDA ICE simulations are presented and discussed. The results consists of the final energy consumption in terms of district heating (which includes domestic hot water and space heating) and electricity (separated between household and facility electricity). No space cooling was considered for neither the existing reference building nor the energy-improved renovation measures. Individual simulations were carried out for all the studied renovation measures involving changes to the building envelope, the ventilation system and the domestic hot water.

It should, however, be mentioned that it is impossible to exactly determine the accuracy of the simulation results. Nevertheless, the results presented in this sub-chapter were considered reasonable and a comparison between the modelled energy consumptions for the different studied cases still makes sense. Furthermore, all the results in this subchapter are expressed in kWh/(A_{TEMP} ·Year), where only the heated area inside the reference building were considered.

6.1.1 Verifications of the calculations and evaluation of the reference building

The first step of the energy simulations was to build an energy model in IDA ICE of the studied reference building in order to verify and compare the results of the energy model with the measured annual specific energy use of the building. Furthermore, only the facility electricity consumption and the total annual use of district heating were measured in the reference building. As described earlier in the report, the reference building model was adjusted by a calibration process since some essential technical data of the studied reference building were missing. The comparison between the measured annual specific energy use and the simulation results of the base case model is presented in Figure 6.1 below.

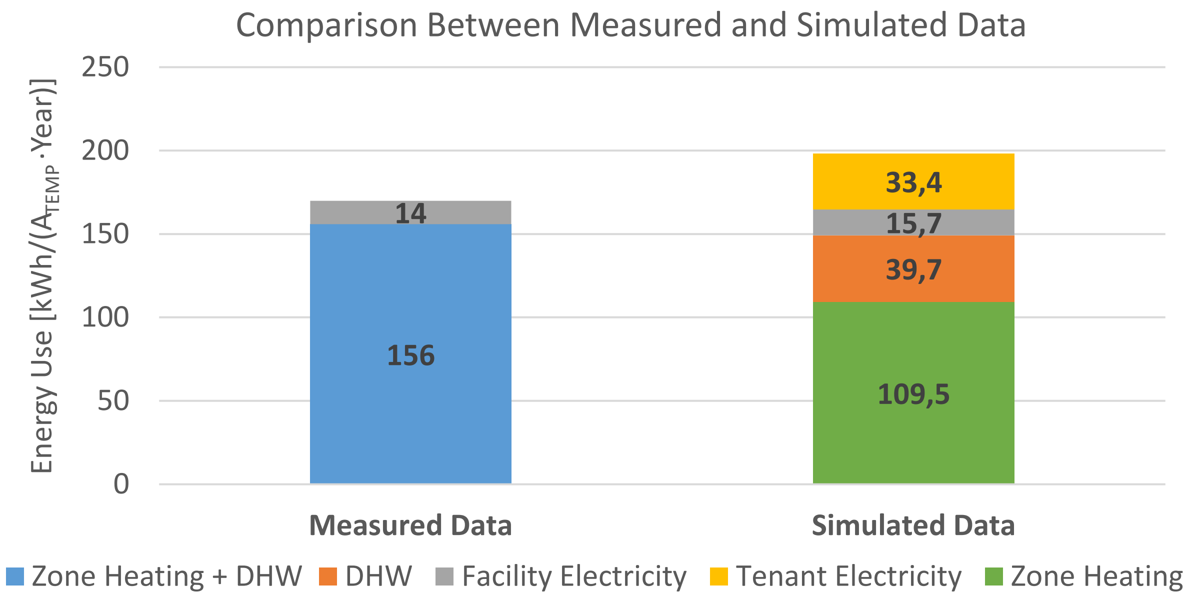


Figure 6.1. The measured energy use and the simulated energy use of the reference building.

The annual tenant electricity consumption, 33.4 kWh/(A_{TEMP}· Year), was obtained as a result of setting the internal gains values for household equipment and lighting in IDA ICE according to the schedules described in the methodology-chapter. The obtained results of the annual household electricity consumption was considered reasonable since the result was rather close to the recommended SVEBY value of about 30 kWh/(A_{TEMP}· Year). (SVEBY, 2012)

The simulation results of the annual energy consumption of the domestic hot water in the reference building was addressed by implementing a daily domestic hot water consumption rate according to the recommended values presented by the *Swedish Energy Agency* (Energimyndigheten, 2012). The simulation results of the annual space heating consumption is a direct result of all input values and settings implemented in the simulation model in IDA ICE such as e.g. the heat set-point temperature and the thermal properties of the building envelope. The obtained results from the energy simulations of the total annual district heating energy need in the reference building was 149.2 kWh/(A_{TEMP}· Year), which is an approximate difference of 4.4 % compared to the measured data of 156 kWh/(A_{TEMP}· Year). Moreover, it is rather common that the simulation results leads to smaller values compared to the measured data since the energy simulations are performed under controlled conditions. Thus, the simulation result of the total annual district heating energy need was considered reasonable.

Furthermore, the annual values obtained from the energy simulation model of the reference building was later on used as reference values for the case study building when the different renovation measures were compared. The obtained simulation results of the reference building were given the name *REF* in the later comparisons with the studied renovation measures.

6.1.2 Resulting annual energy consumption of the building envelope measures

The simulation results of the annual energy need of the building after the implementation of the different renovation measures regarding changes to the building envelope are presented in Figure 6.2and Figure 6.3 below. The results presented in the figures below represents only renovation measures implemented on the building envelope. The annual household electricity consumption for the different studied renovation measures is not presented in the figures since no measures have been conducted in this project that directly affects the household electricity consumption such as e.g. implementing LED-lighting in the apartments. Thus, it will remain the same for all the studied renovation measures conducted in this project. Figure 6.2 below shows the energy results of implementing single renovation measures on the building envelope while Figure 6.3 refers to the energy results of the solutions that consider a combined renovation approach. The names of the different renovation measures presented in Figure 6.2 and Figure 6.3 refers to the *Code of Measure* which are presented and described in detail in Table 5.7 and Table 5.8 in the methodology chapter. The dashed line in the figures indicates the Boverket requirement of the maximum annual energy use for newly constructed multi-family apartment buildings in climate zone 4 in Sweden. The requirement for climate zone 4 is 75 kWh/(A_{TEMP}· Year) which includes the total annual energy consumption for space heating, domestic hot water and facility electricity combined.

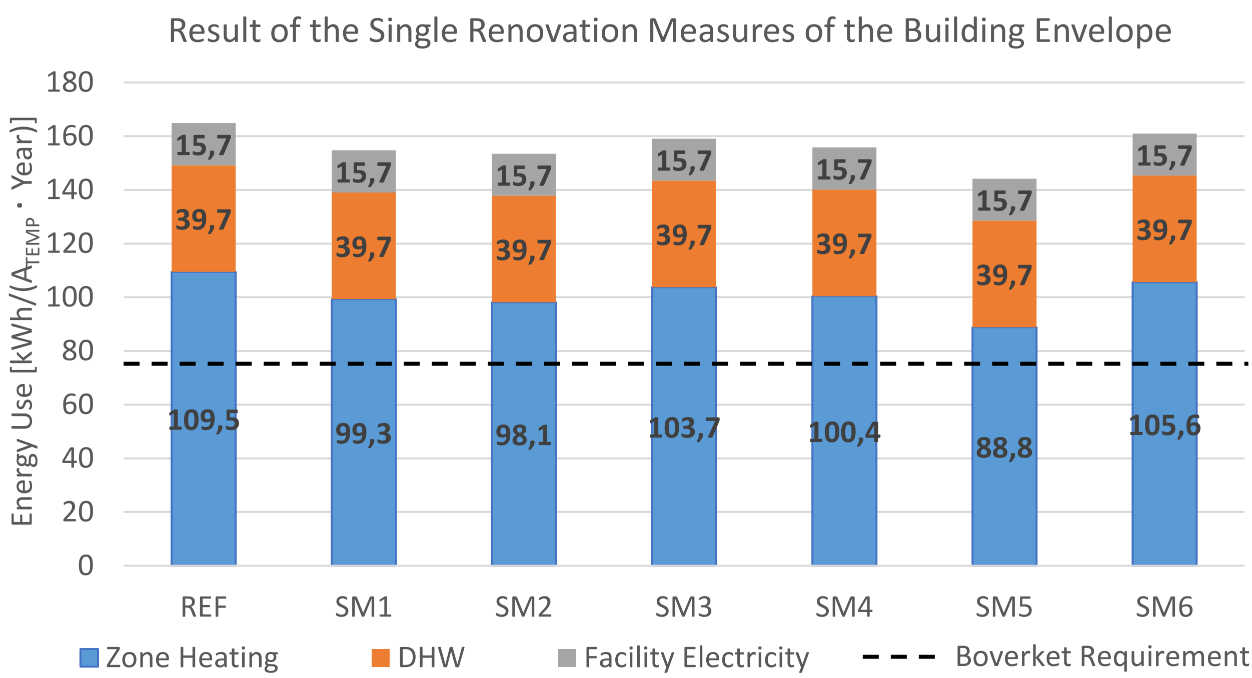


Figure 6.2. Annual energy use of the single measures regarding modifications on the building envelope.

The results presented in Figure 6.2 shows that all the different solutions regarding the single renovation measures implemented on the building envelope have a positive effect on the annual space heating demand of the building. However, the renovation measure concerning externally added insulation to the basement wall (SM6) does not have a profound effect on the annual space heating need in the building. The reason for this is because the internal temperature of the basement before the implementation of the external insulation does not fall below 14 °C even during the coldest months of the year. This can be explained by the fact that the existing basement walls and ceiling are moderately isolated. Furthermore, better results are obtained when insulating the attic floor and the external walls (SM1 to SM4) compared to the measure concerning externally added insulation of the basement wall. However, all these measures lead to rather small savings in terms of energy need for space heating compared to the measure involving window replacement (SM5). In fact, the space heating demand of the reference building can be lowered by approximately 19% by only replacing the existing windows with new low-e windows. This result can be explained by the significantly improved thermal properties of the new windows compared to the old windows as well as the improved airtightness in the building due to less air leakage through and around the new windows.

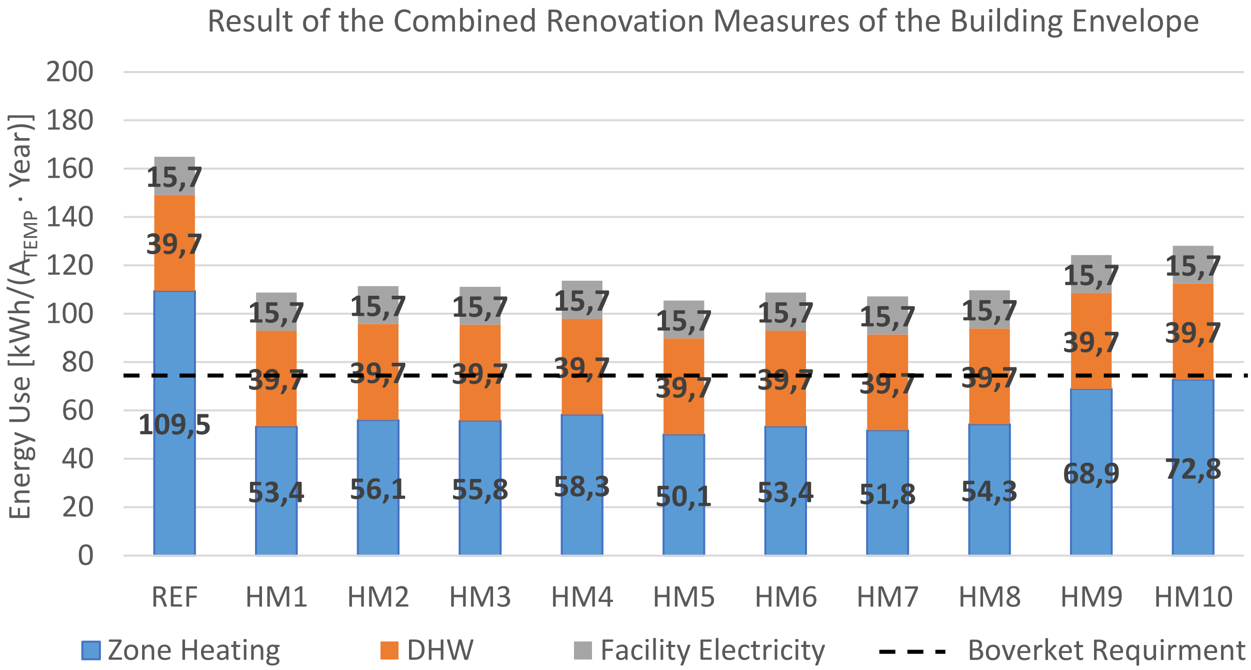


Figure 6.3. Annual energy use of the combined measures regarding modifications on the building envelope.

Figure 6.3 above shows that higher levels of efficiency can be achieved when adopting a combined renovation approach, in other words, foreseeing energy improving actions that affect the whole building envelope. The results show that the largest energy savings are achieved with measure HM5. This renovation measure includes adding the thickest studied insulation on the attic floor (400mm) and the external wall (100mm) as well as all the other single renovation measures combined. The combined renovation approach of the building envelope yields savings in terms of annual space heating need of between 34% (HM10) and 54% (HM5). It should however be pointed out that the combined renovation measures referred to as HM9 and HM10 does not include window replacement. Nevertheless, the results show that all studied combined renovation measures have a profound impact on the annual space heating demand in the building. This can be explained by the fact that the overall heat transfer coefficient of the entire building envelope is significantly improved for all studied combined renovation measures compared to the reference case. The improved thermal properties of the building envelope also entails an improved airtightness in the building. However, none of the studied combined renovation measures implemented on the building envelope are sufficient enough to fulfill the energy requirements established by Boverket. Thus, additional renovation measures have to be combined with the combined renovation measures of the building envelope in order to fulfill the requirements.

6.1.3 Resulting annual energy consumption of the ventilation, IMD and building envelope measures combined

A balanced mechanical ventilation system with a rotary heat recovery was implemented together with the combined renovation measures of the building envelope in order to further reduce the energy need for space heating in the building. The rotary heat exchanger of the balanced mechanical ventilation system enables the system to recover some of the heat from the exhaust air which is then used to heat up the cold incoming supply air. In this way, a significant amount of energy can be saved in terms of specific energy used for space heating. The balanced mechanical ventilation system was implemented in the energy model in IDA ICE together with all ten studied combined renovation measures of the building envelope. The results of the recovered energy of the rotary heat recovery unit for each combined renovation measure is presented in Figure 6.4 below. The abbreviation presented as *BMV* in Figure 6.4 refers to the balanced mechanical ventilation system.

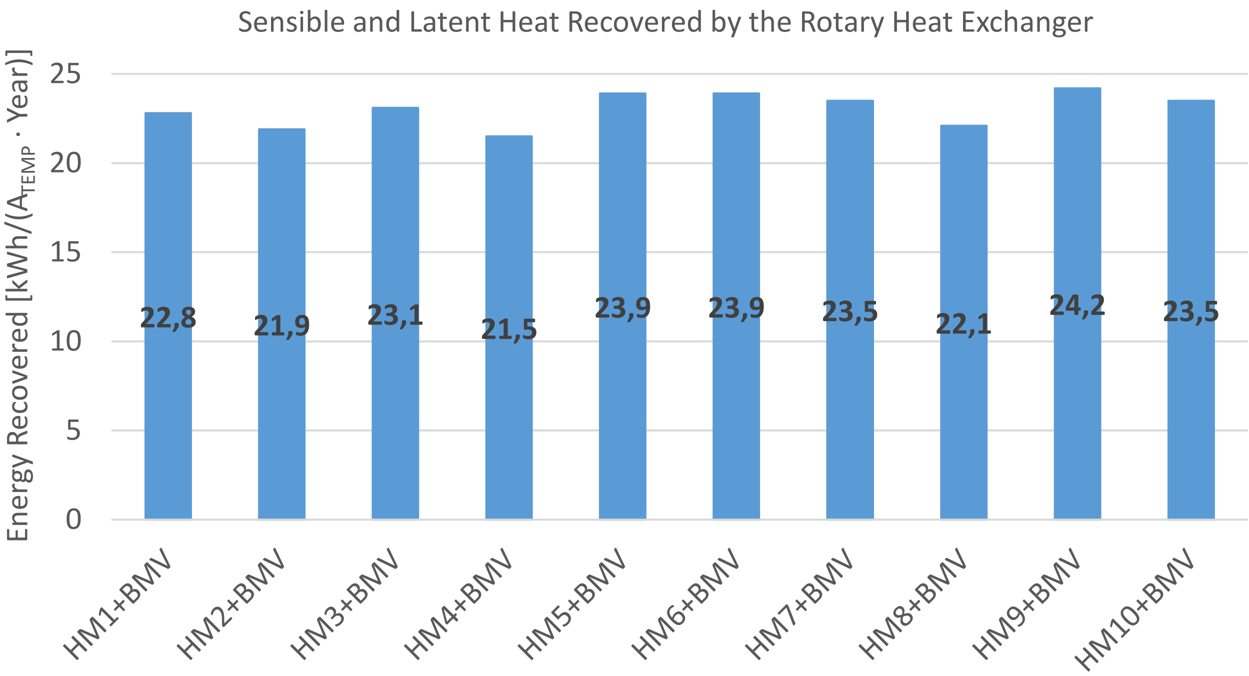


Figure 6.4. Recovered energy of the rotary heat exchanger for each studied combined renovation measure.

The results presented in Figure 6.4 show that significant annual savings in terms of energy need for space heating can be accomplished for all the studied combined renovation measures of the building envelope by implementing a balanced mechanical ventilation system with a heat recovery efficiency of approximately 70%. However, the energy simulations showed that the annual facility electricity consumption increased with 12 to 20%, depending on the simulated combined renovation measure, as a direct result of the implementation of the balanced mechanical ventilation system. This can be explained by the fact that the balanced mechanical ventilation system have more fans and thus a higher specific fan power (SFP) compared to the existing ventilation system. Additionally, the studied ventilation system have also a heating and cooling coil installed in the air handling unit which requires additional electrical energy in order to work.

Regarding the implementation of the individual metering and price charging system of the domestic hot water (abbreviated as IMD) for the studied reference building, a reduction of 35% of the annual domestic hot water consumption was adopted. This value is, however, an estimation of the potential reduction of the annual DHW consumption based on a study conducted by *Energimyndigheten* (Energimyndigheten, 2003). A more accurate assessment of the IMD's impact on the domestic hot water consumption in the reference building can only be determined after the IMD has been implemented in the building. A reduction of 35% means that the annual DHW consumption in the studied reference building decreases from 39.7 kWh/(A_{TEMP}· Year) down to 25.8 kWh/(A_{TEMP}· Year). Thus, the annual DHW consumption was set to 25.8 kWh/(A_{TEMP}· Year) for the combined renovation measures were the combined measures of the building envelope were combined with the new ventilation system and the IMD. The results from the energy simulations of the combined renovation measures are presented in Figure 6.5 below.

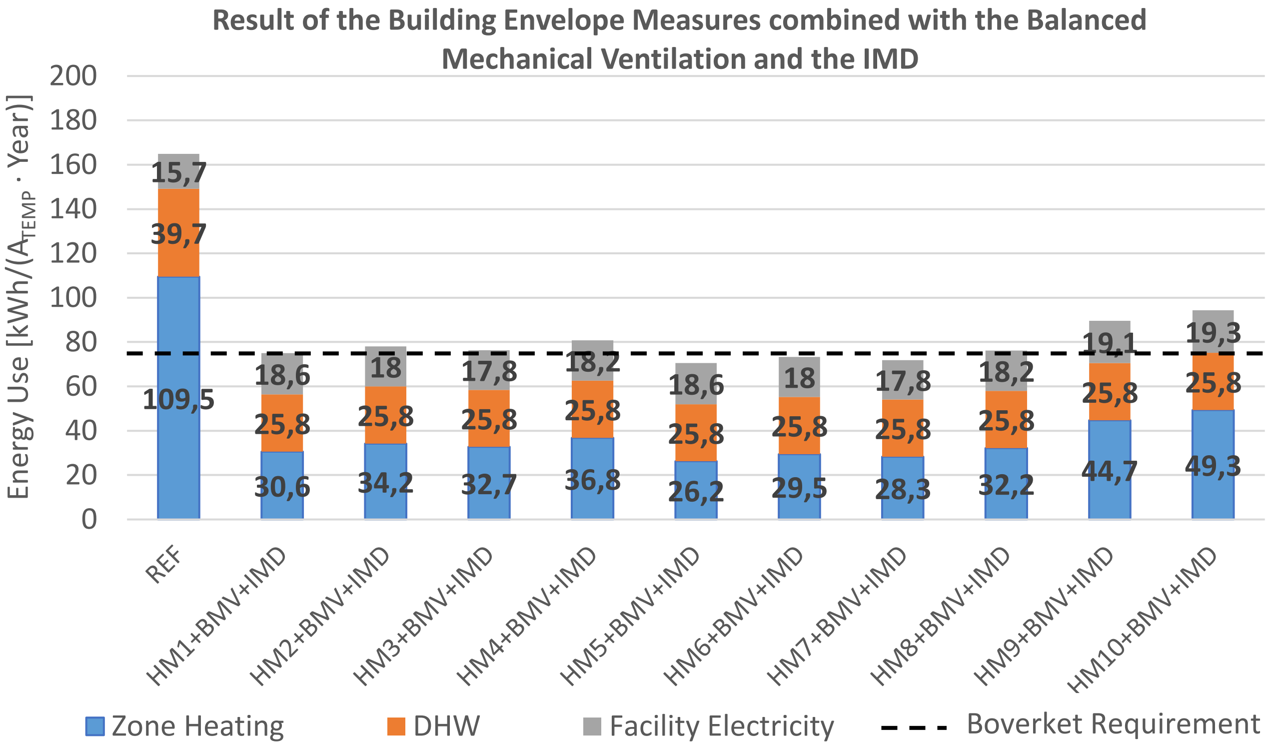


Figure 6.5. Annual energy use in the studied reference building of the combined renovation measures.

The results presented in Figure 6.5 shows that by combining the combined measures of the building envelope with a balanced mechanical ventilation system and IMD of the domestic hot water will reduce the overall specific energy use in the building with 43 (HM10) to 57% (HM5). The category that shows the most significant reduction in terms of annual energy need is the space heating which is reduced by 55 (HM10) to 76 % (HM5) compared to the reference case. However, the annual facility electricity consumption has increased for all the simulated renovation measures as a direct result of the implementation of the balanced mechanical ventilation system. Nevertheless, the results of the energy simulations show that there are four different renovation measures that fulfills the energy requirements established by Boverket. These renovation measures are HM1, HM5, HM6 and HM7.

6.2 Life Cycle Cost Analysis

The cost assessment was carried out for two specific evaluation periods, i.e. 30 and 60 years. The two different studied evaluation periods was used in the cost assessment in order to determine how the different time periods effect the overall financial profitability of the renovation measures. Furthermore, the determination of the initial investment costs and the calculations of the life cycle costs for all the different studied renovation measures are presented in detail in Appendix D. Worth mentioning is that the fixed real interest rate as well as the fixed annual price growth rates of the energy prices, presented in the methodology chapter, have been used for all the life cycle cost analyzes conducted in this project. The results of the life cycle cost assessments performed for all the measures analyzed within this project is reported in the next sub-chapters. Moreover, all the results in the following subchapters are expressed in either SEK/(A_{TEMP} ·Year) or SEK/A_{TEMP}.

6.2.1 LCC of the renovation measures regarding building envelope modifications

First and foremost, the investment costs for all the energy-related measures were evaluated and consequently compared with the results obtained from the Wikells software. The initial investment costs of the combined renovation measures applied on the building envelope are presented in Figure 6.6 below.

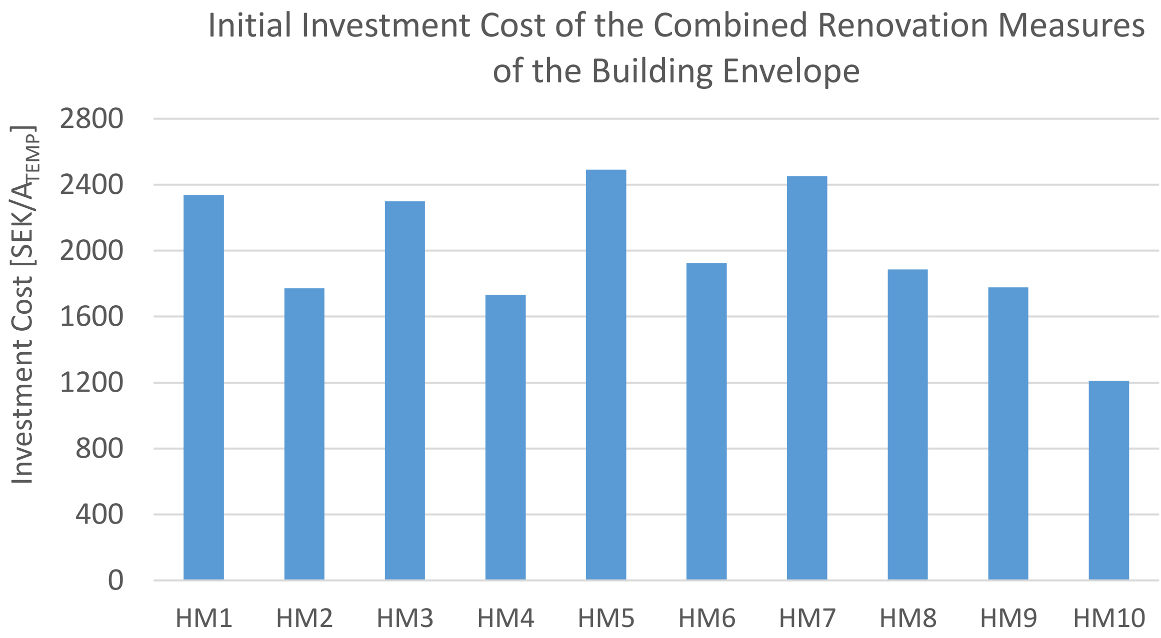


Figure 6.6. Investment costs for the measures regarding modifications to the building envelope.

The results presented in Figure 6.6 shows that the initial investment costs of the combined renovation measures of the building envelope varies a lot between the different packages of renovation measures. The cost calculations conducted in Wikells calculation software showed that the two biggest contributors to the initial investment costs are the window replacement measure and the measure regarding externally added insulation to the basement walls. In fact, the only difference between the two studied combined renovation measures referred to as HM5 and HM10 is that the HM10 package does not include externally added insulation to the basement walls or the window replacement measure. The high initial investment costs of these two specific renovation measures can be explained by the fact that the material costs of the new windows are rather high while the labor costs of the measure regarding externally added insulation to the basement walls are rather high. A more detailed presentation of the results of the estimated initial investment costs of the combined renovation measures are found in Appendix D.

Furthermore, Figure 6.7 and Figure 6.8 shows the total annual life cycle costs of the combined renovation measures with an studied evaluation period of 30 and 60 years respectively. The results presented in the figures below includes the effects of the real interest rate and the annual price growth rates of the district heating and facility electricity throughout the entire evaluation period. The total annual life cycle costs are expressed in SEK/(A_{TEMP} ·Year). Moreover, the energy need for the household electricity has been neglected in the life cycle cost assessments as it remains the same for all the measures.

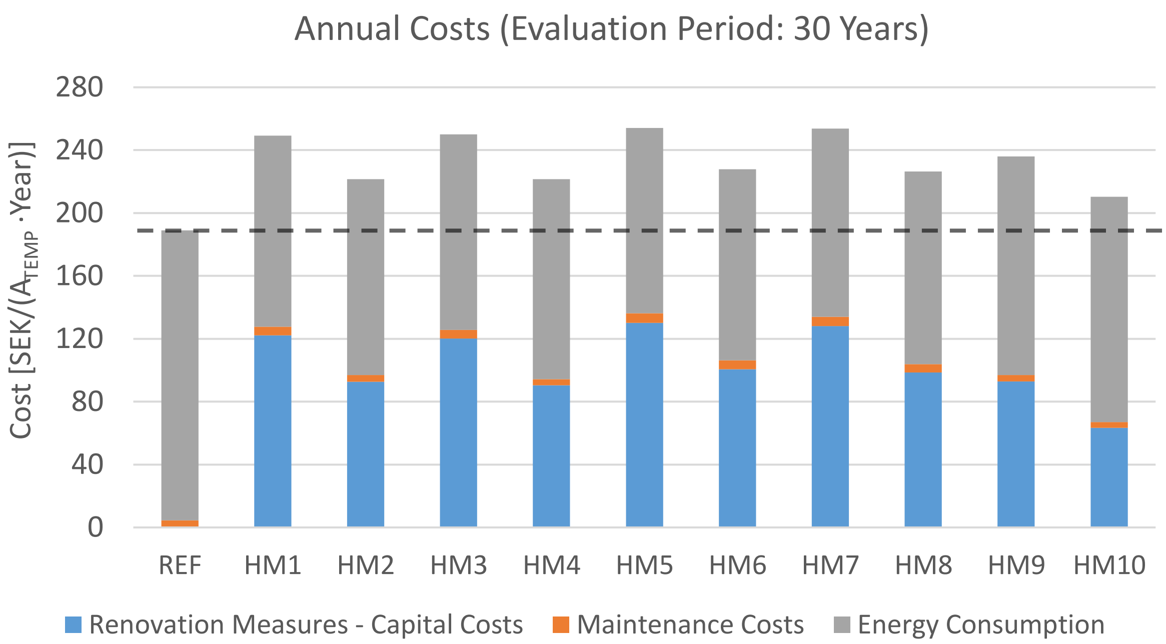


Figure 6.7. Total annual life cycle costs for the measures regarding modifications to the building envelope with an evaluation period of 30 years.

The results presented in Figure 6.7 show that none of the studied combined renovation measures of the building envelope will yield financial savings during the first 30 years after their implementation. This can be explained by the fact that the capital costs of the renovation measures are rather comprehensive. Thus, the extensive capital costs lead to a rather decisive impact on the total annual life cycle cost during a shorter studied evaluation period e.g. 30 years. This trend is clearly shown in Figure 6.7, where the combined renovation measure with the lowest capital costs (HM10) are the most cost-effective option considering an evaluation period of 30 years.

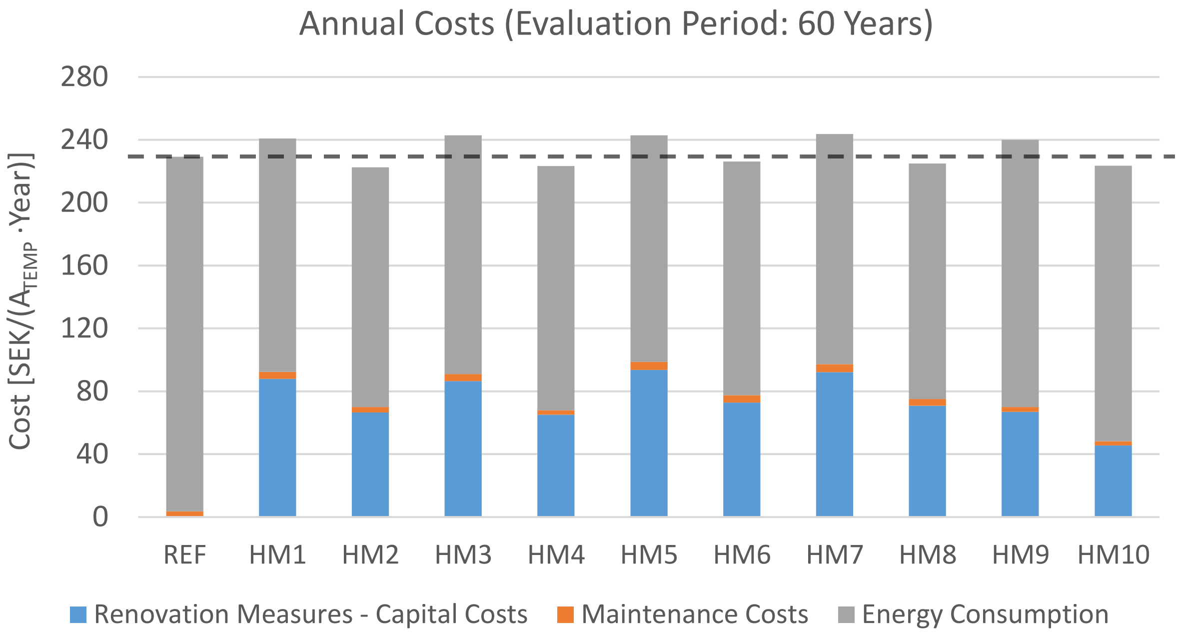


Figure 6.8. Total annual life cycle costs for the measures regarding modifications to the building envelope with an evaluation period of 60 years.

When considering an evaluation period of 60 years then 50% of the studied combined renovation measures turn out to be more cost effective then the reference building. Furthermore, the combined renovation measures that include the measure of externally added insulation of the basement walls (HM1, HM3, HM5, HM7 and HM9) will not yield financial savings the first 60 years after their implementation. This can be explained by the fact that the renovation measure concerning externally added insulation on the basement walls does not yield high potential savings in terms of annual energy use in the building while the capital costs of the measure is rather high.

6.2.2 LCC of the combined renovation measures of the ventilation, IMD and building envelope measures

The renovation measures concerning changes to the ventilation system as well as the implementation of the individual metering and price charging system of the domestic hot water (abbreviated as IMD) were implemented together with the combined renovation measures of the building envelope, as mentioned earlier in the previous sub-chapters. The initial investment costs of the combined renovation measures are presented in Figure 6.9 below.

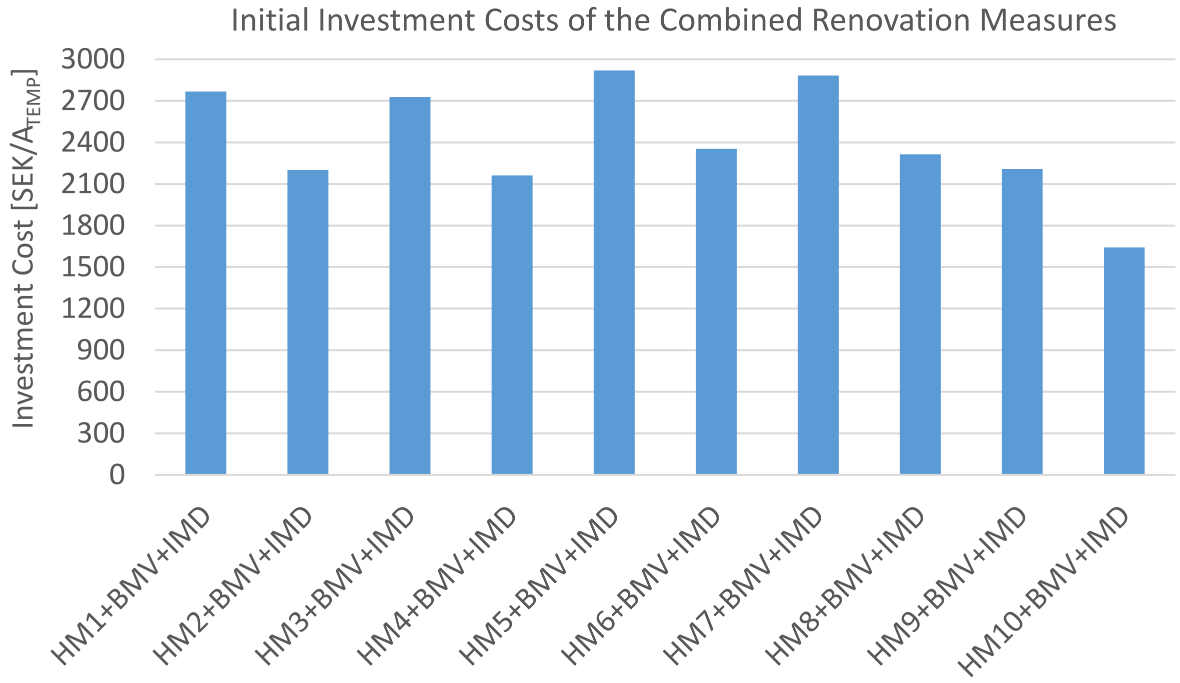


Figure 6.9. Initial investment costs of the combined renovation measures.

The combined renovation measures will implicitly lead to higher initial investment costs for all the studied renovation packages compared to the combined renovation measures of the building envelope. The results presented in Figure 6.9 shows that the implementation of the new ventilation system and the IMD of the domestic hot water will increase the initial investment costs with 15-20% compared to the case where only the combined renovation measures of the building envelope is considered. The renovation measure with the highest initial investment costs is the package of measures referred to as *HM5+BMV+IMD*. This can be explained by the fact that *HM5+BMV+IMD* includes all the single renovation measures of the building envelope with the thickest studied insulation materials combined. On the other hand, the renovation package referred to as *HM10+BMV+IMD* is still the cheapest alternative, in fact it is actually cheaper than all the other studied combined renovation measures before the implementation of the new ventilation system and the IMD of the domestic hot water (See Figure 6.6).

Furthermore, Figure 6.10 and Figure 6.11 show the total annual life cycle costs of the combined renovation measures with an studied evaluation period of 30 and 60 years respectively. The results presented in the figures below includes the effects of the real interest rate and the annual price growth rates of the district heating and facility electricity throughout the entire evaluation period.

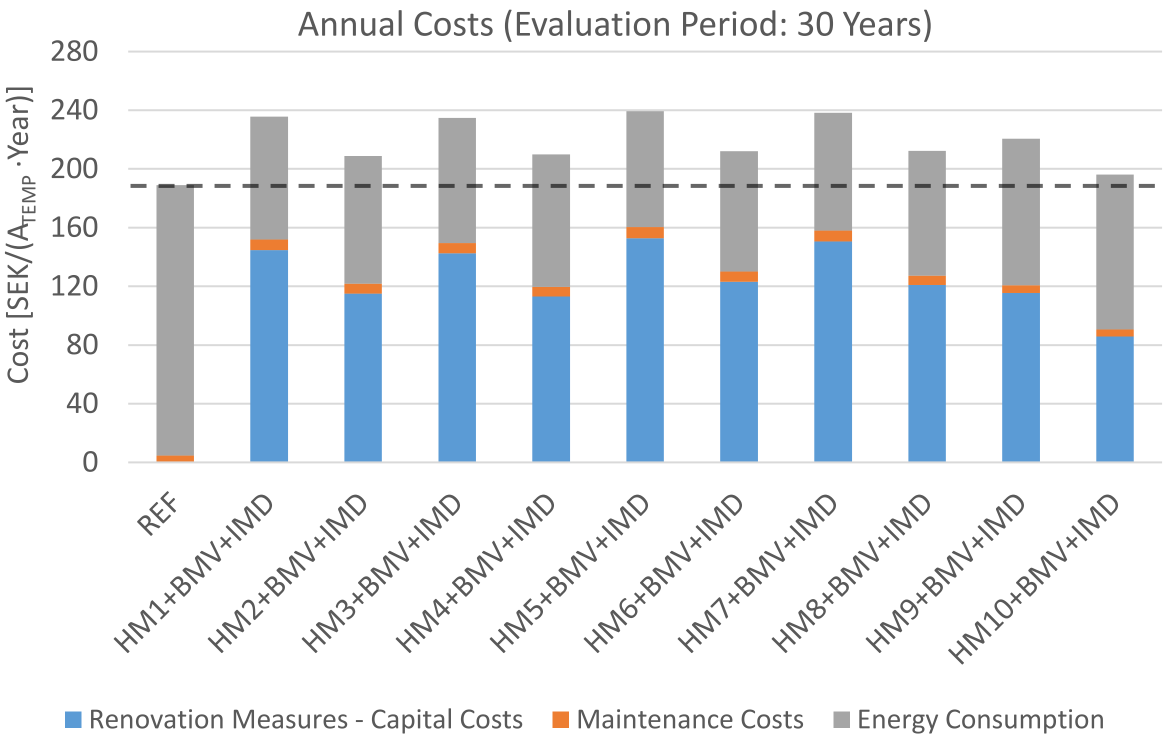


Figure 6.10. Total annual life cycle costs of the combined renovation measures with an evaluation period of 30 years.

The results presented in Figure 6.10 shows that none of the studied combined renovation measures will yield financial savings during the first 30 years after their implementation. This result was rather expected since the capital costs of the combined renovation measures are 15-20% higher than the renovation measures concerning only modifications to the building envelope. Nevertheless, the results show that the annual cost of the energy have decreased with 30-35% compared to the renovation measures concerning only modifications to the building envelope (See Figure 6.7). It is also noticeable that the maintenance costs have increased after the implementation of the new ventilation system and the IMD of the domestic hot water. This is explained by the fact that the combined renovation measures includes more components and thus requires more maintenance then the combined renovation measures of the building envelope.

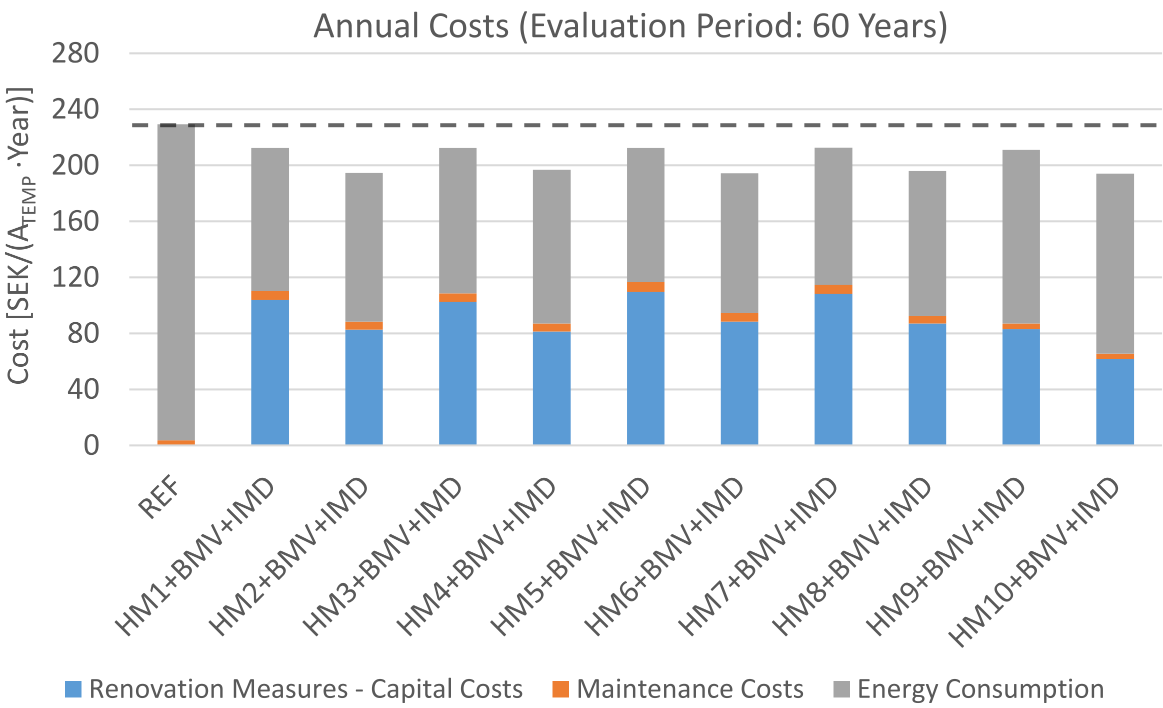


Figure 6.11. Total annual life cycle costs of the combined renovation measures with an evaluation period of 60 years.

When an evaluation period of 60 years is considered then all of the combined renovation measures turn out to be cost effective. In this case, measures that require high investment costs yield greater savings except for the measures where externally added insulation to the basement walls are included. Thus, the best solutions are now strongly related to the annual energy need of the building. Therefore, it can be stated that an ambitious initial investment will yield greater financial savings over time. Thus, all the studied combined renovation measures are best suited as a long term investment in terms of financial profitability. According to Figure 6.11, the solutions with the highest potential savings are *HM6+BMV+IMD* whose relative annual costs are 15.3% lower than the reference case, considering an evaluation period of 60 years.

6.3 Life Cycle Assessment

All of the analyzes conducted in the life cycle assessments were carried out by using *Eco-bat 4.0* software. The software takes into consideration both the annual energy consumption of the building as well as the embodied energy of all the materials used for the renovation. Moreover, the building integrated technical systems (abbreviated as BITS) were also included in the LCA assessments. Additionally, the environmental impact of the transportation of the considered insulation materials were also included in the LCA assessments conducted within this project. Furthermore, all the input data and results from the LCA analyzes conducted in Eco-bat are presented in detail in Appendix E. Moreover, only the total primary energy use as well as the global warming potential of the combined renovation measures were analyzed in the LCA assessment. The reason for this is because the combined renovation measures were the only measures that had renovation packages that fulfilled the energy requirements established by Boverket. The two graphs below (Figure 6.12, and Figure 6.13) presents the results of the environmental impact parameters for all the studied combined renovation measures including the reference case during an evaluation period of 30 years.

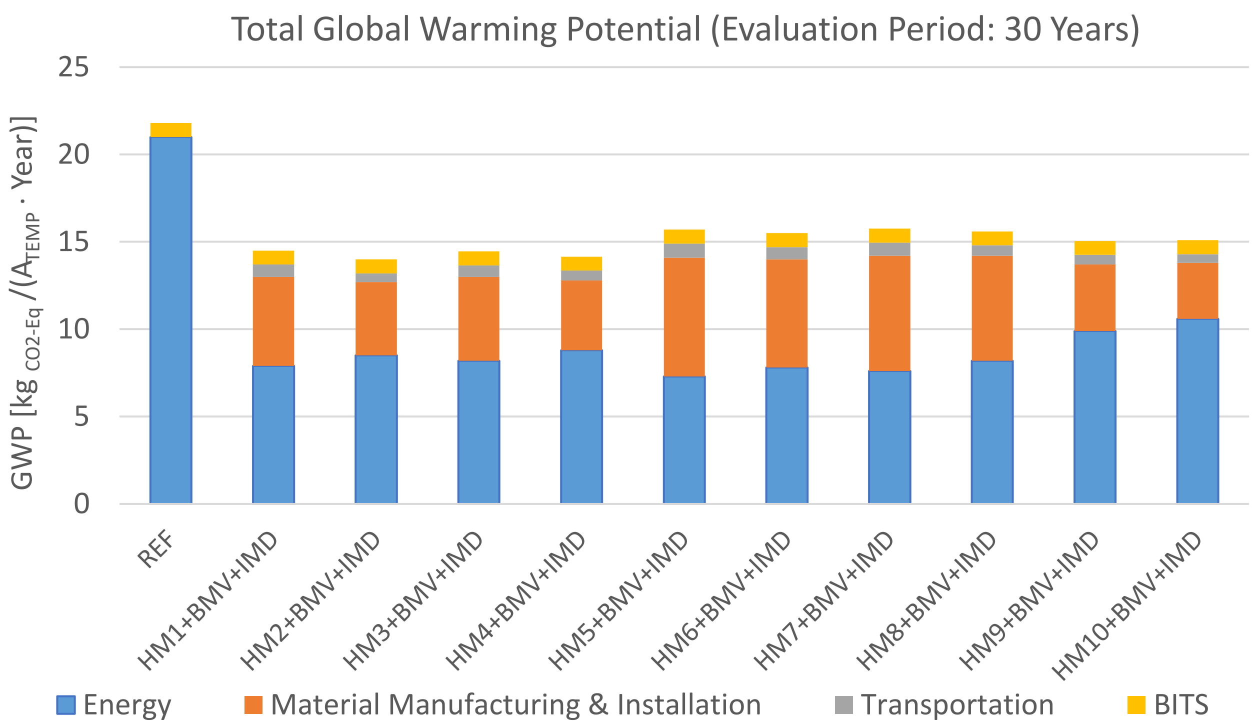


Figure 6.12. Total global warming potential of the combined renovation measures considering an evaluation period of 30 years.

The results presented in Figure 6.12 show that the energy provided by district heating has a huge impact on the carbon dioxide emissions of the studied reference building. Although the material manufacturing and installation significantly affects the overall carbon dioxide emissions, it is still a relatively low contribution compared to the environmental impact of the provided energy to the reference building. Thus, by reducing the overall energy demand of the building will significantly reduce the environmental impacts, in terms of global warming potential, of the building.

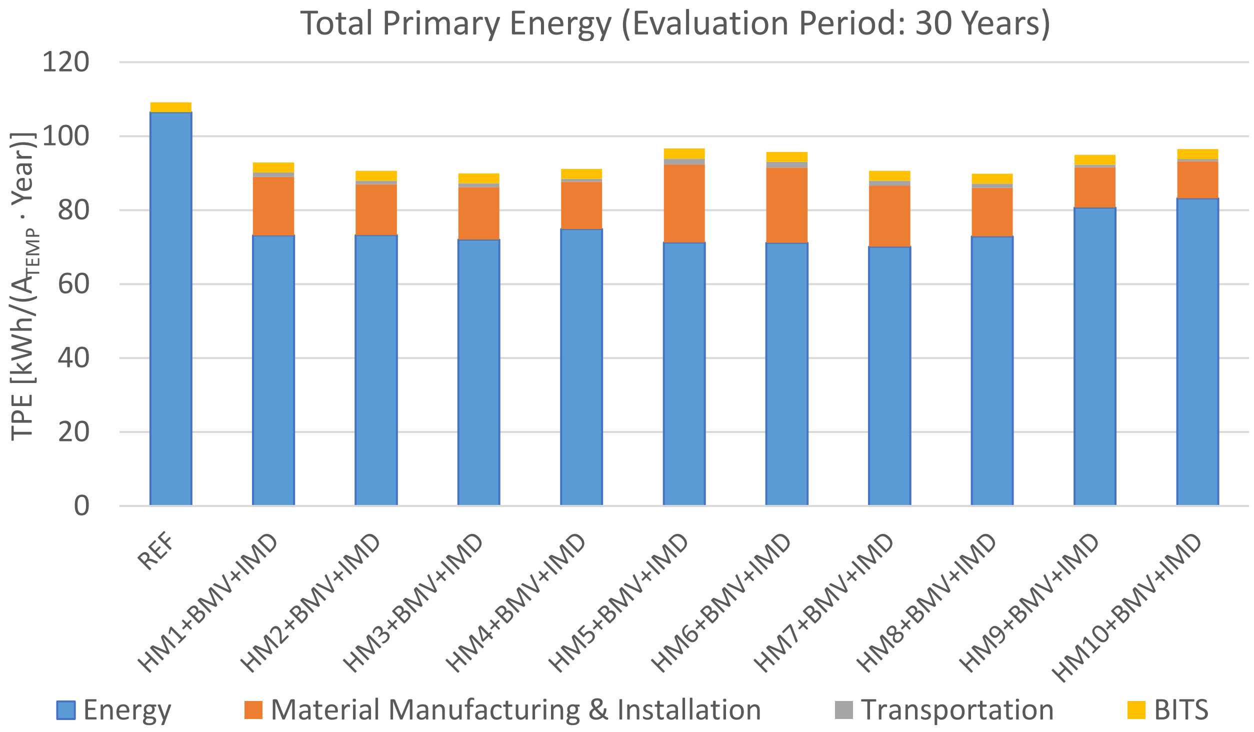


Figure 6.13. Total primary energy of the combined renovation measures considering an evaluation period of 30 years.

The results presented in Figure 6.13 show that the total primary energy use is lower for all the studied combined renovation measures compared to the reference case. However, the reduction of the overall energy need in the building does not affect the annual primary energy consumption of the renovation measures as much as it does for the carbon dioxide emissions (See Figure 6.12). This can be explained by the fact that the total primary energy use of the bought energy was completely determined by the primary energy factors used for the different energy carriers. Additionally, the facility electricity increased by 12 to 20% for all the studied combined renovation measures. The increased energy use of the facility electricity entails a significant negative impact of the total primary energy use since the primary energy factor for the facility electricity was relatively high (260% of the bought energy). Thus, the reduction of the overall energy need in the building, as a result of the implementation of the combined renovation measures, does not significantly affect the total primary energy consumption of the building. Nevertheless, the results presented in Figure 6.13 shows that all the combined renovation measures generates a lower annual primary energy consumption compared to the reference case.

Furthermore, the two graphs below (Figure 6.14 and Figure 6.15) present the results of the environmental impact parameters for all the studied combined renovation measures including the reference case during an evaluation period of 60 years.

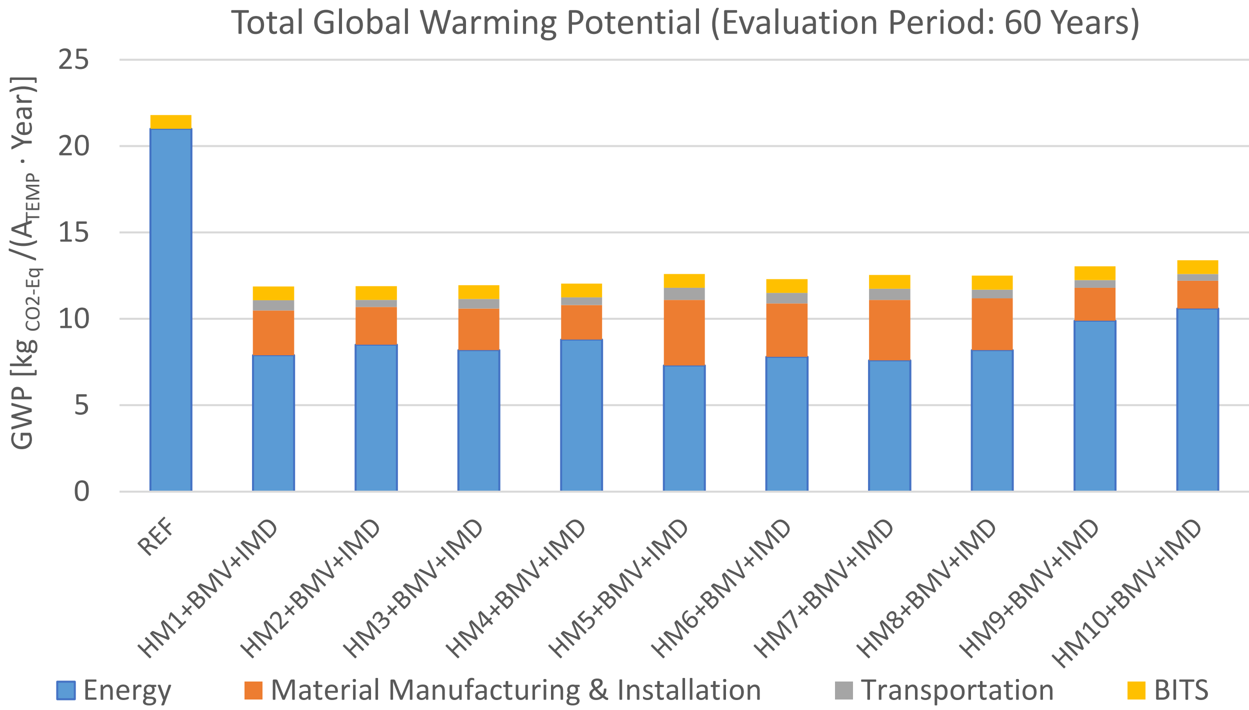


Figure 6.14. Total global warming potential of the combined renovation measures considering an evaluation period of 60 years.

The results presented in Figure 6.14 show that the effects of the material manufacturing and installation have decreased significantly compared to the studied case with an evaluation period of 30 years (See Figure 6.12). This can be explained by the fact that the manufacturing and installation process of the materials for the renovation measures emits carbon dioxide once during the entire service life of the materials. Thus, the total quantity of carbon dioxide emitted due to the manufacturing and installation process of the materials will, more or less, remain the same regardless of which evaluation period that has been used for the assessment. Furthermore, the results show that the significant reduction of the annual energy need in the building have a profound long term effect on the carbon dioxide emissions of the building.

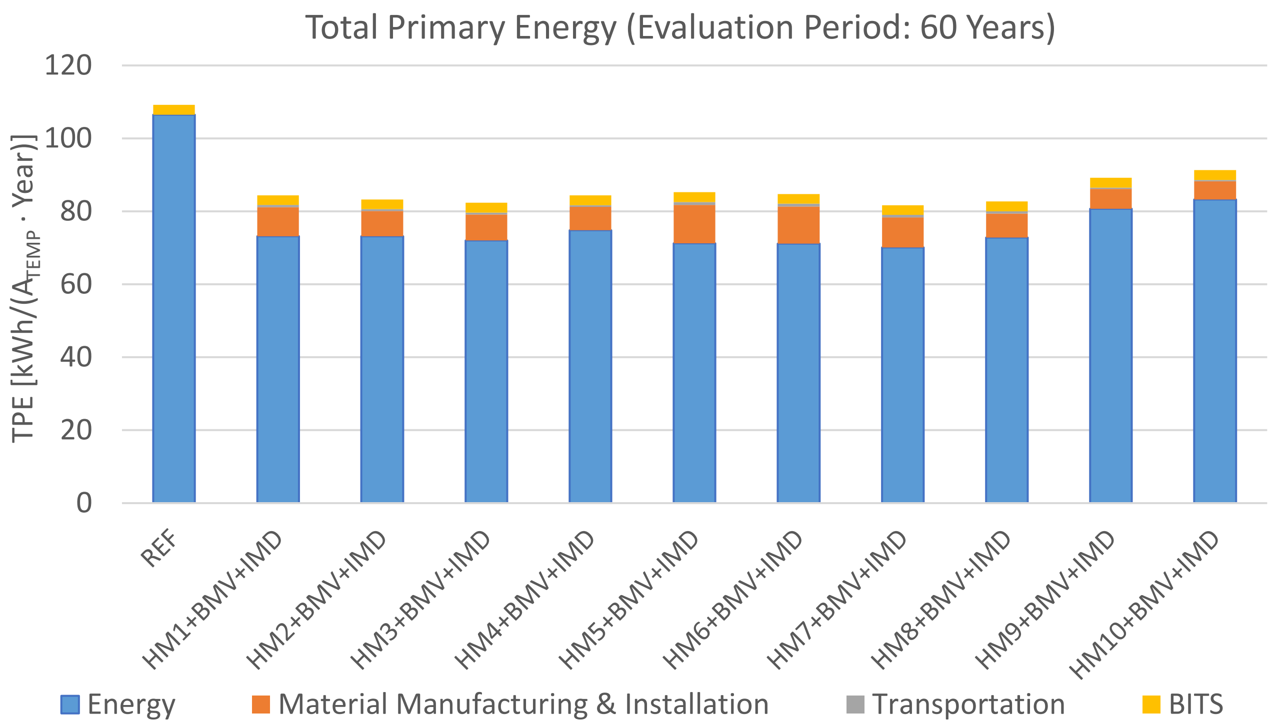


Figure 6.15. Total primary energy of the combined renovation measures considering an evaluation period of 60 years.

The results presented in Figure 6.15 show that all the combined renovation measures generates a lower annual primary energy consumption compared to the reference case. Moreover, the effects of the material manufacturing and installation have decreased significantly compared to the studied case with an evaluation period of 30 years (See Figure 6.13). This trend can be explained by the fact that total quantity of primary energy due to the manufacturing and installation process of the materials will, more or less, remain the same regardless of which evaluation period that has been used for the assessment.

Furthermore, in order to fulfil a cost effective energy and carbon emission optimization process that follows the methodology introduced by Annex 56, the indicators of the total primary energy (TPE) and global warming potential (GWP) were plotted along with the total annual life cycle costs for each studied combined renovation measure. This evaluation was also performed in order to visually present the sustainability of the different studied renovation measures. Figure 6.16 and Figure 6.17, presented below, shows the total life cycle costs of the combined renovation measures together with the corresponding total primary energy consumption and the global warming potential of the same measures. The studied evaluation period of the results presented in Figure 6.16 and Figure 6.17 is 30 years.

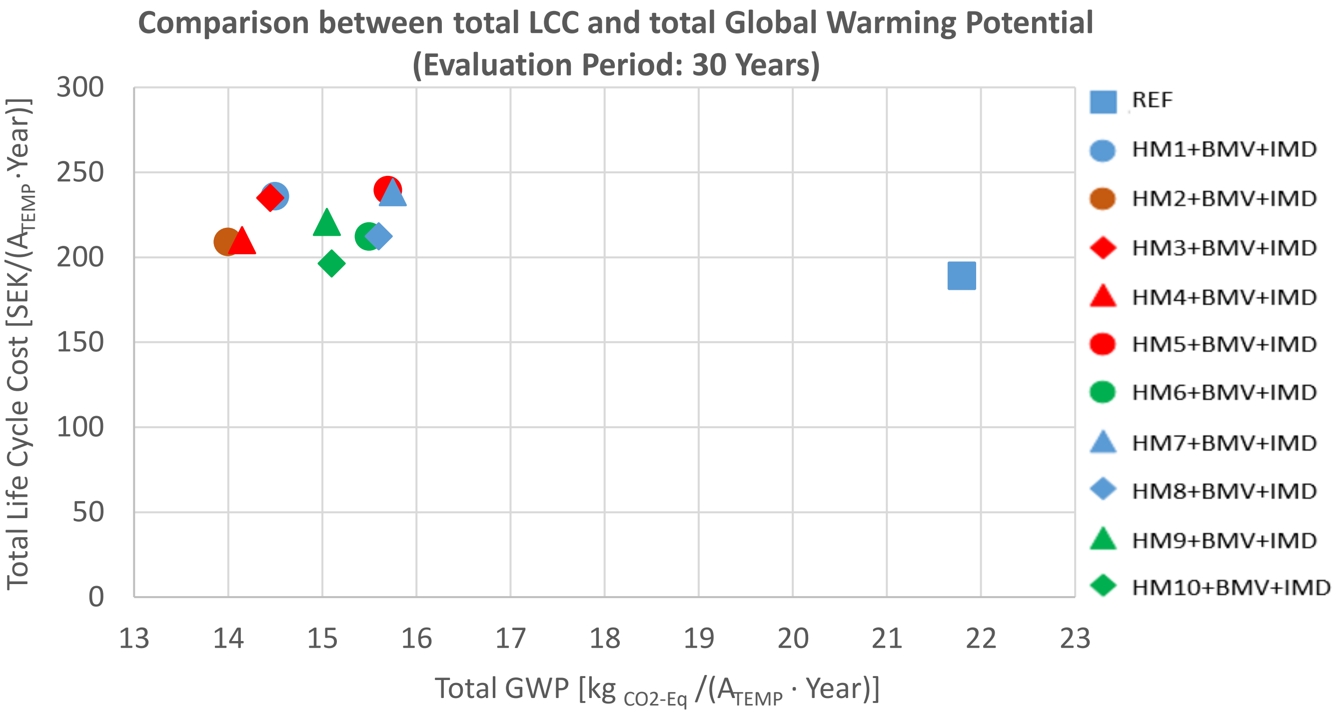


Figure 6.16. Total annual life cycle costs of the combined renovation measures compared to the corresponding carbon dioxide emissions of the renovation measures within an evaluation period of 30 years.

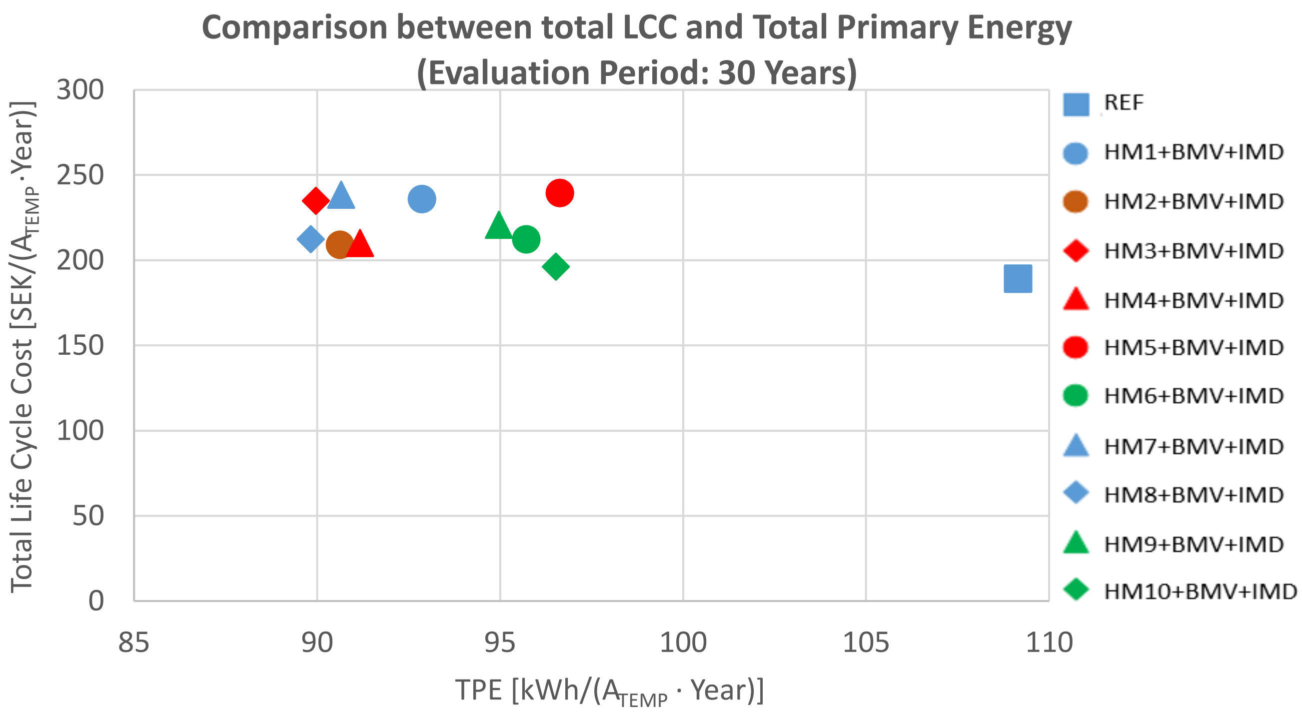


Figure 6.17. Total annual life cycle costs of the combined renovation measures compared to the corresponding total primary energy consumption of the renovation measures within an evaluation period of 30 years.

The results presented in Figure 6.16 and Figure 6.17 shows that none of the studied combined renovation measures are cost-effective compared to the reference case during the first 30 years after their implementation. However, all of the studied renovation measures achieved better results in terms of environmental impact compared to the reference case. Additionally, there are a number of options for the investors to further reduce the initial investment costs of the renovation measures and also accelerate the payback time of the investment. These financial options are discussed further in the *Conclusions and Discussions* chapter in this report. Thus, the packages that fulfill the energy requirements established by Boverket (HM1, HM5, HM6 and HM7) should therefore be taken into consideration by the investors as valid renovation alternatives.

Furthermore, the results of the total life cycle costs of the combined renovation measures together with the corresponding total primary energy consumption and the global warming potential of the same measures are presented in Figure 6.18 and Figure 6.19 below. The studied evaluation period of the results presented in Figure 6.18 and Figure 6.19 is 60 years.

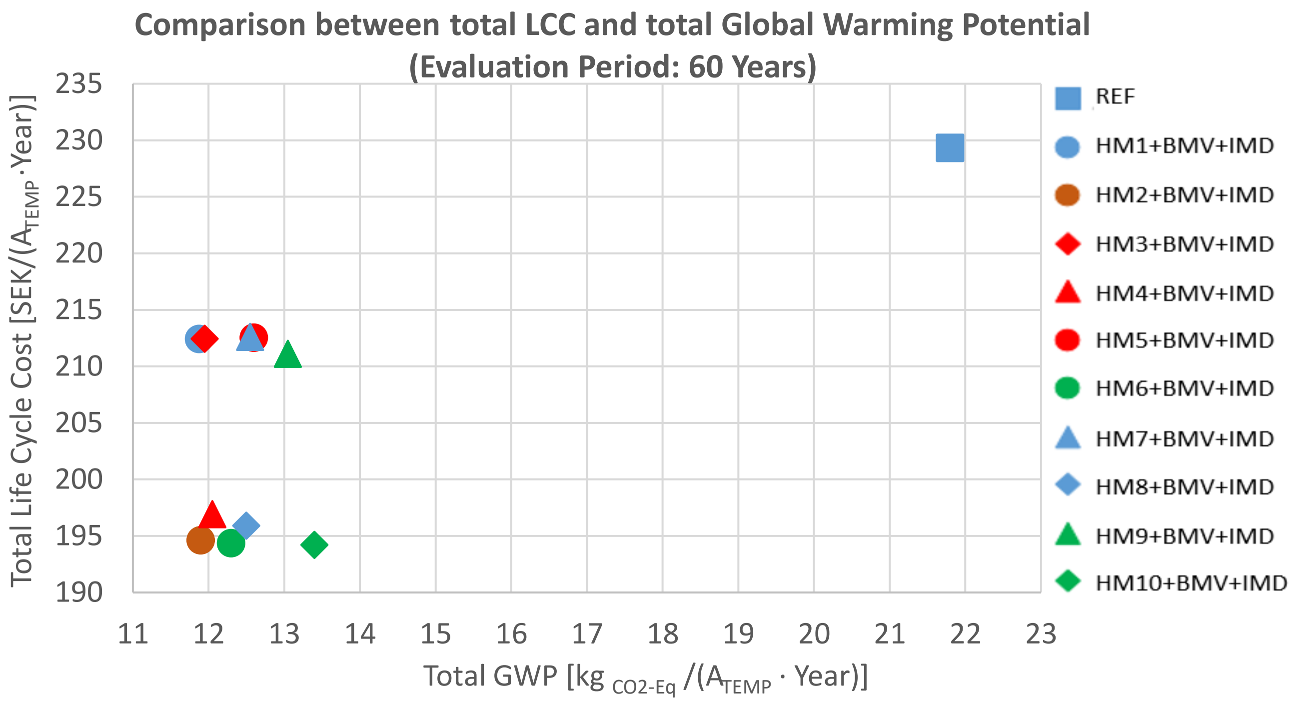


Figure 6.18. Total annual life cycle costs of the combined renovation measures compared to the corresponding carbon dioxide emissions of the renovation measures within an evaluation period of 60 years.

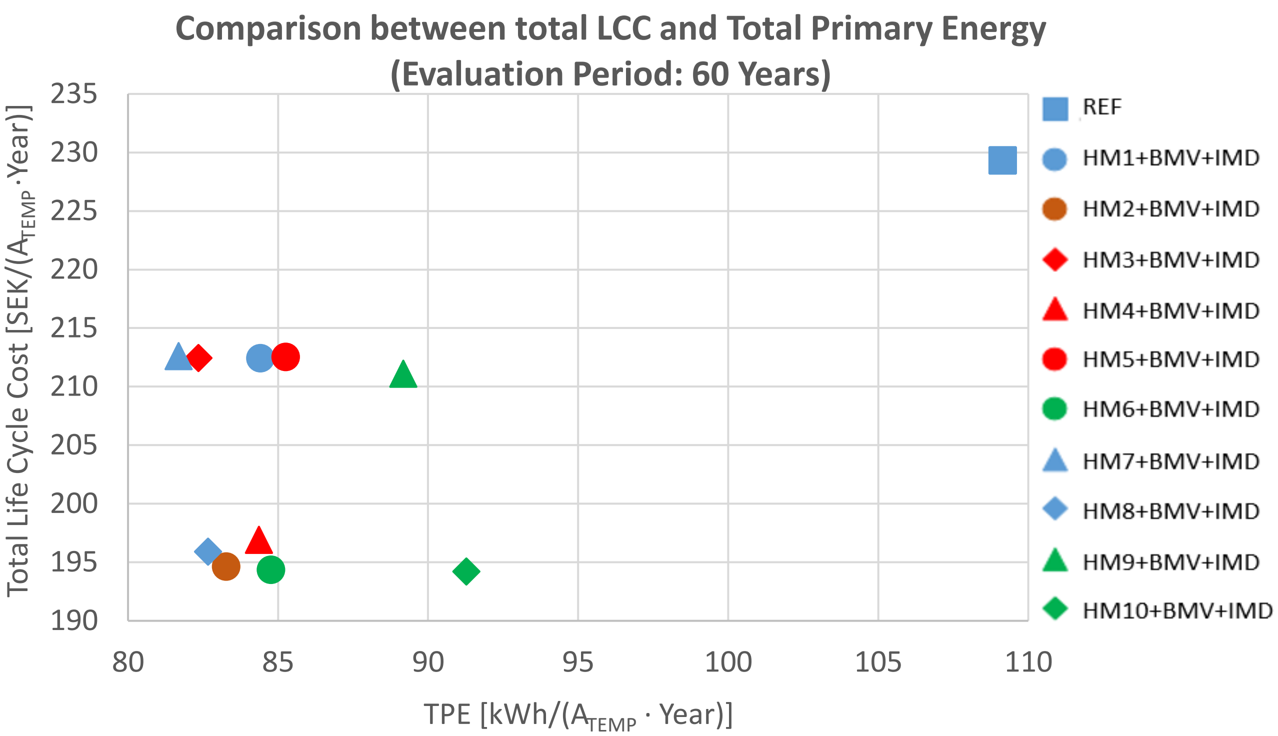


Figure 6.19. Total annual life cycle costs of the combined renovation measures compared to the corresponding total primary energy consumption of the renovation measures within an evaluation period of 60 years.

The results presented in Figure 6.18 and Figure 6.19 shows that all the studied combined renovation measures are sustainable renovation alternatives considering a long term perspective of 60 years. Moreover, the renovation measure referred to as *HM6+BMV+IMD* is the most sustainable option out of all the combined measures that fulfills the energy requirements established by Boverket, considering an evaluation period of 60 years. The results of the *HM6+BMV+IMD* renovation measure indicates a potential reduction of 15 % of the annual life cycle costs compared to the reference case throughout the studied time period of 60 years. Furthermore, the results show that the *HM6+BMV+IMD* renovation measure will also reduce the annual carbon dioxide emissions and annual primary energy consumption with approximately 44 % and 22 %, respectively, compared to the reference case throughout the entire evaluation period.

6.4 Co-benefits

In this sub-chapter the resulting co-benefits of the implementation of the combined renovation measures are presented. The main co-benefits that arise from the proposed renovation measures were established on the basis of the overview provided by Annex 56 (IEA Annex 56, 2014). These specific co-benefits are listed below.

- Indoor reduction of humidity levels and prevention of condensation by increasing temperature of cold surfaces, reducing cold surfaces, eliminating thermal bridges and increasing indoor air temperature which can be achieved thanks to the additionally added insulation of the entire building envelope and windows replacement.

- Reduction of draughts, which is an important aspect of the thermal comfort. It can be addressed thanks to the reduction of air leakage as a direct result of the additionally added insulation on the building envelope as well as the implementation of the new low-e windows.

- Indoor thermal comfort, which mainly depends on the indoor dry-bulb temperature, is improved during the cold months of the year thanks to the additionally added insulation on the building envelope, reduction of air infiltration as well as the implementation of the balanced mechanical ventilation system with heat recovery. However, there is a profound risk for overheating in the building during the summer months due the highly insulated and airtight construction of the building envelope. Nevertheless, the studied reference building is geographically located in a cold climate on the northern hemisphere and thus the indoor thermal comfort is estimated to be improved for the majority of months during the year.

- Reduction of external noise, which can be addressed thanks to the additionally added insulation of the building envelope as well as the improvement of the air leakage in the building. However, the reduction of the external noises makes the internal noises within the building more noticeable, which is regarded as a negative co-benefit.

- The indoor air quality is improved as a direct result of the implementation of the balanced mechanical ventilation system. The new ventilation system reduces the amount of particulates and microbiological contaminants in the indoor air, which improves the indoor air quality.

- The architectural integration is reduced due to the implementation of the externally added insulation on the external walls together with the plaster façade. This measure will significantly change the overall aesthetics of the building. Thus, the architectural integration with the surrounding buildings in the neighborhood will be reduced.

- The sensitivity to energy price fluctuations is reduced due to the substantial reduction of annual energy use in the building.

- Pride and prestige is increased for the tenants in the building due to the energy related improvements of their dwellings along with the ability to influence their monthly housing rent due to the implementation of the individual metering and price charging system of the domestic hot water.

The grading of the co-benefits was carried out by assigning each resulting co-benefit a number that represents the score of the co-benefit. A negative number indicates a negative co-benefit while a positive number indicates a positive co-benefit. The grading of the co-benefits was based on all of the results presented in the previous sub-chapters of the combined renovation measures such as e.g. reduced annual energy use, improved airtightness, improved mean U-value of the building envelope etc. Furthermore, the co-benefit matrix provided by *The International Energy Agency,* which is presented in the *Methodology* chapter, was used as a template for the grading of the resulting co-benefits (IEA EBC, 2015). The final result of the grading of the co-benefits were weighed between -10 and +10, where -10 indicates a radical deterioration of the studied parameter while +10 indicates a radical improvement. It should however be stated that the final results of the grading were considered as estimated and subjective results because of the current lack of reliable studies and documentations within this topic. Based on these conditions, the bar chart presented in Figure 6.20 was developed.

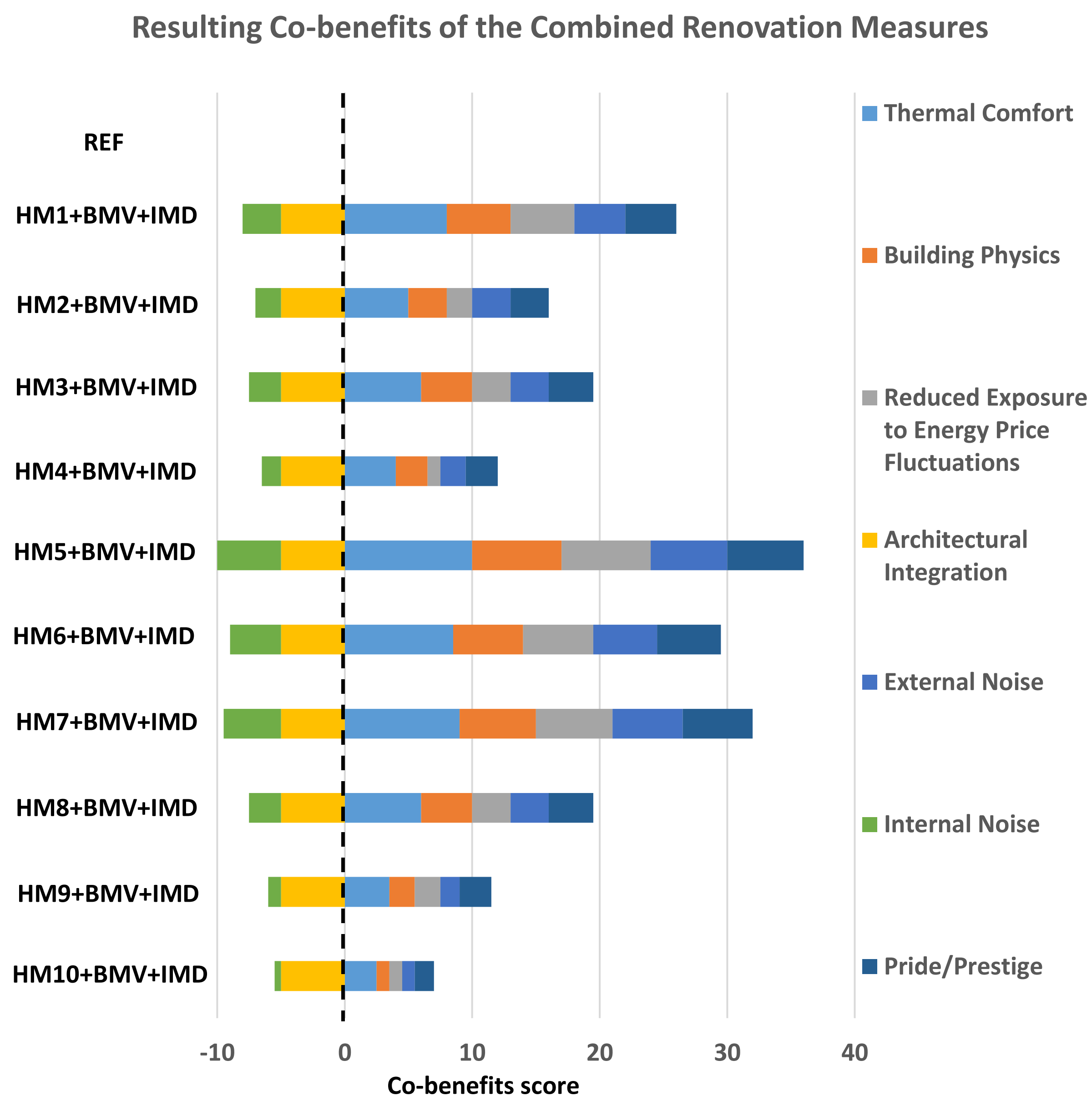


Figure 6.20. Resulting co-benefits of the combined renovation measures.

The results presented in Figure 6.20 shows that measures that progressively improve the quality and the thermal properties of the building envelope will yield several positive co-benefits. The best solution in terms of co-benefits are the renovation measures referred to as *HM5+BMV+IMD* and *HM7+BMV+IMD* which obtain a positive score of 26 and 22.5, respectively. These two combined renovation measures includes the most comprehensive renovation measures of the building envelope. However, they are also the most expensive packages in terms of initial investment costs. Furthermore, it is also clear that the windows replacement measure entails significant co-benefits, consequently it should be considered as a valid renovation alternative in spite of its high investment cost.

7. Discussion and Conclusions

7.1 Legal aids that may increase the cost-effectiveness of the renovation measures

Considering the results obtained in the previous chapters, it is clear that the considered evaluation period has a crucial role in establishing the most financially beneficial package of renovation measures. The obtained results for the life cycle costs indicates that the extensive combined renovation measures are most profitable from a long-term perspective. On the other hand, the combined renovation measures will yield financial losses compared to the reference case during the first 30 years after their implementation. However, there are a number of options for the private investors to reduce the initial investment costs of the renovation measures and also accelerate the payback time of the investment.

The first option is to raise the monthly housing rent after the entire renovation is completed. This option is a very common measure to apply after a major renovation project similar to the ones studied within this project. However, in order to raise the monthly housing rent after the renovation project is completed then the energy related renovation measures should preferably be combined with so-called "*standard raising measures*" such as e.g. refurbishment of the bathrooms in the building. Otherwise, the tenant association (Swedish: Hyresgästföreningen) might legally prevent the increase of the monthly housing rent. Nevertheless, this measure may have devastating consequences for the tenants in the building who may be forced to leave their homes due to the increased monthly housing rent. From a moral perspective, it is thus important that the building owners limit the increase of the monthly housing rent to a reasonable level after the implementation of the renovation measures. This is particularly important for the studied reference building in this project since it is located in an area in Malmö with socioeconomic difficulties. Thus, it is highly likely that some of the tenants in the building are sensitive to sudden price fluctuations of their monthly expenses. From the investor's perspective, an increased monthly housing rent will result in a faster payback time of the investment costs related to the renovation measures. The payback time is thus determined on the increase, in percentage, of the monthly housing rent after the implementation of the renovation measures.

The second option for the private investors to make the combined renovation measures more cost-effective is to apply for a specific governmental subsidy called *Financial Support for renovations and energy efficient measures in certain neighborhoods*. This specific governmental subsidy allows the private investors to apply for financial contributions in projects involving energy efficient renovation measures of buildings located in areas with socioeconomic difficulties. This subsidy was introduced by the Swedish government in order to counter radical increases of the monthly housing rent after major renovation projects and at the same time facilitate the private investors to invest in energy efficient renovation measures. However, there are a number of criteria that must be met in order for the application to be approved. These criteria include e.g. that the total annual energy consumption in the building must at least be 130 kWh/ (A_{TEMP}·Year) or worse and the building must be located in an area which is considered as an area with socioeconomic difficulties. Both of these criteria are met for the studied reference building in this project according to the Swedish regulation referred to as *2016:837* (Boverket (a), 2017). The maximum financial contribution paid by the Swedish government per renovation project is 1000 SEK/A_{TEMP}. If the renovation measures studied within this project were to receive the maximum amount of the governmental subsidy then 2 949 000 SEK out of the initial investment costs for the studied renovation measures would be saved. This contribution would lead to a significant impact on the cost-effectiveness of the renovation measures. The resulting impact on the payback time of the renovation measures when implementing governmental subsidies combined with an increased housing rent is presented in Figure 7.1 below. (Boverket (b), 2017)

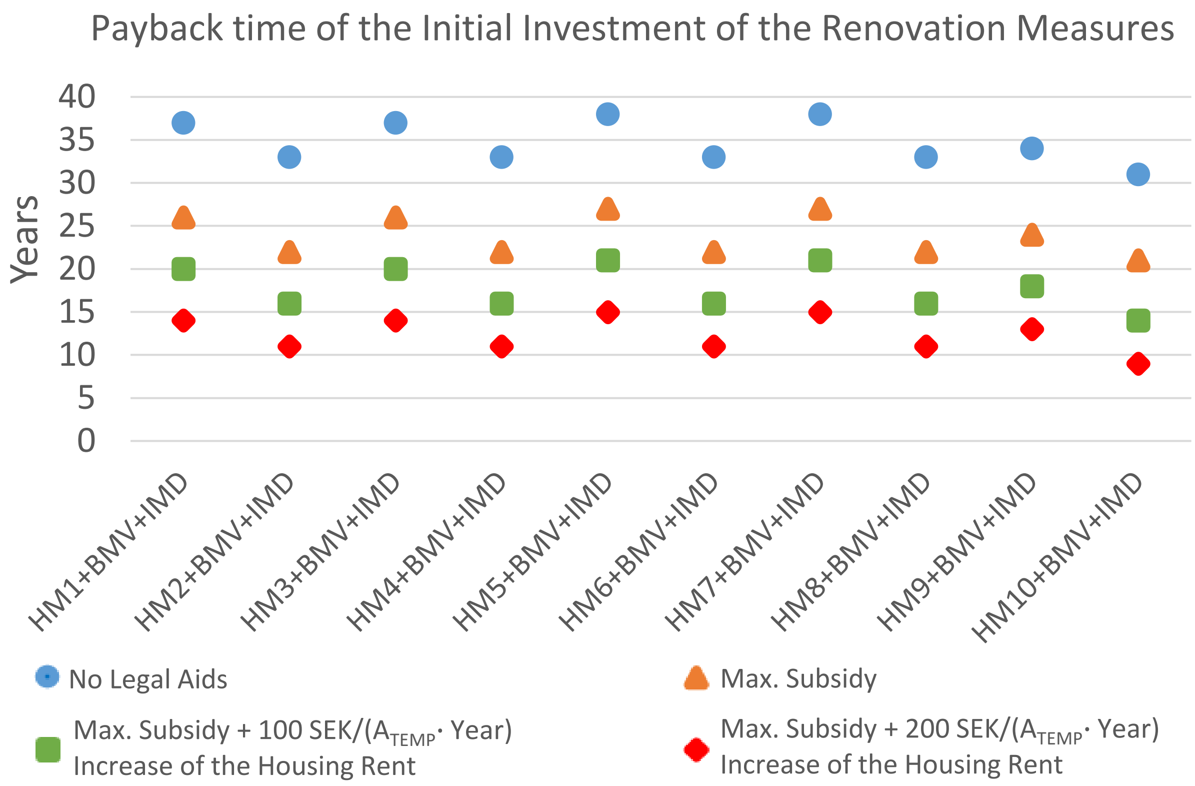


Figure 7.1. Payback time of the initial investment of the renovation measures.

Figure 7.1 above concludes that there is a possibility to make the combined renovation measures cost-effective during the first 10 years after their implementation by reducing the initial investment costs through governmental subventions and by raising the monthly housing rent after the renovation project has ended. However, these legal aids are highly uncertain measures for the private investors to rely upon since there is always a possibility that the application for the governmental subventions is denied and that the tenant association appeal against the proposed increase of the monthly housing rent. Moreover, since many assumptions of the input data were made throughout the life cycle cost assessment, it is not possible to provide a general answer as regard to the choice of the most cost-effective solution when retrofitting buildings with features similar to the studied reference building. Many parameters that have been given fixed values in the life cycle cost calculations may have a decisive influence on the final results of the life cycle costs. These values can only be estimated properly through a thorough sensitive analysis. For instance, a study concerning energy efficiency renovation measures for a Swedish residential building (Bonakdar F., Gustavsson L., & Dodoo A., 2013) points out that different assumption on parameters such as the real interest rate, the energy prices and its corresponding annual price growth rates over time may completely change the sustainability and cost-effectiveness of the renovation measures. Moreover, the study concluded that by assuming a discount interest rate of 3% instead of 6%, improved the cost-effectiveness of their studied energy renovation by 44 to 51 percent (depending on the annual price growth rate of the energy prices) considering an evaluation period of 50 years. This example illustrates the uncertainty of a life cycle cost analysis since it is impossible to properly determine future trends of the interest rates and the energy prices.

7.2 General Discussion and Conclusions

In general, if one focus only on the economic aspect, the most convenient solutions turns out to be strongly dependent on the assumed evaluation period. When a short evaluation period is considered the choice is oriented towards minor renovation solutions, while progressively extending the evaluation period will make the deeper renovation measures more profitable. This balance is dependent on the time it takes to pay off the high investment costs of the renovation measures with the saved energy costs that the measures entails. Real estate owners may, however, be reluctant to invest in the combined renovation measures because of the high investment costs and relatively long payback time related to the renovation measures. Nevertheless, if the positive co-benefits are taken into consideration then the choice become more subjective: some investors may be willing to carry out a major renovation, even neglecting the economic aspect, in order to improve the thermal comfort and indoor air quality of the building, or to be able to increase the financial market value of the property. In that case, the combined renovation represents the best alternative as it entails the most positive co-benefits.

Furthermore, it may be worth investing money in buildings that are current located in suburban areas from a long-term financial perspective and from a social perspective as well. The urban areas are currently expanding quicker than ever before due to the global urbanization. The effect of the urbanization in Sweden, among other things, is that there is currently an ongoing housing crisis, which is especially noticeable in the larger urban areas in Sweden. Thus, it is important from a social perspective that the buildings that were built during the *Million Program* are not demolished by the building owners but rather refurbished and energy-optimized. From a long-term financial perspective it may be worth investing in the suburban areas due to the ongoing expansion of the urban areas in Sweden. The expansion of the urban areas will lead to that the city areas which are currently located on the outskirts of the city will eventually, over time, become more centralized. This effect will, additionally, lead to that a new category of tenants will be interested in the building and in the city area as well. Moreover, the development of the urban areas in Malmö has escalated tremendously during the past 20 years much thanks to the bridge connection between Malmö and Copenhagen and the new metro system. City areas in Malmö like *Hyllie* and *Västra Hamnen* are good examples of areas that have gone through a significant positive development during the past couple of years. However, the potential development of the different city districts are completely dependent on the long-term financial investments of the municipality. Nevertheless, there is still a great potential for the building owners to make long-term financial profits by investing in energy efficient and environmentally friendly renovation measures for buildings located in suburban areas with socioeconomic difficulties. (SCB (d), 2015; Malmö Stad (b), 2010)

If the economic aspect is not taken into consideration, then the results show that the combined renovation measures of the building envelope, the new ventilation system and the IMD of the domestic hot water are the best alternatives to choice since these measures entails greater savings in terms of annual energy use, CO_2 emissions and primary energy use from a “Cradle-to-grave” scenario. Furthermore, the results of the energy simulations show that there are four kinds of renovation solutions that will result in the fulfillment of the energy requirements established by Boverket. The most cost-effective renovation measure that fulfills the energy requirements is the combined renovation measure referred to as *HM6+BMV+IMD*. This renovation package included window replacement as well as the most comprehensive additional insulation of the building envelope except for additionally added insulation of the basement walls which were not included in this package. Thus, this renovation measure is the most suitable option for the private investors to invest in from a financial perspective. However, the combined renovation measure referred to as *HM1+BMV+IMD* is the most suitable option to choose considering a long-term environmental perspective. The results from the energy simulations and the life cycle cost calculations indicates that the renovation measure that involves externally added insulation to the basement walls is not financially beneficial neither from a short-term perspective nor a long-term perspective. The initial investment cost of this specific measure is rather high while the annual energy savings that the measure entails are relatively low. Thus, a conclusion can be drawn that the renovation measure involving externally added insulation to the basement walls is not a good alternative for the studied reference building from an energy optimizing and financial perspective. On the other hand, the renovation measure that involves window replacement where new low-e windows are implemented in the building is an essential measure to implement both from an energy perspective, but also from an overall aesthetic perspective. The energy result shows that the window replacement measure has the greatest impact on the annual energy demand of the reference building out of all studied renovation measures. From an aesthetic point of view, a conclusion can be drawn that the new windows will significantly improve the overall appearance of the studied reference building since the existing windows are in a rather poor condition. Thus, the window replacement measure is not only an important measure to implement in order to improve the thermal properties and air tightness of the building envelope but it is also a highly necessary renovation measure to implement from an "anyway" renovation perspective.

Furthermore, although the results from the energy simulations showed that the annual energy use in the studied reference building can be reduced by up to 57 % if the combined renovation measures are implemented, there are still specific areas on the building envelope where the air leakage and the thermal properties remains unchanged after the implementation. These areas include the connection between the external walls and the balconies as well as the ground slab were the linear thermal bridges and the overall thermal properties remains the same after the implementation of the renovation measures. These unchanged thermal properties on the building envelope was a big contributing factor to the comprehensive renovation measures used for the other areas on the building envelope in order to fulfill the energy requirements established by Boverket. One can discuss whether it is necessary to keep the glazed-in balconies on the building envelope or not. However, a conclusion was made relatively early in the project that the balconies provides an important co-benefit for the tenants in the building and that a demolition of the balconies would not have been financially beneficial for the private investor.

The results of the life cycle assessments conducted within this project indicate that renovation measures that significantly reduces the annual energy need of district heating will also significantly reduce the overall CO_2 emissions and primary energy consumption of the building. The most significant reduction of the CO_2 emissions and the primary energy consumption of the building is accomplished by the most comprehensive renovation measures, where the reduced dependence of district heating is the most contributing factor to the overall reduction. The results of the life cycle assessments indicates that the implementation of the combined renovation measures may potentially reduce the CO_2 emissions and the total primary energy consumption in the building with 45% and 25%, respectively. Thus, the energy carrier and the overall energy consumption in the building are two decisive factors for how environmentally friendly the building will be over time. This conclusion may be an important factor of the private investors' decision-making since a reduction in environmental impact of a building generally increases the market value of the property as well as the pride and prestige of the tenants living in the building. Additionally, the increased pride and prestige of the tenants in the building generally increases the acceptance of increased monthly housing rents after the implementation of the renovation measures. From a social perspective, it is also important to reduce the overall energy demand and the environmental impact of the Swedish building stock in order to fulfill the climate agreements such as the *EU 2020 Directive* and the *Kyoto protocol* which the Swedish government has agreed upon.

Finally, this study shows that it is possible to implement cost-effective and energy efficient renovation measures that successfully reduces the environmental impacts of a building constructed during the *Million Program* by using the methodology established by IEA EBC Annex 56. Additionally, the study shows that it is possible to reduce the annual energy demand of a high energy-consuming building down to a level where the current energy requirements established by Boverket are fulfilled. Nevertheless, as many assumptions were made throughout the entire study and the fact that all the simulations were carried out under controlled conditions, it is not possible to provide a general answer as regard to the choice of the most suitable solution when retrofitting buildings with features similar to the studied reference building. Many parameters such as e.g. the effects of the implemented IMD of the domestic hot water and the internal thermal gains have been assumed based on recommended values from previously conducted scientific studies. These assumptions might have a decisive influence on the final results, which can only be determined through a thorough sensitive analysis after the implementation of the renovation measures. Thus, this report should only be considered as a general guide for cost-effective and energy-efficient renovation measures suitable for multi-family apartment buildings in southern Sweden constructed during the *Million Program* and the approximate results expected when implementing these measures.

8. Further Research

There are a number of measures that could have been further improved in this study. First of all, a sensitive analysis aimed to define the influence of some of the assumed input data throughout the study can be performed in order to improve the accuracy of the final results. This sensitivity analysis should, for example, be performed for the airtightness in the building, the influence of the tenants' behavior, the existing exhaust air flow rates of the ventilation system etc. Furthermore, a moisture safety analysis should be performed in order to ensure that the renovation measures regarding modifications to the building envelope would not lead to disadvantageous moisture conditions in the building materials and hence affect the thermal properties of the materials as well as the tenants' comfort due to potential mold problems. Additionally, a more detailed analysis can also be carried out for the proposed ventilation system where e.g. the new ventilation ducts are presented in detail and the corresponding pressure losses in the entire system are thoroughly calculated. A sensitive analysis regarding the effects on the specific energy use of the implementation of the IMD of the domestic hot water should also be performed in order to obtain more accurate results. Moreover, different renovation solutions such as e.g. daylight harvesting solutions, solutions for the electrical lighting systems, exhaust air heat pumps and renovation measures concerning building integrated energy production systems such as e.g. photovoltaic panels could be analyzed and combined with the assessments conducted within this project. Finally, the possibility to implement different control systems (Swedish: Styr-, regler- och övervakningssystem) that include e.g. forecast control and power limitation could also be analyzed and combined with the assessments conducted within this project.

References

Allen, E & Iano, J. 2008. *Fundamentals of Building Construction: Materials and Methods.* 5th ed. Hoboken, New Jersey: John Wiley & Sons.

Andersson, H., 1986. *Svensk Arkitektur: Ritningar 1640-1970.* 1st ed. *page 242.* Stockholm: Byggförlaget. ISBN: 9789185194674

Autodesk, 2012. *Natural Ventilation.* [Online]
Available at: https://sustainabilityworkshop.autodesk.com/buildings/natural-ventilation
[Accessed 19 February 2017].

Autodesk, 2015. *Glazing Properties.* [Online]
Available at: https://sustainabilityworkshop.autodesk.com/buildings/glazing-properties
[Accessed 2017 February 2017].

Blomsterberg, Å & Nilsson, R. 2014. *Energi- och miljörenovering av miljonprogramshus – Backa röd I Göteborg.* [Online] Available at:
http://www.sundolitt.se/download.aspx?object_id=DFCE3D9B961A4AB0B7D1A46A132CA632.pdf
[Accessed 19 March 2017].

Bonakdar F., Gustavsson L., & Dodoo A. (2013). Implications of energy efficiency renovation measures for a Swedish residential building on cost, primary energy use and carbon dioxide emission. Växjö (Sweden): Linnaeus University.

Bond, A., 2017. *Sales Person at FläktWoods* [Interview] (3 March 2017).

Boverket. 2000. *Har du legionellabakterier i dina vattenledningar?.* [Online]
http://www.boverket.se/globalassets/publikationer/dokument/2000/har_du_legionellabakterier_i_dina_vattenledningar.pdf
[Accessed 5 March 2017].

Boverket, 2014. *Under miljonprogrammet byggdes en miljon bostäder.* [Online]
Available at: http://www.boverket.se/sv/samhallsplanering/stadsutveckling/miljonprogrammet/
[Accessed 30 January 2016]. Permission to publish the illustration image in Figure 1.2 by: Anna Andersson at Boverket.

Boverket, 2016. *BBR 24 – Boverkets byggregler (BFS 2016:13).* [Online]
Available at:
http://www.boverket.se/contentassets/a9a584aa0e564c8998d079d752f6b76d/konsoliderad_bbr_2011-6.pdf
[Accessed 15 February 2017].

Boverket (a). 2017. *Sök socioekonomiskt stöd för ditt bostadsområde.* [Online] Available at: http://www.boverket.se/sv/bidrag--garantier/alla-bidrag-stod-och-garantier/socioekonomiskt-stod/sok-stod-bostadsomraden/ [Accessed 19 April 2017].

Boverket (b). 2017. *Information om stöd till renovering och energieffektivisering i vissa bostadsområden.* [Online] Available at:
http://www.boverket.se/contentassets/72f5fcea8afc41fe84a10aed50bf45ed/informationsbroschyr-om-stod-till-renovering-och-energieffektivisering-i-vissa-bostadsomraden.pdf
[Accessed 19 April 2017]

Building Energy Software Tools. 2015. *IDA Indoor Climate And Energy.* [Online]
Available at: http://www.buildingenergysoftwaretools.com/software/ida-indoor-climate-and-energy
[Accessed 28 February 2017].

Buildings Performance Institute Europe (BPIE). 2013. *A Guide To Developing Strategies For Building Energy Renovation.* [Online]
Available at: http://bpie.eu/documents/BPIE/Developing_Building_Renovation_Strategies.pdf
[Accessed 27 January 2017].

Building Physics. 2013. *HEAT2 - Heat transfer in two dimensions.* [Online]
Available at: http://www.buildingphysics.com/index-filer/heat2.htm
[Accessed 1 March 2017].

Bülow-Hübe, H. 2010. *Utformning av klimatskärm.* Lund (Sweden): Lund University – Facility for Energy and Building Design. Permission to publish illustration image in Figure 3.1 by: Helena Bülow-Hübe at Fojab Architects.

Celind, J., 2017. *Technical Data and General Information regarding PROFESSORN 11* [Interview] (19 January 2017).

Eco-bat. 2016. *ECO-BAT 4.0.* [Online]
Available at: http://www.eco-bat.ch/index.php?option=com_content&view=article&id=64&Itemid=61&lang=en
[Accessed 1 March 2017].

Electrolux, 2009. *Hygrotork - HT400E.* [Online]
Available at:
http://tools.professional.electrolux.com/Mirror/Doc/ELS/PDS/PS_438906840_HT%20400%20E_SE.pdf. [Accessed 21 February 2017].

Elitfönster. 2017. *Inåtgående 3-glas fönster – Sidhängt 3-glas, Underkantshängt 3-glas.* [Online]
Available at: http://www.elitfonster.se/images/20/13248/Harmoni-ETIL-AL_ETIUL-AL.pdf.
[Accessed 16 March 2017].

Energiföretagen. 2016. *Fjärrvärmepriser för flerbostadshus 2015-2016.* [Online] Available at:
https://www.energiforetagen.se/link/f0d2c06d19d74eb9aedff1633a619fbd.aspx?v=nonce-3325f652-f57a-4ecc-b0b8-75ed51782e4c. [Accessed 18 March 2017].

Energikontoret Skåne. 2010. *Att bygga energieffektivt – fakta och råd om energi för dig som går i nybyggnadstankar.* [Online] Available at:
https://energiradgivningen.se/system/tdf/att_bygga_energieffektivt.pdf?file=1.
[Accessed 18 March 2017].

Energimyndigheten. 2003. *Individuell Värmemätning I Svenska Flerbostadshus – En Lägesrapport.*
[Online] Available at:
http://hotpot.se/hsb-slutrapport.pdf
[Accessed 11 March 2017].

Energimyndigheten. 2009. *Att tilläggsisolera hus – fakta, fördelar och fallgropar.* [Online]
Available at: https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=2829
[Accessed 3 February 2017]. Permission to publish illustration image in Figure 3.2 by: Per Bengtsson – Responsible Illustrator at Grön idé.

Energimyndigheten. 2012. *Vattenanvändning i hushåll - med schabloner och mätningar i fokus.*
[Online]
https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=2591
[Accessed 9 March 2017].

Energimyndigheten. 2015. *Energiläget 2015.* [Online]
Available at:
https://www.energimyndigheten.se/contentassets/50a0c7046ce54aa88e0151796950ba0a/energilaget-2015_webb.pdf
[Accessed 3 February 2017]. Permission to publish illustration image in Figure 1.1 by: Jessicka Strandell – Communicator at Energimyndigheten.

E.ON. 2016. *Miljövärden 2016 – Lokala miljövärden för Malmö-Burlöv.* [Online] Available at: https://www.eon.se/content/dam/eon-se/swe-documents/swe-eon-miljovarden-2016.xlsm [Accessed 19 March 2017].

European Commission (a), 2016. *Directive of the European Parliament and the on the Council on the promotion of the use of energy from renewable sources (recast).* [Online] Available at: https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf [Accessed 1 February 2017].

European Commission (b). 2016. *Proposal For A Directive Of The European Parliament And Of The Council Amending Directive 2010/31/EU On The Energy Performance Of Buildings.* [Online] Available at: https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v10.pdf [Accessed 13 February 2017].

European Commission (c). 2016. *Energy Efficiency Directive.* [Online] Available at: http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive [Accessed 28 January 2017].

European Commission (d). 2016. *Buildings Under The EED.* [Online] Available at: http://ec.europa.eu/energy/en/topics/energy-efficiency-directive/buildings-under-eed [Accessed 27 January 2017].

European Environment Agency (EEA), 2016. *Primary energy consumption by fuel.* [Online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/primary-energy-consumption-by-fuel-6/assessment-1 [Accessed 27 January 2017].

Eurostat, 2014. *Consumption of Energy.* [Online] Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy [Accessed 1 February 2017].

Eurostat (a), 2016. *Gross inland energy consumption per capita.* [Online] Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Gross_inland_energy_consumption_per_capita,1990-1998-2006-2014,_toe_per_capita_new.png [Accessed 1 February 2017].

Eurostat (b), 2016. *Europe 2020 indicators - climate change and energy.* [Online]
Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Europe_2020_indicators_-_climate_change_and_energy
[Accessed 1 February 2017].

EQUA. 2016. *IDA Indoor Climate And Energy.* [Online]
Available at: http://www.equa.se/en/ida-ice
[Accessed 28 February 2017].

Formas Fokuserar, 2012. *Miljonprogrammet - Utveckla eller avveckla?.* Stockholm: Edita AB .
ISBN 978-91-540-6069-6

Green Building Advisor, 2014. *Exhaust Ventilation.* [Online]
Available at: http://www.greenbuildingadvisor.com/green-basics/exhaust-ventilation
[Accessed 20 February 2017]

Grahn, A., 2005. *Hyreshöjning vid renovering - En utredning av hyresvärdens möjligheter,* Luleå: Luleå Tekniska Högskola.

Hitta.se, 2017. *Map Viewer: Professorsgatan 9, Malmö.* [Online]
Available at:
https://www.hitta.se/kartan!~55.56976,13.01859,17.6495248460733z/tr!i=H0hvQ4Ja/search!st=plc!q=Professorsgatan%208%2C%20Malm%C3%B6!b=55.56921:13.01585,55.57031:13.02132!t=combined/tileLayer!l=1. [Accessed 20 February 2017].

IEA Annex 56. 2014. *Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation.* [Online]
Available at: http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf
[Accessed 22 January 2017].

IEA EBC. 2015. *Co-benefits of energy related building renovation,* Braga (Portugal): IEA - Energy in Buildings and Communities Programme .

International Energy Agency (IEA). (2013). *Transition to sustainable buildings: Strategies and opportunities to 2050 / International Energy Agency*. Paris: OECD/IEA. Available at:
http://www.iea.org/publications/freepublications/publication/Building2013_free.pdf
[Accessed 2 March 2017].

International Energy Agency (IEA). 2014. *Energy Indicators For Year 2014.* [Online]
Available at:
http://www.iea.org/statistics/statisticssearch/report/?year=2014&country=SWEDEN&product=Balances
[Accessed 20 January 2017].

Jansson T, & Persson P. 1962. *Original façade and floor plan drawings of PROFESSORN 11.* [Online]
Gathered from: Malmö City Archives. Permission to pubilsh the illustration images in Figure 5.9 by: Jonas Larsson & Ivan Bosnjak at Stena Fastigheter (property owner)

Kingspan. 2016. *Kooltherm K5 Fasadisolering – Utvändig Fasadisolering* [Online]
Available at: http://www.kingspaninsulation.se/getattachment/0da21055-3ab3-404b-86be-693b10adbb0c/Kooltherm-K5-Fasadisolering.aspx?disposition=attachment
[Accessed 16 March 2017]. Permission to publish illustration image in Figure 5.10 by: David Albinsson – Employee at Kingspan Sweden.

Kääntä, P., 2013. *Renoveringen av miljonprogrammet.* 1st ed. Stockholm: Svensk Byggtjänst.

Lasher, W. (2008). *Practical financial management*. Page 442-446. Mason, Ohio: Thomson South-Western. ISBN: 0-324-42262-8.

Lund University (EBD, Faculty of Engineering). 2016. *IEA EBC Annex 56.* [Online]
Available at: http://www.ebd.lth.se/english/research/ongoing-research-projects/iea-ebc-annex-56/
[Accessed 20 January 2017].

Malmö Stad (a), 2017. *Graddagar för uppvärmning.* [Online]
Available at: http://miljobarometern.malmo.se/klimat/klimat-och-vaderstatistik/graddagar-for-uppvarmning/
[Accessed 20 February 2017].

Malmö Stad (b), 2010. *Så förtätar vi Malmö.* [Online]
Available at: http://malmo.se/download/18.1c002f7b12a6486c372800012053/Fortatning-Dialog+PM.pdf
[Accessed 22 February 2017].

Manuall, 2012. *Electrolux W365H Tvättmaskin.* [Online]
Available at: http://manuall.se/electrolux-w365h-tvattmaskin/
[Accessed 16 February 2017].

Power Knot. 2009. *COPs, EERs, and SEERs - How Efficient is Your Air Conditioning System?.* [Online]
Available at: http://www.powerknot.com/how-efficient-is-your-air-conditioning-system.html
[Accessed 18 February 2017].

Regeringskansliet, 2008. *Regeringens proposition 2008/09:162 : En sammanhållen klimat- och energipolitik – Klimat.* [Online]
Available at: http://www.regeringen.se/contentassets/cf41d449d2a047049d7a34f0e23539ee/en-sammanhallen-klimat--och-energipolitik---klimat-prop.-200809162
[Accessed 28 January 2017].

Rockwool. 2013. *Environmental Product Declaration – Rockwool Isolering.* [Online]
Available at: http://epd-norge.no/getfile.php/EPDer/Byggevarer/Isolasjon/NEPD-00131E_rev1_ROCKWOOL-isolering.pdf
[Accessed 16 March 2017].

Rockwool (a). 2017. *HardRock ElementBatts.* [Online]
Available at: http://www.rockwool.se/produkter/hardrock-elementbatts/
[Accessed 16 March 2017].

Rockwool (b). 2017. *Isolering av yttervägg av betong.* [Online]
Available at: http://www.rockwool.se/produkter/vagg/yttervagg/yttervagg-av-betong/#isolering-av-kallarvagg-och-kallargolv. [Accessed 16 March 2017].

Rode, C et al. 2015. *Holistic method for energy renovation of buildings: focus on users involvement.* [Online]
Available at:
http://www.eurac.edu/en/research/technologies/renewableenergy/publications/Documents/EURAC-RenEne_GDegan-CRode-DVettorato-MCastagna_IBPSA-Italy2015.pdf
[Accessed 17 February 2017].

Rörby, M., 1996. *En miljon bostäder.* Stockholm: Arkitektmuseet, 1996 .

SABO. 2015. *Individuell Mätning Och Debitering (IMD).* [Online] Available at: http://www.sabo.se/aktuellt/nyheter_s/2011/jun/Documents/Individuell%20m%C3%A4tning%20och%20debitering%20-%20rekommendation.pdf [Accessed 13 March 2017].

SABO, 2017. *Miljonprogrammet.* [Online]
Available at: http://www.allmannyttan.se/historia/tidslinje/miljonprogrammet/
[Accessed 30 January 2017]

Saint Gobain - ISOVER. 2015. *Nya energihushållningskrav i BBR.* [Online]
http://www.isover.se/news/nya-energihushallningskrav-i-bbr
[Accessed 1 February 2017]. Permission to publish the illustration image in Figure 1.3 by: Katarina Holmström at Saint-Gobain ISOVER

SBC, 2014. *Servicehandbok - T3190/T3190C.* [Online]
Available at:
https://www.sbc.se/Foreninghemsida/Templates/Public/Pages/TinyMCEImageLoader.aspx?DocumentId=144156
[Accessed 17 February 2017].

Schöck Isokorb. 2015. *Thermal Bridging Guide.* [Online]
http://www.schoeck.co.uk/view/5993/Thermal_Bridging_Guide_Schoeck_Isokorb_%5B5993%5D.pdf
[Accessed 14 March 2017].

SEB. 2017. *Historiska bolåneräntor.* [Online] Available at:
https://seb.se/pow/apps/HistoriskaBorantor/villaframe.aspx [Accessed 16 March 2017].

Statistiska Centralbyrån, SCB, (a). 2017. *Inflation I Sverige 1831-2016.* [Online] Available at: http://www.scb.se/contentassets/2c6de261f74c4bd3bb237f63c3031df1/pr0101_2016m12_di_06-07_sv.xls [Accessed 17 March 2017].

Statistiska Centralbyrån, SCB, (b).2016. *Prisutveckling på energi samt leverantörsbyten, fjärde kvartalet 2016*. [Online] Available at:
http://www.scb.se/contentassets/d63c71df083941c4beeebcb1870918e7/en0304_2016k04_sm_en24sm1701.pdf [Accessed 18 March 2017].

Statistiska Centralbyrån, SCB, (c).2007. *Prisutveckling på el och naturgas samt elleverantörsbyten 1:a kvartalet 2007*. [Online] Available at:
http://www.scb.se/statistik/EN/EN0304/2007K01/EN0304_2007K01_SM_EN24SM0701.pdf
[Accessed 18 March 2017].

Statistiska Centralbyrån, SCB, (d).2015. *Dagens urbanisering – inte på landsbygdens bekostnad*. [Online] Available at: http://www.scb.se/sv_/Hitta-statistik/Artiklar/Dagens-urbanisering--inte-pa-landsbygdens-bekostnad/ [Accessed 18 March 2017].

Sustainable Energy Authority of Ireland (SEAI). 2009. *Waste Heat Recovery Potential for HVAC Systems.* [Online]
Available at:
http://www.seai.ie/%E2%80%A6/HVAC%E2%80%A6/Waste_Heat_Recovery_Potential_for_HVAC_%20Systems_Report.pdf [Accessed 10 March 2017].

SVEBY, 2012. *Brukarindata Bostäder - Svebyprogrammet Version 1.0 (2012-10-10).* [Online]
Available at: http://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf
[Accessed 16 February 2017].

Swedish National Testing Institute and Nordtest. 1981. *Energihushållning i byggnad: Provning - utvärdering symposium arrangerat av Swedish National Testing Institute and Nordtest,* Stockholm: Swedish National Testing Institute.

Swedish Standards Institute (a) (SIS), 2007. *Byggnaders termiska egenskaper - Värmegenomgångskoefficienter - Beräkningsmetod (ISO 13789:2007).* [Online]
Available at: http://www.sis.se/byggnadsmaterial-och-byggnader/skydd-av-och-i-byggnader/v%C3%A4rmeisolering/ss-en-iso-137892007
[Accessed 18 February 2017].

Swedish Standards Institute (b) (SIS), 2007. *Köldbryggor i byggnadskonstruktioner - Beräkning av värmeflöden och yttemperaturer - Del 2: Linjära köldbryggor (ISO 10211-2:2001).* [Online]
Available at: http://www.sis.se/byggnadsmaterial-och-byggnader/skydd-av-och-i-byggnader/ss-en-iso-10211-2
[Accessed 14 March 2017]

Swedish Standards Institute (SIS), 2009. *Byggmaterial och produkter - Fukt- och värmetekniska egenskaper - Tabeller med beräkningsvärden och metoder för bestämning av termiska egenskaper för deklarering resp. beräkning - Tekniskt korrigendum 1 (ISO 10456:2007/Cor 1:2009).* [Online]
Available at: http://www.sis.se/byggnadsmaterial-och-byggnader/byggnadsmaterial/allm%C3%A4nt/ss-en-iso-104562007-ac2009
[Accessed 18 February 2017].

Timmermann, C at Scneider Electric. 2014. *Energirenovering av miljonprogrammet.* [Online]
Available at: http://kfsk.se/energikontoretskane/wp-content/uploads/sites/5/2014/12/Charlie-Timmermann-Hur-lonsam-ar-energirenovering.pdf
[Accessed 16 February 2017].

United Nations. 2016. *Towards Low-GHG And Resilient Buildings.* [Online]
Available at:
http://www.globalabc.org/uploads/media/default/0001/01/0d6a71a346ea7e6841b1b29c77eba6d6ae986103.pdf
[Accessed 4 February 2017]

VVS Företagen. 2009. *Renoveringshandboken för hus byggda 1950-75..* 1st ed. Stockholm : Wallén Grafiska AB.

Wall, Boris at Arkitekt Axel Carlsson AB. 1997. *Architectural Facade Drawings of PROFFESORN 11. Drawing Number: A03-61-07.* Gathered from: Malmö City Archives. Permission to publish the illustration image in Figure 4.3 by: Boris Wall (responsible architect) & Ivan Bosnjak & Jonas Larsson at Stena Fastigheter (property owner).

Westin, S. (2011). *"... men vart ska ni då ta vägen?" Ombyggnation ur hyresgästernas perspektiv*. (*...but where then will you reside? The Tenant's Perspective of Renovation*), Institute for Housing and Urban Research, Uppsala University: Uppsala.

Westin, S. (2012). Affärsmässigt boende. Ordfront Magasin, 3rd Edition, 24-25.

Wikells. 2017. *Kalkylprogram - Sektionsdata.* [Online]
http://www.wikells.se/kalkylprogram.aspx
[Accessed 1 March 2017].

Appendix A: Floor layout of all floors in the studied reference building

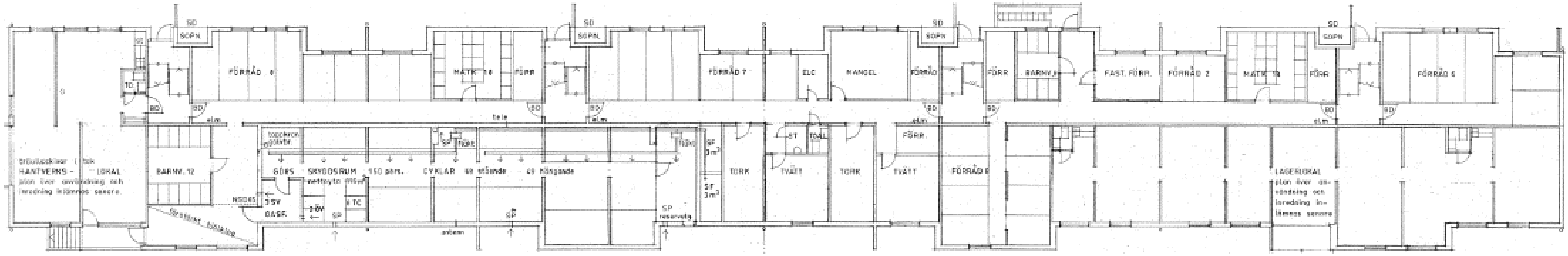


Figure A1. Floor layout of the basement floor of the studied reference building. (Jansson & Persson, 1962)

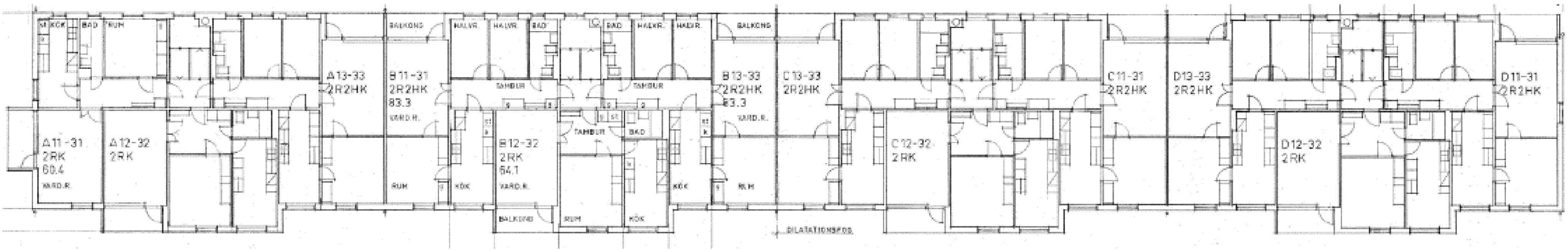


Figure A2. Floor layout of the first to the third floor of the studied reference building. (Jansson & Persson, 1962)

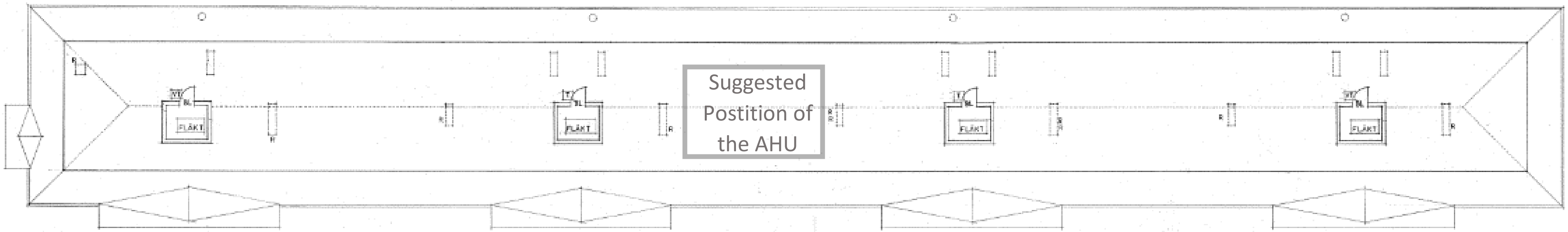


Figure A3. Floor layout of the attic floor of the studied reference building including the four ventilation shafts on the roof where the existing exhaust air fans are located. (Jansson & Persson, 1962)

Note that the plan drawings are presented at an incorrect scale in the figures above. Thus, some deviations from reality might be found in the drawings.

References Appendix A:

Jansson T, & Persson P. 1962. *Original façade and floor plan drawings of PROFESSORN 11.* [Online]
Gathered from: Malmö City Archives. Permission to pubilsh the illustration images presented in Figure A1, A2 and A3 by: Jonas Larsson & Ivan Bosnjak at Stena Fastigheter (property owner)

Appendix B: Resulting linear thermal bridges

Firstly it should be pointed out that the thermal bridges resulting in linear transmittances lower than 0.01 W/(m·K) were not modelled in the energy simulation software since they were considered negligible. Moreover, some of the resulting linear transmittances have a negative value, that is mainly due to the fact that external dimension were considered in the calculation. Furthermore, all the linear thermal bridges were calculated according to the EN ISO 10211-2 standard. (SIS, 2007)

Reference Case:

The linear thermal bridges were calculated by assuming a fixed temperature difference between the internal and external side of the building envelope. This temperature difference was set to 21℃ (0℃ outside, 21℃ inside). From this procedure the thermal coupling coefficient, L_{2D}, was calculated.

<u>Case TB1 – External Walls and Roof:</u>

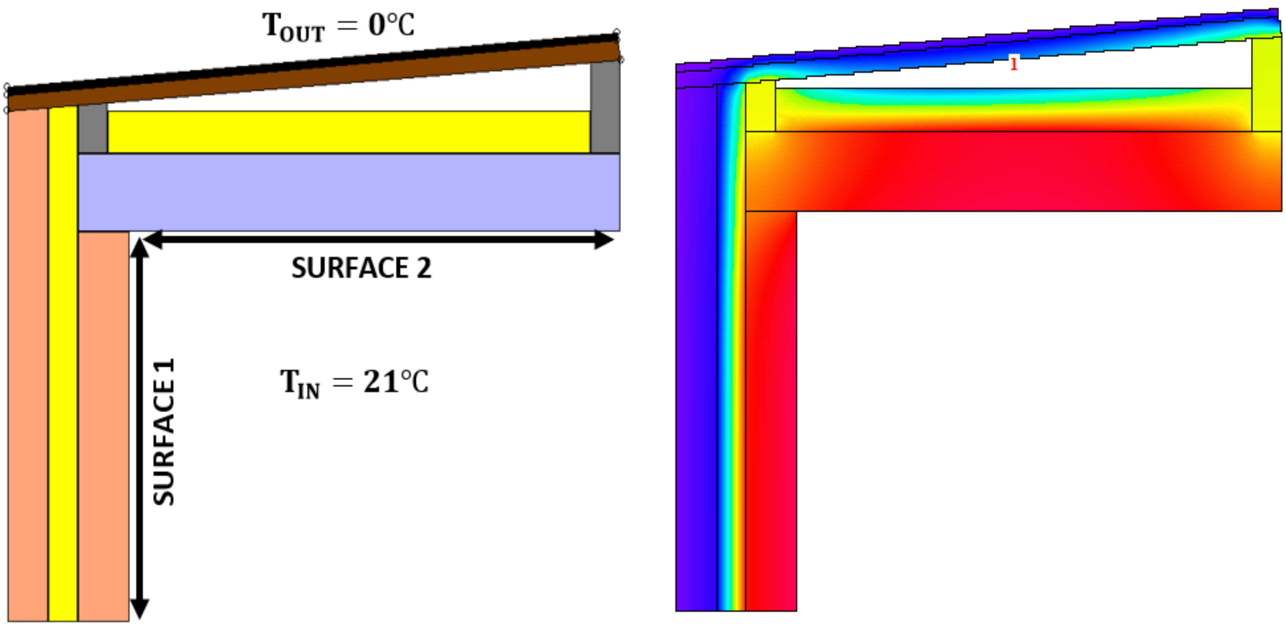


Figure B1. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B1. Resulting values from the HEAT2 simulations.

$\sum Q$	25.164 W/m
U-Value $_{\text{SURFACE 1}}$	0.315 W/m^2·K
U-Value $_{\text{SURFACE 2}}$	0.29 W/m^2·K
L_1	1.2 m
L_2	1.3 m
ΔT	21℃

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{25.164\, W/m}{21°C} \approx 1.198\, W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 1.198 - 0.315 \cdot 1.2 - 0.29 \cdot 1.3 \approx 0.44\, W/(m \cdot K)$$

Case TB2 – External Walls and Balcony:

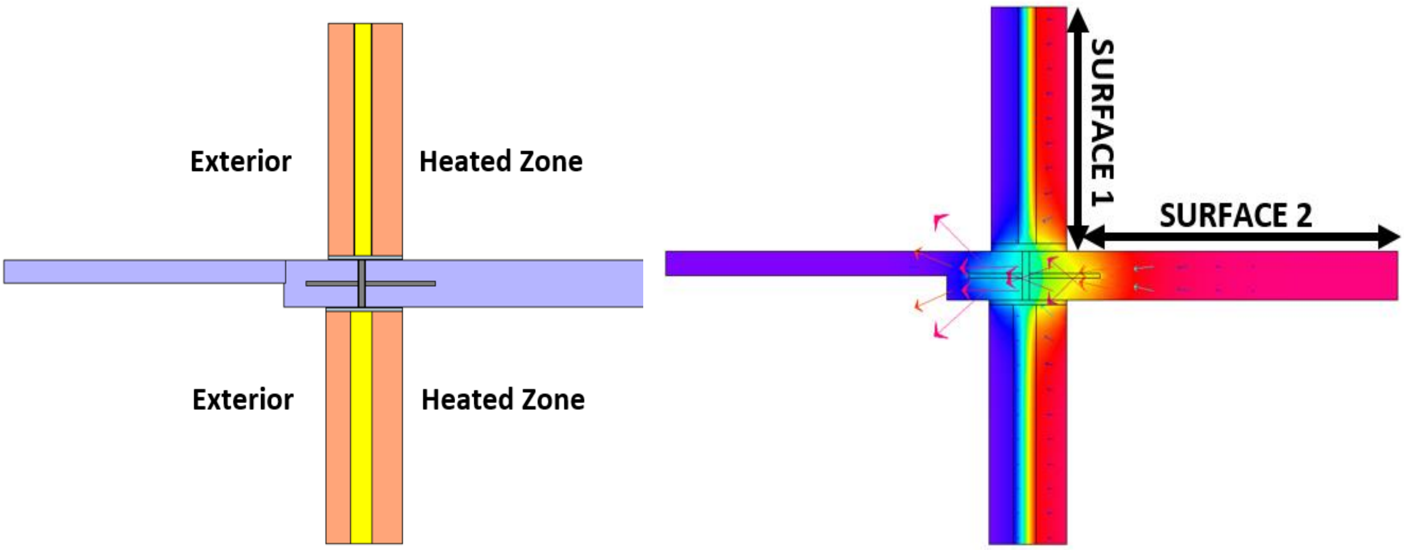


Figure B2. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B2. Resulting values from the HEAT2 simulations.

$\sum Q$	36.875 W/m
U-Value SURFACE 1	0.315 W/m^2·K
U-Value SURFACE 2	0.415 W/m^2·K
L_1	1.0 m
L_2	1.5 m
ΔT	21°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{36.875\, W/m}{21°C} \approx 1.756\, W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 1.756 - 0.315 \cdot 1.0 - 0.415 \cdot 1.5 \ \approx 0.82\, W/(m \cdot K)$$

Case TB3 – External Walls and Basement Ceiling

Unheated Zone to Exterior:

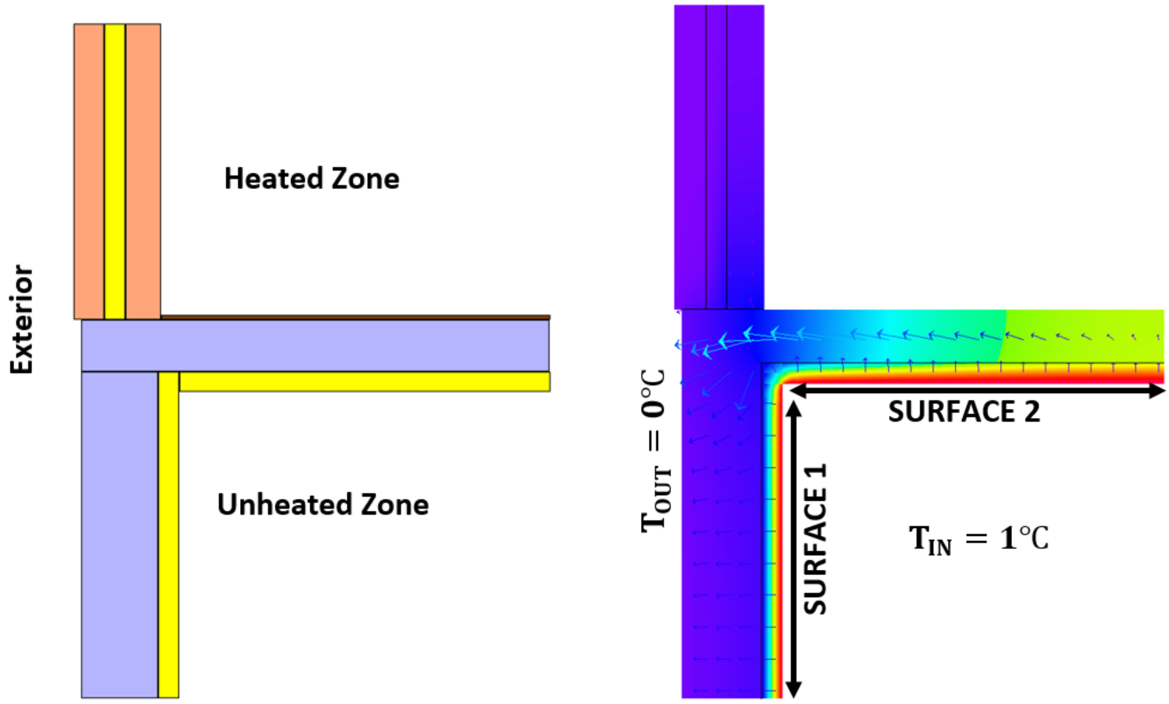


Figure B3. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B3. Resulting values from the HEAT2 simulations.

$\sum Q$	0.938 W/m
U-Value SURFACE 1	0.35 W/m²·K
U-Value SURFACE 2	0.35 W/m²·K
L_1	1.2 m
L_2	1.5 m
ΔT	1°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{0.938\, W/m}{1℃} = 0.938\, W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 0.938 - 0.35 \cdot 1.2 - 0.35 \cdot 1.5 \approx -0.007\ W/(m \cdot K)$$

Heated Zone to Unheated Zone:

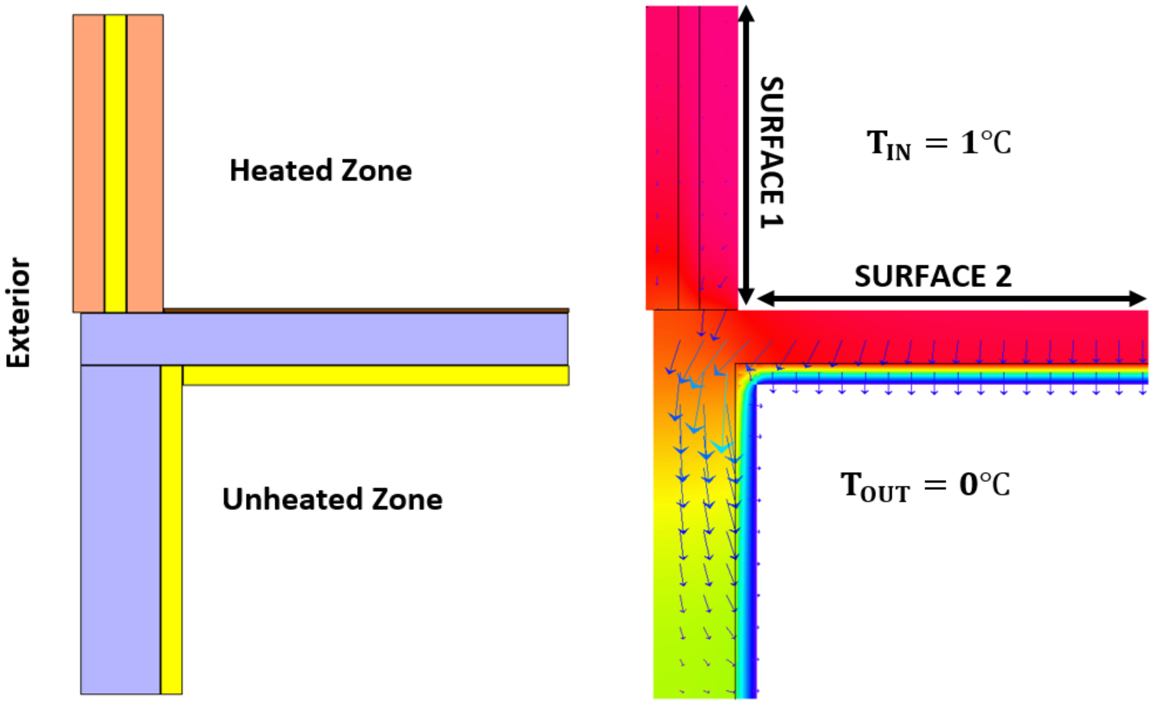


Figure B4. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B4. Resulting values from the HEAT2 simulations.

$\sum Q$	0.925 W/m
U-Value SURFACE 1	0.32 W/m²·K
U-Value SURFACE 2	0.35 W/m²·K
L_1	1.15 m
L_2	1.5 m
ΔT	1°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{0.925\ W/m}{1°C} = 0.925\ W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 0.925 - 0.32 \cdot 1.15 - 0.35 \cdot 1.5 \approx 0.03\ W/(m \cdot K)$$

Heated Zone to Exterior:

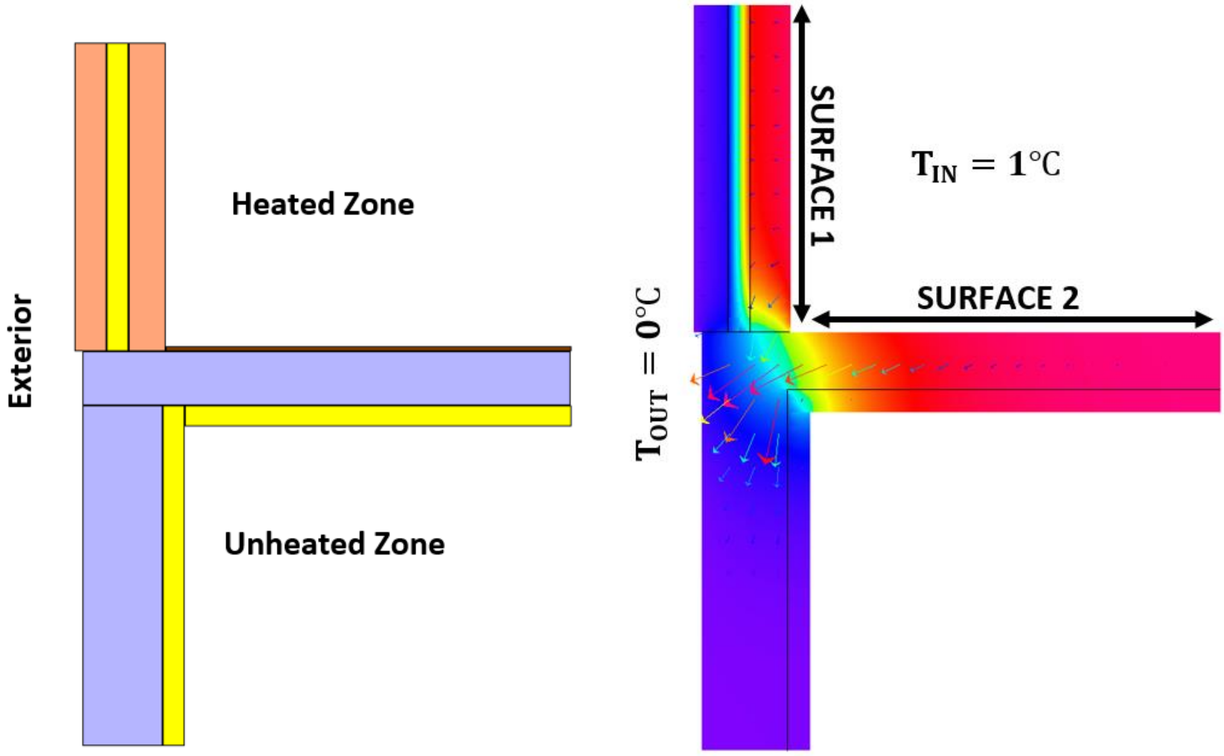


Figure B5. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B5. Resulting values from the HEAT2 simulations.

$\sum Q$	1.1599 W/m
U-Value SURFACE 1	0.32 W/m^2·K
U-Value SURFACE 2	0.35 W/m^2·K
L_1	1.15 m
L_2	1.5 m
ΔT	1°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{1.1599\ W/m}{1°C} = 1.1599\ W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 1.1599 - 0.32 \cdot 1.15 - 0.35 \cdot 1.5 \approx 0.27\, W/(m \cdot K)$$

Case TB4 – External Walls and Floor

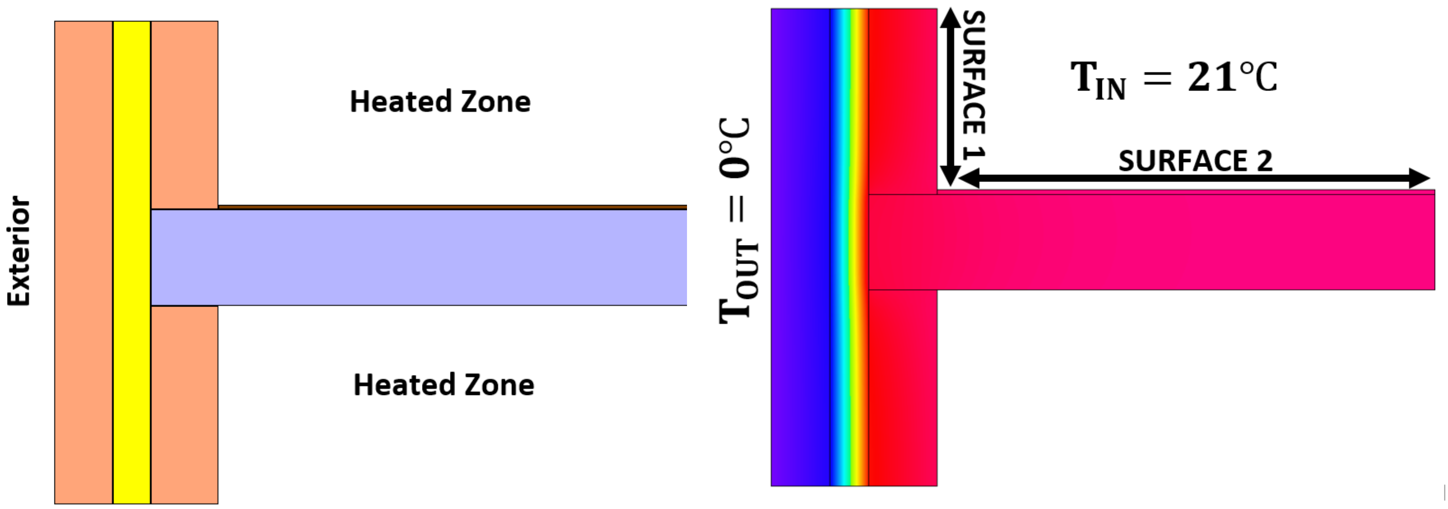


Figure B6. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

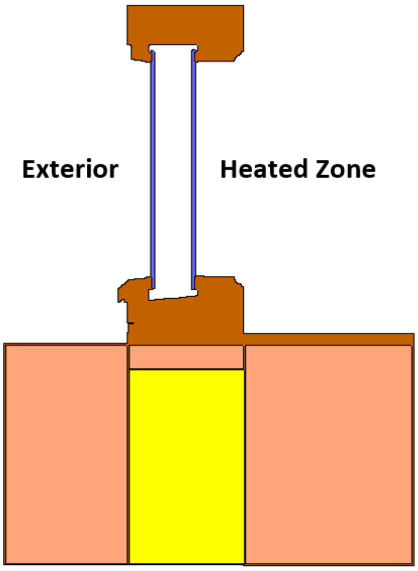
Table B6. Resulting values from the HEAT2 simulations.

$\sum Q$	18.95 W/m
U-Value SURFACE 1	0.32 W/m²·K
U-Value SURFACE 2	0.42 W/m²·K
L_1	0.58 m
L_2	1.5 m
ΔT	21°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{18.95\, W/m}{21°C} \approx 0.90\, W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 0.90 - 0.32 \cdot 0.58 - 0.42 \cdot 1.5 \approx 0.09\, W/(m \cdot K)$$

Case TB4 – External Walls and Windows



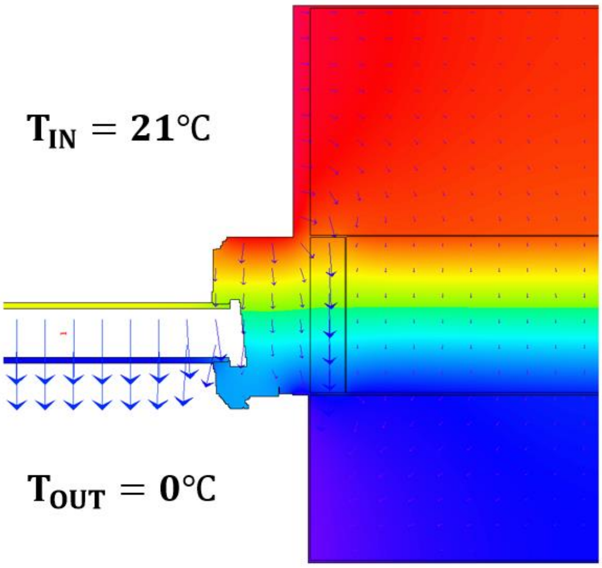


Figure B7. HEAT2 simulation model of the junction (left) and the temperature distribution in the components (right).

Table B7. Resulting values from the HEAT2 simulations.

$\sum Q$	78.453 W/m
U-Value $_{\text{SURFACE 1-WINDOW}}$	2.8 W/m²·K
U-Value $_{\text{SURFACE 2-FRAME}}$	1.6 W/m²·K
L_1	1.1 m
L_2	0.25 m
ΔT	21°C

$$L_{2D} = \frac{\sum Q}{\Delta T} = \frac{78.453\ W/m}{21°C} \approx 3.74\ W/(m \cdot K)$$

$$\Psi = L_{2D} - \sum_{i=1}^{N_i} U_i \cdot L_i = 3.74 - 2.8 \cdot 1.1 - 1.6 \cdot 0.25\ \approx 0.256\ W/(m \cdot K)$$

Renovation measures

All thermal bridges were reassessed for all the measures that foresee changes to the building envelope. In order to limit the extent of the paper the resulting linear thermal bridges have been summarized in Table B8 below. As it can be seen in the table, some thermal bridges related to measures that involve high levels of insulation were not evaluated since their resulting effects would be negligible for the building energy simulations.

Table B8. Results of the linear thermal bridges from the HEAT2 simulations of the combined renovation measures of the building envelope.

Thermal Bridges Ψ [W/mK]		**HM1**	**HM2**	**HM3**	**HM4**	**HM5**	**HM6**	**HM7**	**HM8**	**HM9**	**HM10**
TB1	Heated Zone to Exterior	0.082	0.082	0.120	0.120	0.05	0.05	0.07	0.07	0.05	0.05
TB2	Heated Zone to Exterior	0.820	0.820	0.820	0.820	0.820	0.820	0.820	0.820	0.820	0.820
TB3	Heated Zone to Exterior	0.123	0.212	0.123	0.212	0.07	0.09	0.07	0.102	0.07	0.09
	Heated Zone to Unheated Zone	-	0.02	-	0.02	-	0.01	-	0.01	-	0.01
	Unheated Zone to Exterior	-	-	-	-	-	-	-	-	-	-
TB4	Heated Zone to Exterior	0.02	0.02	0.02	0.02	-	-	-	-	-	-
TB5	Heated Zone to Exterior	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.156	0.156

References Appendix B:

Swedish Standards Institute (SIS), 2007. *Köldbryggor i byggnadskonstruktioner - Beräkning av värmeflöden och yttemperaturer - Del 2: Linjära köldbryggor (ISO 10211-2:2001).* [Online]
Available at: http://www.sis.se/byggnadsmaterial-och-byggnader/skydd-av-och-i-byggnader/ss-en-iso-10211-2
[Accessed 14 March 2017].

Appendix C: Determination of the size of the AHU

Minimum required air flow rate: $0.35\ \mathrm{L/s\ per\ m^2}$

(Hygienic requirements according to the Swedish building regulations)

Ventilated Area: 2949 $\mathrm{m^2}$

Ratio between the supply- and exhaust air flow: 0.95 ($Q_{SUPPLY}/Q_{EXHAUST} = 0.95$)

Chosen air velocity rate for the balanced ventilation system: 2.5 m/s

Calculation of the minimum required air flow rate of the supply air fan:

$$0.35\ \mathrm{L/s} \cdot 2949\ \mathrm{m^2} = 1032\ \mathrm{L/s} = 1.032\ \mathrm{m^3/s}$$

Calculation of the minimum required air flow rate of the exhaust air fan:

$$\frac{1.032\ m^3/s}{0.95} = 1.086\ \mathrm{m^3}/s$$

The ventilation fans shall be able to work properly even in extreme conditions. Thus, an adjustment factor of 1.30 was implemented for both the exhaust- and supply air fans.

New dimensioning supply air flow:

$1.032\ \mathrm{m^3/s} \cdot 1.30 = 1.34\ \mathrm{m^3/s}$ (Corresponds to 0.45 $\mathrm{L/s\ per\ m^2}$for the ventilated area)

New dimensioning exhaust air flow:

$1.086\ \mathrm{m^3}/s \cdot 1.30 = 1.41\ \mathrm{m^3}$/s (Corresponds to 0.48 $\mathrm{L/s\ per\ m^2}$ for the ventilated area)

The air handling unit was chosen from the company *FläktWoods* product catalog based on the dimensioning exhaust air flow (1.41 $\mathrm{m^3}$/s) and the chosen air velocity of the ventilation system (2.5 m/s). The specific AHU that was chosen for this study is called *FläktWoods EQ Master*. The size selection of the air handling unit is presented in Table C1.

Table C1. The chosen AHU size marked in green from FläktWoods quick choice table of the EQ Master AHU. (FläktWoods, 2012)

	Luftflöde m^3/s (m^3/h)				Filter		Utvändigt tvärsnitt		
	Max (3,5 m/s över filter)	Luftkylare (inbyggd luftkylare) fronthastighet, m/s 2,0 m/s	2,5 m/s	3,0 m/s	Filter-kassetter	Kassetter	Agg. bredd, mm	Agg. höjd, mm enkel-våning	Agg. höjd, mm dubbel-våning
005	0,7 (2520)	0,4 (1400)	0,5 (1800)	0,6 (2160)	287x592		800	476	952
008*	1,1 (4032)	0,7 (2520)	0,9 (3240)	1,1 (3960)	792x392		1100	576	1152
009	1,3 (4680)	0,7 (2520)	0,8 (2880)	1,0 (3600)	592x592		800	776	1552
011*	1,6 (5760)	1,0 (3600)	1,3 (4680)	1,5 (5400)	2x492x492		1200	676	1352
014	1,9 (6840)	1,0 (3600)	1,3 (4680)	1,6 (5760)	592x592 287x592		1100	776	1552
018	2,5 (9000)	1,4 (5040)	1,8 (6480)	2,1 (7560)	2x592x592		1400	776	1552
020	2,8 (10080)	1,5 (5400)	1,9 (6840)	2,3 (8280)	592x592 2x287x592 287x287		1100	1076	2152
023	3,3 (11808)	2,2 (7920)	2,7 (9720)	3,3 (11880)	2x592x592 287x592		1700	926	1852
027	3,8 (13680)	2,1 (7560)	2,6 (9360)	3,1 (11160)	2x592x592 2x287x592		1400	1076	2152
032	4,5 (16200)	2,6 (9360)	3,3 (11880)	4,0 (14400)	4x392x792		1800	1026	2052
036	5,0 (18000)	2,6 (9360)	3,3 (11880)	4,0 (14400)	4x592x592		1400	1376	-
041	5,7 (20520)	3,2 (11500)	4,0 (14400)	4,8 (17280)	3x592x592 3x287x592		2000	1076	2152
045	6,3 (22680)	3,4 (12240)	4,2 (15120)	5,0 (18000)	4x592x592 2x287x592		1700	1376	-

Summary:

Size of the AHU (Height x Width): 776mm x 1400mm (Size 18)

Product Name: Fläkt Woods EQ Master

Dimensioning Air Flow Rate: $1.41\ \mathrm{m}^3/\mathrm{s}$

Air Flow Rate Capacity of the chosen AHU: $1.80\ \mathrm{m}^3/\mathrm{s}$ at an air velocity rate of 2.5 m/s

Refereneces Appendix C:

FläktWoods. 2012. *Luftbehandlingsaggregat eQ – Katalog Oktober 2012.* [Online] Available at: http://resources.flaktwoods.com/Perfion/File.aspx?id=4f521c40-fd6b-428e-adb4-4e7012347c17 [Accessed 14 March 2017]. Permission to publish the illustration image in Table C1 by: Magnus Sjärnqvist - Regional Manager Southern Sweden at FläktWoods.

Appendix D: Investment Costs & LCC Results of the Renovation Measures

Table D1. Initial investment costs of the studied renovation measures.

Renovation Measure	Code of Cost Calculation	Materials and Measures Conducted	Material Cost (SEK)	Installation Cost (SEK)
Balanced Mechanical Ventilation System	**A1**	1 pcs FläktWoods EQ Master AHU (Size 18)	122 400 [1]	3234
		180 pcs CTVB-100 Air Diffusers	112 500	15 600
		36 pcs KGEB-100 Adjustable Valves	8892	2318
		36 pcs KGEB-125 Adjustable Valves	9388	2645
		72 pcs Cleaning Hatches	20 448	5674
		72 pcs Silencers	67 716	7687
		468m Circular Ventilation Ducts (100mm)	105 987	58 186
		360m Circular Ventilation Ducts (125mm)	106 452	46 715
		Summary:	**553 783**	**142 059**
		Overhead Expenses Material:	60 905	
		Overhead Expenses Work:	204 184	
		Total Summary:	**960 931**	
Externally Added Insulation to the Basement Wall	**B1**	1330 m^2 Excavation of Surrounding Soil	0	133 000
		1330 m^2 Removal of cold asphalt on basement wall	0	92 250
		1845 m^2 Fiber Cloth applied on the basement wall	19 384	32 221
		1845 m^2 Rockwool Drainage Insulation (100mm)	342 248 [2]	230 625
		1330 m^2 Filling up of Surrounding Soil	0	99 750
		Summary:	**361 632**	**587 846**
		Overhead Expenses Material:	74 287	
		Overhead Expenses Work:	646 631	
		Total Summary:	**1 670 396**	

Externally Added Insulation on the External Walls	**C1**	Scaffolding applied on the external walls	0	204 167
		1683 m² Plaster, Wire Lath and Kooltherm K5 (100mm)	977 621 [3]	802 541
		Summary:	**977 621**	**1 006 708**
		Overhead Expenses Material:	108 967	
		Overhead Expenses Work:	767 845	
		Total Summary:	**2 861 141**	
	C2	Scaffolding applied on the external walls	0	204 167
		1683 m² Plaster, Wire Lath and Kooltherm K5 (80mm)	818 242 [3]	773 541
		Summary:	**818 242**	**977 708**
		Overhead Expenses Material:	91 267	
		Overhead Expenses Work:	521 451	
		Total Summary:	**2 408 668**	
Added Insulation on the Attic Floor	**D1**	983 m² Removal of existing mineral wool insulation	0	12 297
		983 m² HardRock ElementBatts Insulation (400mm)	363 651 [4]	122 875
		Summary:	**363 651**	**135 172**
		Overhead Expenses Material:	36 457	
		Overhead Expenses Work:	175 462	
		Total Summary:	**710 745**	
	D2	983 m² Removal of existing mineral wool insulation	0	12 297
		983 m² HardRock ElementBatts Insulation (300mm)	259 453 [4]	122 875
		Summary:	**259 651**	**135 172**
		Overhead Expenses Material:	26 423	
		Overhead Expenses Work:	175 462	
		Total Summary:	**596 708**	

Window replacement. **New 3-pane Argon filled Low-e Windows**	**E1**	Scaffolding applied on the external walls (No cost. Window replacement is carried out together with the renovation measures of the external walls.)	0	0
		195 pcs Existing Window Removal	0	99 500
		248m Cutting and smoothing of the brick wall	0	39 672
		195 pcs Low-E Argon Filled Windows from Elitfönster	977 500 [5]	277 500
		195 pcs Sealing around the windows	9 750	78 750
		Summary:	**987 250**	**495 422**
		Overhead Expenses Material:	98 725	
		Overhead Expenses Work:	520 716	
		Total Summary:	**2 102 113**	
Installation of the new Smart Water Meters for the IMD	**F1**	New Smart Water Meters for the Domestic Hot Water (Investment: 6000 SEK/Apartment. Installation: 2500 SEK/Apartment.)	216 000 [6]	90 000
		Summary:	216 000	90 000
		Total Summary:	**306 000**	

Input data: *Labor Cost: 250 SEK/Hour (Assumed value including employer fees). All prices were based on the current Swedish work tariff according to the Wikells calculation software as well as the current prices from the producers or resellers of the specific products studied for the combined renovation measures.*

References: *1. (Bond, 2017). 2. (Beijer Byggmaterial (a), 2017) 3. (Buildingmaterials, 2017). 4. (Beijer Byggmaterial (b), 2017). 5. (Beijer Byggmaterial (c), 2017). 6. (Energimyndigheten, 2003)*

Table D2. Result of the annual life cycle costs of the studied renovation measures. Evaluation period: 60 years.

Code of Renovation Measure	Annual Costs of the Initial Investment (SEK/Year) *(Initial Investment · Annuity)*	Annual Maintenance Costs (SEK/Year)	Annual Costs of Electricity (SEK/Year) *(Annual Consumption · Current Prices · Adjustment Factor)*	Annual Costs of District Heating (SEK/Year) *(Annual Consumption · Current Prices · Adjustment Factor)*
REF	-	10 616	60 901	604 610
HM1	259 249	12 976	60 901	377 274
HM2	196 403	9732	60 901	388 206
HM3	255 089	13 271	60 901	386 999
HM4	191 980	8552	60 901	397 130
HM5	276 321	15 040	60 901	363 901
HM6	214 687	13 860	60 901	377 274
HM7	271 898	14 745	60 901	370 790
HM8	209 084	12 386	60 901	380 919
HM9	197 288	9142	60 901	440 084
HM10	134 474	7962	60 901	455 889
HM1+BMV+IMD	306 991	18 579	72 149	228 552
HM2+BMV+IMD	243 882	17 104	69 821	243 141
HM3+BMV+IMD	302 626	17 694	69 046	237 061
HM4+BMV+IMD	239 754	16 809	70 596	253 677
HM5+BMV+IMD	323 800	20 053	72 149	210 721
HM6 +BMV+IMD	261 075	17 989	69 821	224 095
HM7+BMV+IMD	319 672	18 874	69 046	219 232
HM8+BMV+IMD	256 858	15 335	70 596	235 035
HM9+BMV+IMD	244 767	12 386	74 087	285 690
HM10+BMV+IMD	181 953	11 501	74 863	304 331

Input data: *Evaluation Period: 60 years. Real Interest rate: 3.19%. Annual price growth rate district heating: 2.0%. Annual price growth rate facility electricity: 1.7%. Current price district heating: 0.85 SEK/kWh. Current price electricity: 0.88 SEK/kWh. Annuity: 3.76%. Adjustment factor district heating: 1.62. Adjustment factor electricity: 1.49.*

Table D3. Result of the annual life cycle costs of the studied renovation measures. Evaluation period: 30 years.

Code of Renovation Measure	Annual Costs of the Initial Investment (SEK/Year) *(Initial Investment · Annuity)*	Annual Maintenance Costs (SEK/Year)	Annual Costs of Electricity (SEK/Year) *(Annual Consumption · Current Prices · Adjustment Factor)*	Annual Costs of District Heating (SEK/Year) *(Annual Consumption · Current Prices · Adjustment Factor)*
REF	-	13 565	51 409	492 524
HM1	360 368	15 925	51 409	307 332
HM2	273 077	12 681	51 409	316 245
HM3	354 470	16 220	51 409	315 255
HM4	266 885	11 501	51 409	323 508
HM5	383 960	17 989	51 409	296439
HM6	296 669	16 809	51 409	307 332
HM7	378 062	17 399	51 409	302 051
HM8	290 771	15 335	51 409	310303
HM9	273 962	12 091	51 409	358 499
HM10	186 672	10 911	51 409	371 374
HM1+BMV+IMD	426 425	21 528	60 906	186 182
HM2+BMV+IMD	339 135	20 053	58 941	198 066
HM3+BMV+IMD	420 527	20 643	58 286	193 114
HM4+BMV+IMD	333 237	19 758	59 596	206 649
HM5+BMV+IMD	450 312	23 002	60 906	171 657
HM6 +BMV+IMD	362 727	20 938	58 941	182 551
HM7+BMV+IMD	444 119	21 823	58 286	178 589
HM8+BMV+IMD	256 829	18 284	59 596	191 464
HM9+BMV+IMD	340 315	15 335	62 543	232 728
HM10+BMV+IMD	253 024	14 450	63 198	247 913

Input data: *Evaluation Period: 30 years. Real Interest rate: 3.19%. Annual price growth rate district heating: 2.0%. Annual price growth rate facility electricity: 1.7%. Current price district heating: 0.85 SEK/kWh. Current price electricity: 0.88 SEK/kWh. Annuity: 5.23%. Adjustment factor district heating: 1.32. Adjustment factor electricity: 1.26.*

References Appendix D:

Beijer Byggmaterial (a).2017. *Markskiva Industri 921.* [Online] Available at:
https://www.beijerbygg.se/store/privat/byggmaterial/isolering/stenull/markskiva-industri-921?artikel=522511
[Accessed 11 March 2017].

Beijer Byggmaterial (b).2017. *Flexibatts.* [Online] Available at:
https://www.beijerbygg.se/store/privat/byggmaterial/isolering/stenull/flexibatts-c600-1390381445164-46?artikel=416386
[Accessed 11 March 2017].

Beijer Byggmaterial (c). 2017. *Vridfönster AFH Trä/Alu Vitmålad.* [Online] Available at:
https://www.beijerbygg.se/store/privat/f%C3%B6nster/vridf%C3%B6nster/vridf%C3%B6nster-afh-vitm%C3%A5lad-tr%C3%A4-alu?artikel=717002
[Accessed 12 March 2017].

Bond, A., 2017. *Sales Person at FläktWoods* [Interview] (3 March 2017).

Buildingmaterials. 2017. *Kingspan Insulation Boards K5 External Board.* [Online] Available at:
http://www.buildingmaterials.co.uk/kingspan-insulation-boards-k5-external-board-1200mm-x-600mm.html
[Accessed 11 March 2017].

Energimyndigheten. 2003. *Individuell Värmemätning I Svenska Flerbostadshus – En Lägesrapport.* [Online] Available at:
http://hotpot.se/hsb-slutrapport.pdf
[Accessed 11 March 2017].

Appendix E: Input data & Results of the Life Cycle Impact Assessment

Firstly, it should be pointed out that the upstream and core process of the IMD system for the domestic hot water was neglected in the life cycle impact assessments conducted in Eco-bat 4.0 since the software has no input option for this specific measure. Thus, only the effects of the IMD on the domestic hot water consumption, operational phase, was accounted for in the life cycle impact assessments conducted in Eco-bat 4.0. Furthermore, the environmental impacts due to the transportation of the building materials was only considered for the specific products studied for the combined renovation measures on the building envelope (See Table 5.8). Moreover, all the energy input data in Eco-bat 4.0 of the studied renovation measures were based on the obtained energy results from the energy simulations of each specific package of measures. The input data in Eco-bat of the energy carriers and the building integrated systems (BITS) are presented in Table E1 below.

Table E1. Input values for the local district heating in Eco-bat 4.0.

Input Categories	Input Values
Primary Energy Factor – District Heating	0.44 [1] (Percentage of total primary energy use per supplied energy)
Percentage of Fossil Fuels	38.18 % [1]
Percentage of Recycled Fuels	59.26 % [1]
Percentage of Renewable Fuels	1.95 % [1]
Global Warming Potential (GWP)	0.140 $kgCO_2eq/kWh$ [1]
References: 1. (E.ON, 2016).	

Furhtermore, the primary energy factor used for the facility electricity was set to 2.6, this value corresponds to the recommended value for Swedish low-voltage electricity according to IEA EBC Annex 56 (IEA Annex 56, 2014). Moreover, the grid losses was neglected in the life cycle impact assessment since they are rather difficult to determine. Thus, the efficiency of the supplied electricity was set to 100% in Eco-bat. Furthermore, the input values for the building integrated technical systems (BITS) are presented in Table E2 below.

Table E2. Input values for the building integrated technical systems (BITS) in Eco-bat 4.0.

Input Categories	Input Values
Heating and Cooling Distribution	
- *Type of Heating Distribution System*	Radiators
- *Service Life*	30 Years (Default setting in Eco-bat 4.0)
Ventilation	
- *Type of Ventilation System*	Balanced Mechanical Ventilation
- *Service Life*	30 Years (Default setting in Eco-bat 4.0)
- *Specific air flow rate*	1.41 m^3/s (According to the air flow values presented in Appendix C)

The environmental impacts due to the transportation of the specific products studied for the combined renovation measures of the building envelope is presented in Table E3.

Table E3. Input values in Eco-bat 4.0 of the transportation distance of the specific products studied for the combined renovation measures of the building envelope.

Product	**Place of Production**	**Distance to the building site**	**Assumed Transportation Vehicle**
Elitfönster 3-pane Low-E Window	Vetlanda (Sweden)[1]	274km (Approx.)	Lorry
FläktWoods EQ Master AHU	Jönköping [2] (Sweden)	292km (Approx.)	Lorry
Kingspan - Kooltherm K5 Insulation	Tiel [3] (The Netherlands)	799km (Approx.)	Lorry
RockWool – Hardrock Elementbatts	Vamdrup [4] (Denmark)	276km (Approx.)	Lorry
RockWool – Drainage Insulation	Vamdrup [4] (Denmark)	276km (Approx.)	Lorry
References: 1. (Elitfönster, 2017). 2. (FläktWoods, 2017). 3. (Kingspan, 2017). 4. (Rockwool, 2013).			

Furthermore, the environmental impact due to the material usage for the different combined renovation measures were also evaluated in the life cycle assessments. The weight and quantity of each material related to the specific renovation measures were implemented into Eco-bat 4.0. The exact weight and quantity of the materials and products implemented into Eco-bat 4.0 for each studied renovation measure were based on the list of materials and products presented in Appendix D and their corresponding densities (See Table D1). Moreover, unique material files were created in Eco-bat 4.0 for the specific insulation materials studied for the combined renovation measures of the building envelope. The environmental impact during the upstream and core process of these specific products were gathered from different *Environmental product declarations (EPDs)* from the manufacturers and thereafter implemented in Eco-bat 4.0 as self-created material files. The references to the *Environmental product declarations* used to create the unique material files of the insulation materials can be found in Table E3 above. The other products and materials included in the different studied renovation measures were chosen from the materials library in Eco-bat 4.0. Thus, these products and materials obtained the defualt values in Eco-bat 4.0 regarding the environmental impact during the upstream and core process.

Moreover, after the implementation of all the input data described and presented above then two separate simulations, one with an evalutation period of 60 years and one with an evaluation period of 30 years, were carried out for each studied combined renovation measure in the Eco-bat 4.0 software. The environmental parameters studied in all simulations conducted in the software were: *The Total Primary Energy Use (TPE)* and *The Global Warming Potential (GWP)*.

The final results of the life cycle impact assessment conducted in Eco-bat 4.0 is presented in the tables below.

Table E4. Results of the life cycle impact assessment of the studied reference building.

Renovation Measures	Environmental Parameter	Manufacturing & Installation	Transport	Total BITS	Total Energy Use
Studied Evaluation Period: 60 Years					
REF	GWP [$kgCO_2eq/(A_{TEMP}·Year)$]	-	-	0.80	21.00
	TPE [$kWh/(A_{TEMP}·Year)$]	-	-	2.69	106.47
Studied Evaluation Period: 30 Years					
REF	GWP [$kgCO_2eq/(A_{TEMP}·Year)$]	-	-	0.80	21.00
	TPE [$kWh/(A_{TEMP}·Year)$]	-	-	2.69	106.47

Table E5. Results of the life cycle impact assessment of the combined renovation measures. Studied evaluation period: 60 years.

Renovation Measures	Environmental Parameter	Manufacturing & Installation	Transport	Total BITS	Total Energy Use
HM1+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	2.58	0.60	0.80	7.90
	TPE [kWh/(A_{TEMP}·Year)]	7.94	0.61	2.69	73.18
HM2+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	2.20	0.40	0.80	8.50
	TPE [kWh/(A_{TEMP}·Year)]	6.92	0.47	2.69	73.2
HM3+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	2.40	0.55	0.80	8.20
	TPE [kWh/(A_{TEMP}·Year)]	7.11	0.53	2.69	72.02
HM4+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	2.0	0.30	0.80	8.80
	TPE [kWh/(A_{TEMP}·Year)]	6.39	0.42	2.69	74.86
HM5+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	3.88	0.70	0.80	7.30
	TPE [kWh/(A_{TEMP}·Year)]	10.53	0.81	2.69	71.24
HM6+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	3.10	0.60	0.80	7.80
	TPE [kWh/(A_{TEMP}·Year)]	10.19	0.75	2.69	71.13
HM7+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	3.50	0.65	0.80	7.60
	TPE [kWh/(A_{TEMP}·Year)]	8.28	0.64	2.69	70.08
HM8+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	3.00	0.50	0.80	8.20
	TPE [kWh/(A_{TEMP}·Year)]	6.58	0.56	2.69	72.84
HM9+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	1.90	0.45	0.80	9.90
	TPE [kWh/(A_{TEMP}·Year)]	5.44	0.36	2.69	80.68
HM10+BMV+IMD	GWP [$kgCO_2eq/(A_{TEMP}$·Year)]	1.60	0.40	0.80	10.60
	TPE [kWh/(A_{TEMP}·Year)]	5.05	0.31	2.69	83.22

Table E6. Results of the life cycle impact assessment of the combined renovation measures. Studied evaluation period: 30 years.

Renovation Measures	Environmental Parameter	Manufacturing & Installation	Transport	Total BITS	Total Energy Use
HM1+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	5.10	0.70	0.80	7.90
	TPE [kWh/(A$_{TEMP}$·Year)]	15.80	1.20	2.69	73.18
HM2+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	4.20	0.50	0.80	8.50
	TPE [kWh/(A$_{TEMP}$·Year)]	13.80	0.94	2.69	73.2
HM3+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	4.80	0.65	0.80	8.20
	TPE [kWh/(A$_{TEMP}$·Year)]	14.22	1.04	2.69	72.02
HM4+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	4.00	0.55	0.80	8.80
	TPE [kWh/(A$_{TEMP}$·Year)]	12.80	0.82	2.69	74.86
HM5+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	6.80	0.80	0.80	7.30
	TPE [kWh/(A$_{TEMP}$·Year)]	21.10	1.61	2.69	71.24
HM6+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	6.20	0.70	0.80	7.80
	TPE [kWh/(A$_{TEMP}$·Year)]	20.40	1.50	2.69	71.13
HM7+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	6.60	0.75	0.80	7.60
	TPE [kWh/(A$_{TEMP}$·Year)]	16.60	1.28	2.69	70.08
HM8+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	6.00	0.60	0.80	8.20
	TPE [kWh/(A$_{TEMP}$·Year)]	13.20	1.12	2.69	72.84
HM9+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	3.80	0.55	0.80	9.90
	TPE [kWh/(A$_{TEMP}$·Year)]	10.88	0.72	2.69	80.68
HM10+BMV+IMD	GWP [kgCO$_2$eq/(A$_{TEMP}$·Year)]	3.20	0.50	0.80	10.60
	TPE [kWh/(A$_{TEMP}$·Year)]	10.00	0.62	2.69	83.22

References Appendix E:

Elitfönster. 2017. *Med Rötterna i Jönköping – Utveckling och Tillverkning på Tre Orter I Sverige.* [Online]
Available at: http://www.flaktwoods.se/om-oss/produktionsanlaggningar/
[Accessed 16 March 2017].

E.ON. 2016. *Miljövärden 2016 – Lokala miljövärden för Malmö-Burlöv.* [Online] Available at: https://www.eon.se/content/dam/eon-se/swe-documents/swe-eon-miljovarden-2016.xlsm [Accessed 19 March 2017].

FläktWoods. 2017. *Produktionsenheter.* [Online]
Available at: http://www.elitfonster.se/kontaktuppgifter-elitfonster/produktionsenheter/
[Accessed 16 March 2017].

IEA Annex 56. 2014. *Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation.* [Online]
Available at: http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf
[Accessed 22 January 2017].

Kingspan. 2014. *Environmental Product Declaration – Kooltherm K5 Kingspan Insulation.* [Online]
Available at: http://www.kingspaninsulation.se/getattachment/Miljo-och-hallbarhet/Kooltherm-K5---EPD_KSI_20130227_IAC1_EN.PDF.aspx
[Accessed 16 March 2017].

Rockwool. 2013. *Environmental Product Declaration – Rockwool Isolering.* [Online]
Available at: http://epd-norge.no/getfile.php/EPDer/Byggevarer/Isolasjon/NEPD-00131E_rev1_ROCKWOOL-isolering.pdf
[Accessed 16 March 2017]

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services