TOWARDS ZERO EMISSION BUILDINGS

A Holistic Guide for Homeowners through EPBD Compliance and the Renovation Passport Framework

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Master thesis in Energy-efficient and Environmental Buildings

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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.

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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.

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Abstract

This master thesis presents a suggested Renovation Passport for two typical 1960s single-family houses. Following the recently approved Energy Performance of Buildings Directive (EU 2024/1275A), all member states are to implement voluntary Renovation Passports by 2026, which will aid in reaching the 2050 goal of a decarbonized building stock. The aim of Renovation Passports is to provide long-term guidance and information on energy improving measures when homeowners plan for future renovations.

Energy simulations in IDA ICE were conducted for six locations in Sweden, in order to calculate the energy demand reduction for the 25 different steps of building envelope improvements. Additionally, the impact of installing different heat pumps and mechanical ventilation with heat recovery was assessed. Embodied and operational CO_2 emissions for all renovation scenarios were calculated, with the environmental payback time and the investment costs presented.

Two renovation packages (BBR-standard and PH-standard) were identified as suitable based on Life Cycle Assessment (LCA), investment costs, and practical feasibility. The BBR-standard was following the current Swedish Building code, BBR29, for new constructions to reach the Energy Performance Certificate (EPC) class C. The PH-standard was constructed to follow the quantitative building envelope goals for Passive Houses, in addition to reaching the EPC class A. For the BBR-standard, multiple renovation scenarios resulted in the desired EPC class, while the installation of a highly efficient heat pump being the single most effective measure in reducing CO_2 emissions and energy use. However, to reach the desired energy class and reduce the energy demand, envelope improvements were needed, such as new windows, attic insulation, and added external wall insulation.

For Building 1, the BBR-standard package yielded a 66 % lifetime emissions reduction, and reduced energy use by 75 %, while the PH-standard yielded a 70 % lifetime emissions reduction and reduced energy use by 90 %. The results showed similar trend for building 2, however, due to the higher form factor (envelope-to-floor ratio), the PH-standard represented more embodied carbon emission, yielding higher lifetime emissions than the BBR-standard for the same building.

The proposed Renovation Passport is an interactive tool for homeowners to assess the data from this master thesis on CO_2 emissions, energy demand, energy use, and investment costs for each of the investigated renovation measures. 22 500 combinations of renovation scenarios are available for each building type and location, based on the homeowners' preferences or need, making this Renovation Passport suitable for guiding future energy-efficient and environmentally favorable renovations.

Preface

This master thesis represents the final part of the two-year master program “Energy-efficient and Environmental Building Design” at Lund University and marks the end of my five-year academic journey. During my study time at LTH, the main focus has been on renovating both residential and office buildings, and to improve energy demand and thermal comfort while keeping a low carbon footprint throughout the process. However, it became clear to me that many homeowners lack knowledge of these measures and where to start a deep stage renovation project, when aiming towards higher energy efficiency. When the EU first announced the revised EPBD in early 2023 it was called “a forced renovation act” by the media. Renovation measures were described as unnecessary and expensive, with the potential of forcing some homeowners to sell their houses. My idea was to conduct thorough research on the topic, and to deliver an easy-to-use digital tool, where the findings of my research could be explained in a straightforward way for homeowners to select renovation plans according to their customized renovation passport, and to develop a long-term renovation plan.

Acknowledgement

I am grateful for being enrolled in this master program which has been the highlight of my academy journey. In a time of artificial intelligence, I feel the need to declare that the writing of this master thesis was conducted without any help of generative AI. I stand by my work as 100 % my own doing!

However, ChatGPT has been of major help when processing and organizing output-data from IDA ICE into Excel, and for providing codes when creating the interactive Excel sheet, as well as the generated logos and images in the proposed Renovation Passport and for the front-page illustration of this master thesis.

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Finally, my deepest gratitude goes to CO-supervisor Jonas Gremmelspacher at Greenshape AB for answering texts and calls on short notice, supplying me with an office space when needed and pushing me to believe in my work and move on to the next step.

Thank you all,
Sincerely

Jens Lundgren
Lomma, June 2024

Definitions and abbreviations

ACH	Air Change Rates per hour.
ATA-HP	Air To Air Heat Pump.
A_{temp}	Floor area (m²) heated to more than 10 °C.
ATW-HP	Air To Water Heat Pump.
BBR 29	Current building code in Sweden, provided by Boverket.
BRP	Building Renovation Passport.
Boverket	The National Board of Housing, Building and Planning.
DHW	Domestic Hot Water.
Energy demand	Energy supplied by the heating unit in order to maintain a desired temperature, sometimes referred to as raw energy.
Energy use	Energy supplied to the heating unit. Sometimes referred to as specific energy or bought energy.
EPBD	Energy Performance of Buildings Directive.
EPC	Environmental Product Declaration.
GHG	Greenhouse Gas Emissions.
GSHP	Ground Source Heat Pump.
HVAC	Heating, Ventilation, Airconditioning and Cooling.
Lambda	Thermal transmittance in W/(m·K).
LCA	Life Cycle Assessment.
LCC	Life Cycle Costing.
MVHR	Mechanical Ventilation system with Heat Recovery.
sCOP	Seasonal Coefficient of Performance. Calculated as the average annual COP for heat pumps, for both DHW and space heating.
***UA*-value**	Heat transfer coefficient for a given area in W/K.
***U*-value**	Heat transfer coefficient in W/(m²·K).

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1 Introduction

1.1 Background and Problem Motivation

Nearly half the world's population lives in areas that are directly vulnerable to climate change. In the next coming 25 years, it is estimated that a net addition of 250 000 annual deaths caused by the effects of climate change will occur if no action is taken. Complying with the Paris deal from 2015 and limiting global warming to 1.5 °C compared to preindustrial levels, is of absolute importance for safeguarding future generations and the planets' ecological balance (WHO, 2023).

Globally, the real estate industry accounts for 34 % of the final energy use, with the vast majority, 30 %, of the final energy use attributed towards building operations (International Energy Agency, 2023). There are great potential savings within the building sector, which is responsible for 40 % of the final energy use in the European Union, as well as 36 % of the greenhouse gas emissions. The 2050 goal of a decarbonized building stock could lead to reduced energy poverty, energy bills for households cut in half, and a net addition of 1.2 million job opportunities in the building and energy sectors. That is, if the annual 1 % renovation rate is increased towards the needed rate of 3.5 %, in order to reach to goal of Zero Emission Buildings by 2050 (European Climate Foundation, 2022).

The Energy Performance of Building Directive (EPBD, Directive EU 2024/1275) was approved by the European parliament in early 2024. The aim is to enhance the renovation pace of the worst performing buildings in the EU and help facilitate the European Green Deal. Decarbonize the building sector and for Europe to be climate neutral by 2050, with reaching the milestone of decreasing the primary energy use by 20 % - 22 % by 2035. All member states shall introduce a scheme for renovation passports, by 29 May 2026. Renovation passports will provide guidance and knowledge for homeowners on what renovation measures to take for improving energy efficiency, thermal comfort, and sustainability. Renovation passports are to be of voluntary use for building owners unless the member states decide otherwise (The European Parliament, 2024).

Sweden has improved its energy efficiency for the real estate and building sector over the last decades, which according to the National Board of Housing and Planning, Boverket (2024) account for 22 % of the national economy's GHG emissions, where a quarter is attributed towards space heating. Residential buildings in Sweden represent 3 % of the final energy use for building operations in EU, while Germany and France represent the two major consumers, with 22 % and 16 %, respectively (European Commission, 2024).

Furthermore, 75 % of the current building stock in Europe is considered energy inefficient. This offers a great opportunity to set up a long-term plan on how to renovate these buildings. To strive for a decarbonized building stock, it is important to incorporate Life Cycle Assessment (LCA) calculations for both the operational energy in the current and renovated state, and for the embodied emissions of the applied renovation materials (European Environment Agency, 2022).

According to Energimyndigheten (2021), approximately one third of the residential building stock in Sweden is built during the time period of 1960 to 1980, which are representable for the most energy intensive buildings. Additionally, many of these buildings are at the end of their first life cycle, with an urgent need for a sustainable holistic renovations approach in order to last yet another cycle. This master thesis aims to provide guidance for homeowners, by providing an interactive renovation passport for typical 1960s archetypes.

1.2 Aim and purpose

The aim of this master thesis is to generate reliable data, and to create a digital tool for producing renovation passports for two typical archetypes of 1960s single-family houses. The suggested measures from these passports could be used as generalized guideline for homeowners regarding what measures to take for reducing energy demand, energy use and CO_2 emissions in a long-term perspective.

Following research questions will aid in gathering the quantitative and qualitative data, needed for producing these renovation passports:

- What renovation measures are practically, economically, and environmentally feasible when renovating towards a Zero Emission Building?
- What are the disadvantages and potential risks for these renovation measures?
- What is the environmental payback time for these measures?
- What is the most effective sequence of renovation measures to ensure the maximum benefits in the subsequent scenarios?

1.3 Limitations

This master thesis was limited to two archetypes of single-family houses from the 1960s, and geographically limited to six cities in the two provinces called Götaland and Svealand in Sweden.

Price estimations were conducted by using the online tool from Wikells Sektionsfakta (2024), where prices are gathered from previous projects and recalculated to today's worth. Though substantial renovation needs for buildings from this era are assumed, only the costs that were attributed towards energy efficiency renovation were considered, i.e., the additional costs when a renovation process was already in place. Following materials are not considered for any renovation scenario:

Demolition work, façade materials, painting work, wind protective board, vapor barriers, flooring, digging or drainage work, scaffolding.

Life-Cycle Costing (LCC) were excluded from this master thesis due to uncertainty in assumptions regarding current and future energy prices. Electricity prices differ due to the four electricity price areas in Sweden, and also depending on the user's subscription with the electricity company. Prices are presented as SEK / saved $kWh_{50\ years}$. Thereby it is easier for the single user to evaluate the costs depending on their electricity price.

For the Life Cycle Analysis (LCA), only the metric Carbon Dioxide emissions equivalent (CO_2eq.) was considered, due to its impact on Global Warming Potential (GWP). Data for operational emissions due to electricity and district heating were assessed from the Boverket Climate Database (Boverket, 2024b). No future energy mixes, nor different emissions scenarios were considered.

Photovoltaic panels and solar thermal panels were not included in this master thesis.

1.4 Disposition

- Chapter 2 provides background information on the Swedish building stock. Typical archetypes and building techniques from the 1960s, in addition to statistics from surveys are presented which explain why these buildings are suitable for deep renovation and candidate for a customized Renovation Passport. An explanation on the current situation and history about the EPBD and Building Renovation Passports are given, and the chapter is concluded with proposed, suitable renovation measures.

- Chapter 3 explains the methodology in detail, providing all input data for simulations and calculations.

- Chapter 4 presents all results from the simulations and calculations for Building 1 and Building 2, respectively. Only the Stockholm location is given throughout the result chapter, in order to avoid excessive amount of data since most results were comparable. Only when significant discrepancies were found between the selected six locations, data is presented. Otherwise, data for the remaining five cities are presented in the appendix. All results are discussed continuously as they are presented.

- Chapter 5 presents the suggested Renovation Passport.

- Chapter 6 provides summarized answers to the research questions and discussions on the limitations.

- Chapter 7 concludes this master thesis by providing the main findings and suggesting further research.

2 Background and literature review

2.1 Energy Performance of Buildings Directives

The Energy Performance of Buildings Directive (EPBD) was first introduced in 2002, by the Directive 2002/91/EC, in order to make the energy performance of buildings individually transparent. In 2010, the adapted recast (directive 2010/31/EU) required member states to apply Energy Performance Certificates (EPCs), for all new constructions and buildings undergoing sale or rental processes. EPCs include the energy performance of the building, categorized in lettering A-G. The recast in 2018 (EPBD 2018/844) further aimed to reach the 2050 goals of a decarbonized building stock, where more user friendly and publicly available EPCs were requested (European Commission, 2023).

The revised EPBD from December 2023 was approved by the parliament in early 2024 and published in May 2024. Member states have two years to incorporate the EPBD into the building code (The European Parliament, 2024).

A selection of the goals for the revised EPBD are presented below:

- By 2030, the average primary energy use of residential buildings has to be reduced by at least 16 % compared to 2020 levels, and by 2035 reduced by 20 % to 22 % compared to 2020 levels (article 9).
- 55 % of the reduction is attributable towards the 43 % worst performing buildings (article 9).
- Every member state should present a national renovation plan, with the goal of renovating all buildings towards ZEB by 2050 (article 3).
- Member states shall by 29 May 2026 introduce a scheme for Renovation Passports, based on the framework in Annex VIII. Renovation Passports shall be voluntary for homeowners (article 12).

The following is a selection of guidelines from the EPBD appendix, section “Annex VIII, requirements for Renovation Passports.” These are underlying for the scope of this master thesis and for the suggested Renovation Passport:

- Information about the current energy performance of the building (1 a).
- The estimated savings in primary and final energy consumption, in kWh and in percentage compared to the energy consumption prior to the step (1 e ii.)
- The estimated reduction of operational greenhouse gas emissions (1 e iii).
- Expected energy class after the completed renovations (1 e v).
- Estimated costs for conducting the renovations (2 b iii).
- Life-cycle greenhouse gas emissions for the materials and equipment (2 Vi).

2.1.1 Definition of Zero Emission Building

Following the EPBD, Directive EU 2024/1275A, all new publicly owned buildings have to comply with the newly implemented definition of Zero Emission Building (ZEB) by 2028, and for all new buildings by 2030. Although, it is up to the member states to define the quantitative goals for a ZEB within the following two years, which will replace the previous term of Net Zero Energy Buildings (NZEB). Quantitative definitions are explained in Table 2.A.

Table 2.A Quantitative definitions. ZEB defined in the EPBD (The European Parliament, 2024). nZEB and NZEB defined by HI-SMART (n.d.), CO-founded by the Eramus+ Programme of the European Union.

Abbreviation	Quantitative definition
ZEB	Zero Emission Building. Primary energy use <10 % of nZEB
nZEB	nearly Zero Energy Building. Primary energy use >0 kWh/(m²/y)
NZEB	Net Zero Energy Building. Primary energy use = 0 kWh/(m²/y). At least 100 % renewable energy is being produced at site on an annual basis

A qualitative definition of a ZEB is given in the EPBD:

"The zero-emission building, with very low energy demand, zero on-site carbon emissions from fossil fuels and zero or a very low amount of operational greenhouse gas emissions." (The European Parliament, 2024, p. 4)

Energy sources that are considered as renewable:

"Different options are available to cover the energy needs of a zero-emission building: energy generated on site or nearby from renewable sources such as solar thermal, geothermal, solar photovoltaics, heat pumps, hydroelectric power and biomass, renewable energy provided by renewable energy communities, efficient district heating and cooling, and energy from other carbon-free sources." (The European Parliament, 2024, p. 5)

U.S. Department of energy (2023) defines a Zero Emission Building as a highly energy efficient building, free of onsite emissions from energy use, and powered solely from clean energy. While only focusing on operational emissions, the report states that embodied emissions are not considered, but might be included in future versions.

2.1.2 Building Renovation Passports

According to Fabbri et al. (2016), there is a great need for Building Renovation Passports (BRPs), a comprehensive report, tailored to a specific building, on how to renovate and make sustainable investments. A step-by-step renovation roadmap towards a united goal, including both the economic and environmental impacts are both essential important. After assessing three proposed BRPs, the author suggested the following general definition:

"A Building Renovation Passport is defined as a document - in electronic or paper format - outlining a long-term (up to 15 or 20 years) step-by-step renovation roadmap for a specific building, resulting from an on-site energy audit fulfilling specific quality criteria and indicators established during the design phase and in dialogue with building owners. The expected benefits in terms of reduced heating bills, comfort improvement and CO_2 reduction are a constitutive part of the BRP and are explained in a user-friendly communication." (Fabbri et al., 2016, p. 6)

The Building Performance Institute Europe (BPIE) released a report on the potential benefits and Key Performance Indicators (KPI) to include, when constructing national BRPs (Fabbri, 2017). When starting a deep-staged renovation, it is of essence to apply the renovation measures in correct order and with a long-term plan, to avoid lock-in effects. Examples of lock- in effects could include changing the roof without extending the eaves or wall overhang by not taking into consideration that the walls will be extended. Installing PVs or solar thermal before controlling the remaining technical lifetime of the roof. Each building is unique, and initially, an onsite energy audit should be performed to offer a custom-tailored user-friendly renovation plan. The report suggests the following KPIs when constructing a BRP: Energy consumption, CO_2 emissions, thermal and acoustic comfort, indoor air quality and daylight (Fabbri, 2017).

In a qualitative study, Sesana & Salvalai (2018) compared suggested BRPs from Belgium (Woningpas), Germany (Sanierungsfahrplan) and France (Passeport efficacité énergétique). Five commonly adapted principles were considered the core structure between the three passports; long-term perspective, timing, and sequencing of the renovation measures, building owner engagement, attractiveness, and user-friendliness in addition to a simple and automated software for the energy experts who perform the audit and generate the passport. All three passports were funded by public authorities and launched in 2018. The study showed that due to different building laws and national energy goals, different KPIs were used in the BRPs whereas the voluntary passports are non-comparable in a quantitative way. Sesana & Salvalai (2018) emphasized the importance of common European KPIs to be included in the BRPs on a European or global level.

Sesana et al., (2019) criticizes the EPCs for lacking sufficient information on future renovation options towards a Net Zero Energy Building and highlights that a BRP could be of great interest for a building owner while predicting future economical investments and be of help towards investors or lenders.

By applying long-term renovation strategies, a 35 % cut down on greenhouse gases due to building operations in the EU by 2030 is highly achievable. Half the EU member states set the goal of reducing CO_2 equivalents in the operational phase of buildings by 80 %, by 2050 compared to their reference year. Maduta et al. (2023) compared the renovation road map of several member states. A general misconception is the definition of a nZEB or NZEB. Another difference between members states is the energy demand limits, and the annual rate of renovations, which vary from 1 % - 6 %, depending on the country. By phasing out fossil fuels and replacing oil and gas burners by installing heat pumps, a 41 % energy use reduction and 94 % GHG reduction could be obtained for the European Union by 2050, compared to 2019 levels. Another key factor entails installation of Photovoltaics (PVs), where the production exceeds the bought energy on a yearly basis. Furthermore, Maduta et al. (2023) highlights the importance of avoiding lock-in effects when performing deep renovations, and that guidance for homeowners is needed on what measures to perform and in what order.

Deep-renovation rates need to increase to a minimum of 2.5 % annually, in order to reach a 48 % energy reduction by 2050 (European Commission. Joint Research Centre., 2021)

Attia et al. (2022) compared nZEB regulations and definition in ten east European countries. Finding that EPCs, conversion factors and primary energy carriers were incorrectly used and calculated, making them neither trustworthy nor comparable. The national goals often failed to phase out fossil fuels and to meet the 2050 EU goals. Seven out of ten countries lacked guidelines regarding heating or cooling demand, and the combined primary energy use varied from 32 kWh/m² - 220 kWh/m², making the nZEB definition highly variable in the EU region.

2.1.3 Energy efficiency renovation measures in Sweden

In a recent study, Holm et al. (2023) examined the understanding of energy usage and renovation practices in Sweden. Out of the 2003 respondents, 43 % have not performed any renovation measure in order to reduce energy consumption, mainly due to lack of knowledge regarding profitability and due to financial constraints. Among the households that have undergone renovation measures, the most frequently performed renovations entail window replacement (19 %), heat pump installation (17 %) and installation of PV panels (10 %), added wall and attic insulation (8 %). 31 % of the respondents reported lowering of the indoor temperature to below 18 °C - 21 °C as a passive energy saving strategy.

Figure 2.1 visualizes the energy classes of the Swedish residential building stock. The data contains both single-family and multi-family houses. The data is originally from the Swedish EPC-database called Gripen, by Boverket. The Gripen-database is only accessible for certified energy experts, whereas the data is in Figure 2.1 was presented by (The Swedish Energy Agency, 2022a). Energy class C is the standard in the current building code BBR29, for new constructions. Approximately 20 % of the current building stock falls in the two worst performing energy classes, F and G, respectively. It should be considered that for single-family houses, only newly constructed buildings in addition to the ones undergoing sale or rental processes require a mandatory EPC. The numbers in Figure 2.1 include multi-family houses, which are required a valid EPC according to the law (2006:985). Therefore, it is uncertain whether the EPC numbers are representative for the entire single-family building stock.

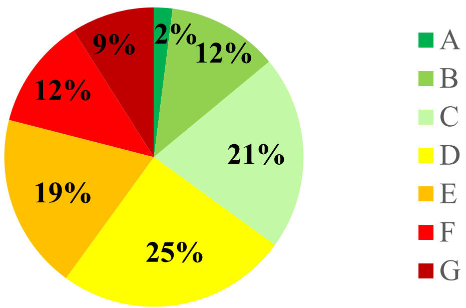


Figure 2.1 Percentage of the residential building stock within each energy class.

The public housing companies in Sweden provides approximately 1 million rental apartments, 11 % of this building stock requires deep renovation of the building envelope and technical installations in order to meet the EPBD directive (Sveriges Allmännytta, 2024). Furthermore, a long-term renovation plan is advocated, where energy saving measures should be conducted simultaneously as other planned actions, for best economically feasibility. A recast of the current EPCs might be in place, where suggested energy saving renovations measures would include the embodied emissions of materials, in comparison with operational emissions savings. This would aid in the process of long-term renovation decision making (Sveriges Allmännytta, 2024).

The Swedish Energy Agency (2022b) emphasizes the importance of starting energy efficient measures in an adequate order, starting with lowering the energy demand by changing appliances, user behavior, followed by an examination of the building to point out potential renovation practices. This aligns well with the structure of the Kyoto pyramid, see Figure 2.2. The Kyoto pyramid was originally created by Dokka and Rodsjo (2005), and later used extensively within the field of energy efficient building design and lays the foundation for the renovation scenarios in this master thesis, starting with improving the building envelope, while changing heating system is to be performed as a final step, when the heating demand is reduced. This avoids oversizing of the heating system and unnecessary use of resources.

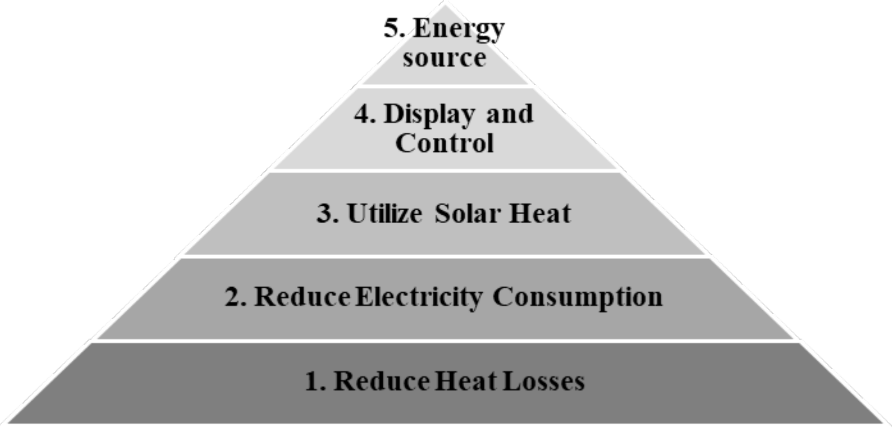


Figure 2.2 The Kyoto Pyramid.

2.1.4 Energy efficient renovation subsidies

Counterproductive to the guidelines of the Swedish Energy Agencies' recommendation, Boverket grants two subsidies for energy efficient renovations, although in the opposite order according to the Kyoto pyramid (Boverket, 2024a).

1. Change of heating system. Although only eligible if the previous heating system consisted of direct electricity.
2. Renovating the building envelope. Only eligible if the owner has been granted subsidy nr 1.

Both of which are applicable for 50 % of the material costs, at a total amount of 30 000 SEK each.

For the installation of Photovoltaic Panels, the Swedish tax agency grants a 20 % income tax reduction at a total amount of 50 000 SEK / (person / year).

An additional subsidy, in Swedish called "Renovering Och Tillbyggnad" (ROT), translated as "Renovation and Extension," offers a total 50 000 SEK tax deduction per person, or maximum 30 % of the total labor work. For this master thesis, no subsidy is assumed granted when calculating or presenting investment costs.

2.1.5 Swedish building stock history

Housing shortage has characterized Sweden since the mid-19th century. Simplistic building requirements, purposed for increasing the rate of construction has had higher priority than regulations on energy use and thermal comfort. A quarter of the population emigrated to America during the time period of 1850-1930, in hope of better work opportunities and higher living standards. Sweden was still categorized as a country with one of the poorest housing standards in Europe in the 1930s, where overcrowded accommodations with the lack of indoor toilets and central heating were a threat to the public health. Governmental efforts in terms of subsidized loans to enhance constructions had insufficient effect on the shortage of housing (Nylander, 2018).

The increasing urbanization during the mid-20-th century led to a high demand for housing in the cities. In 1950, approximately 65 % of the seven million population were living in the cities, which increased to 90 % of the eight million population in 1975. Increasing economic wealth and a higher social standard after the second world war led to a high demand for goods, services, and affordable living. At the same time, the old building stock was considered outdated. Poor living standards led to the demolition of city centers for the opportunity for new constructions. The rapidly increasing demand for housing led to the 1964 parliament decision called "The Million Program"; to build one million living units in the following decade (Björk et al., 2012).

The total building stock in Sweden comprises of 4.8 million residential units, where 42 % entails single-family houses, remaining entails apartments. Houses built in the 1960s and 1970s represent 14 % and 21 % respectively, of the current building stock (Energimyndigheten, 2021).

2.1.6 1960s houses

In 1965 – 1974 during the million-program era, approximately 300 000 single-family houses and 700 000 apartment units in multi-family houses were constructed, and the housing shortage was thereby eliminated in the mid-1970s. During this era, Sweden had the highest number of newly built housing units per capita in the world, 11 units per 1 000 inhabitants, leaving Germany and Soviet Union on a shared second place with 10 units per 1 000 inhabitants. Housing construction was mainly done by prefabricated building parts. Governmental subsidized loans for factories, plants and machinery paved the way for this industrial building technique. The architectural role took a step back, and standardized measurements characterized the construction technique. Agricultural land in the outskirts of cities and in suburban areas was transformed into large scale residential housing projects where series of similar detached houses or rowhouses were built. A majority of the single-family houses were bought and constructed as "catalogue houses." Standardized villas, prefabricated in factories, and advertised in housing catalogues where the assembly to a certain degree could be performed by the homeowner himself (Nylander, 2018).

A vast majority of the single-family houses built in the 1960s were constructed as one-story buildings, either with or without basement. Typical floorplans included two to four bedrooms, a living room, a separate secluded kitchen and one bathroom. Basements generally housed a hobby room, food storage, and a boiler room (Björk et al., 2015). Brick facades were predominantly used in the first half of the decade, inspired by Danish architecture. In the second part, facade materials of wood panel and bricks made of limestone sand (locally called Mexi-bricks) were used, often in combinations between the two (Jonsson, 1990).

Figure 2.3 displays the energy source for space heating and Domestic Hot Water (DHW) in single-family houses built during 1961-1970, data presented by the Energy Agency (Energimyndigheten, 2021). Houses built in 1961-1975, data from a the BETSI survey (Boverket, 2009). Both sources present comparable results where direct electricity, heat pumps and district heating represent approximately 30 % each. It should be noted that Air-To-Air heat pumps are included in the data for direct electricity, and no separate division between Air-To-Air heat pumps and direct electricity were found. The BETSI data is 12 years older than the data from the Swedish Energy Agency, in addition to covering a wider construction time span, which could explain the substantial difference in oil burners.

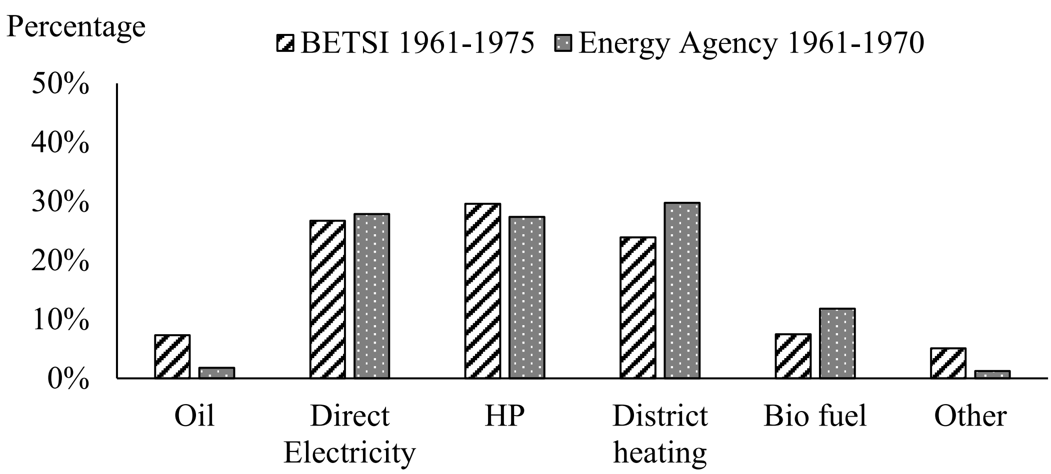


Figure 2.3 Energy sources for buildings built between 1961-1975. Data from the BETSI survey and from the Swedish Energy Agency.

2.1.6.1 BETSI survey

Boverket (2009) conducted a survey of the Swedish building stock, on behalf of the governmental request. Statistics on Energy demand, technical standard, and indoor environment in a total of 1 800 single-family houses and multifamily houses that were measured during the heating season of 2007/2008 in a selection survey called BETSI. Both fully, semi, and non-renovated buildings from the total Swedish building stock were included. Wood was found to be the most common facade material for single family houses. Three times as popular as brick. Concrete tiles are the most common roofing material, followed by clay tiles.

For natural draught ventilation, with only inlet and outlet ventilation grills, the ventilation is driven by wind, temperature difference and pressure difference between the indoor and outdoor environment. Natural draught ventilation is 90 % predominant in single-family houses built before 1975, and 60 % for the entire building stock. To ensure sufficient ventilation in buildings without a chimney and oil/wood burner in the basement, ventilation ducts and fan driven ventilation were more commonly installed in buildings from the mid-70s and forward.

2.1.6.2 Building regulations

Urban planning guidelines have shaped the outline of Swedish cities and communities since the Middle Ages. In 1874, the first building law was formulated and controlled the size and placement of new buildings. It was later changed in 1907 and 1931, to control hygienic factors and indoor climate concerning moisture and daylight (Björk et al., 2012). The first building requirements to control the minimum *U*-values for the building envelope was released in 1947, called BABS 1946.

BABS 1960 and SBN 1967 were the applicable building regulations during the 1960s, presented in Table 2.B. The terms “energy use” or “power demand” were not introduced in any building codes until SBN 1975. A probable explanation is the oil crisis in the beginning of the 1970s. SBN 1975 also introduced a maximum window-to-floor-area ratio, to reduce heat losses. In addition, SBN 1975 was the first building code to require monitoring devices for energy use, and a maximum peak power demand of the heating system. The first quantitative energy demand requirements, expressed as (kWh / m²), were introduced in BBR 12, from 2006 (Boverket, 2016).

Table 2.B presents the current building regulations during the 1960s for the building envelope. In addition to the surveyed data for building envelope characteristics during the 1960s from the BETSI report, a report from Formas (2012), in addition to the Swedish book on typical archetypes during 1890-2010 named “Så Byggdes Villan”, (Björk et al., 2015). Note that all *U*-values from the latter were calculated and are given as a variable range depending on the lambda value for the included materials, which were not specified.

U-values for exterior walls and roofs are generally reported that of a higher standard than the building requirements in BABS, while windows and slab on ground are reported as equal to BABS. Notable is that 0.7 ACH were required in the 1960s, while measurements showed that 75 % of all houses in the survey have lower air flow rates than today’s requirements of 0.35 l/(s·m²), corresponding to approximately 0.5 ACH, while the average value in the BETSI survey was reported as corresponding to 0.4 ACH. Furthermore, it was reported in BETSI that 30 % of all the investigated houses had some sort of mold issues in the basement or attic, where a probable cause was insufficient ventilation (Boverket, 2009).
Mechanical ventilation or airtightness were not required in any building requirements in the 1960s. Building requirements for heat recovery were introduced in 1989 but later scrutinized in 1994.

Table 2.B Summary of U-values for the building envelope and air change rates.

Building part	Building codes	Surveys and archetypes for 1960s houses		
	BABS 1960, SBN 1967	BETSI	Formas	Calculated. Constructions by Björk et al (2009).
		U-value / (W/(m²·K))		
Exterior wall	0.5 - 0.8	0.28 - 0.37	0.4	0.35 - 0.45
Roof/attic	0.4	0.22	0.26	0.30 - 0.37
Windows and doors	3.1	2.4	3.0	2.5 - 3.3
Slab on Ground / basement	0.5	-	0.5	0.45 - 0.6
Ventilation /ACH	0.7	0.4	N/A	N/A

2.2 1960s Building Techniques and Possible Renovation Measures

2.2.1 Cold attics

Insulating the attic floor is often recommended in EPCs as an inexpensive measure with short payback time. The procedure is relatively easy for homeowners to perform themselves. Attics are considered cold attics when there is no insulation added to the interior side of the roof. The temperature corresponds thereby to the outdoor environment. When adding insulation to the attic floor, less heat transfer occurs from the indoor environment to the attic, resulting in a lower attic temperature than prior to the added insulation. Warm and humid indoor air transfers by vapor diffusion through the attic floor and could potentially condensate on cold surfaces in the attic, which could result in microbiological growth (Hagentoft, 2003).

It is recommended to add a vapor barrier on the warm side of the attic floor construction before adding non-hygroscopic insulation materials, such as glass wool and rock wool. When adding hygroscopic insulation materials, such as cellulose fiber, the use of vapor barrier is not recommended (Björk et al., 2011). All of the above-mentioned insulation materials come in slabs, or as loose fill. The latter is provided in bags or can be ordered as a “blown-in,” which facilitates economy of scales.

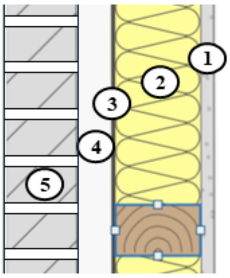
Nik et al. (2012) studied the potential risk of mold growth in cold attics in four cities in Sweden. Gothenburg and Malmö showed an increased risk of mold growth after adding insulating to the attics due to the higher relative humidity and slightly warmer winters, compared to the attics in Stockholm and Östersund. Mechanical ventilation with a supply air fan that is controlled by the difference in relative humidity in the supply air and the attic space, was shown to be the most effective ventilation, to minimize the risk of mold growth. Ventilation supplied by grills in the gable or openings along the eaves resulted in a higher risk of mold growth.

2.2.2 Exterior walls

Most single-family houses in the 1960s were constructed with wood as load bearing construction. Wood panels or façade bricks functioned as façade cladding, with a ventilated air gap behind to dry out the construction. Construction details are presented in Figure 2.4, originally by Björk et al. (2015) redrawn for this thesis. Adding insulation to the exterior wall is preferable placed to the exterior side of the construction. The façade cladding would need to be disassembled, extension studs need to be added to hold the new insulation layer and finally the wind barrier and air gap needs to be added before applying the preferred façade cladding. For this thesis, it is assumed that the old façade materials to be outdated, and in great need of replacement. When adding insulation externally, windows might need to be placed further out, in order to avoid a "hollow" look. Furthermore, the overhang of the roof might not cover the extended walls, which is yet another reason to have a long-term renovation plan.

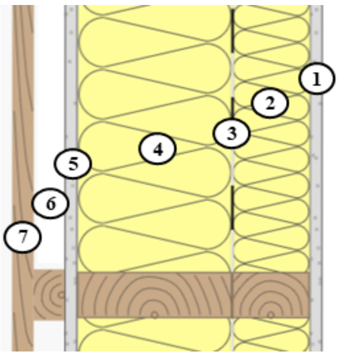
Adding insulation to the interior side of the construction should be performed with caution since the condensation point is moved into the construction. If the original construction consists of a vapor barrier, it needs to be placed at a maximum of one-third into the new construction. Drawdowns of insulating internally includes the diminished floor area and thermal bridges from the intermediate floor slab not to be reduced (Hagentoft & Sandin, 2017). Internal insulation might be the only available option if building permits deny the change of the façade.

On the other hand, if insulation is placed externally, the vapor barrier is preferable place behind the gypsum board when the new insulation layer is <150 mm, but could be placed according to Figure 2.5, between the insulation slabs if the new insulation layer is >150 mm. This solution is protecting the vapor barrier from being damaged if the gypsum board is penetrated.



1. Gypsum board (12.5 mm)
2. Glass wool insulation (75 mm) embedded between wood studs (75 x 45 mm)
3. Wood fiber board (3.5 mm)
4. Ventilated air gap (30 mm)
5. Façade cladding, brick (63 mm), alternatively wood panel (28 mm x 120 mm)

Figure 2.4 Original construction for 1960s exterior walls.



1. Gypsum board (12.5 mm)
2. Insulation (75 mm) embedded between wood studs (75 x 45 mm)
3. Vapor barrier / PE foil (0.2 mm)
4. Added insulation (50-250 mm)
5. Wind barrier, gypsum board (12.5 mm)
6. Ventilated air gap (30 mm)
7. Façade cladding, brick (63 mm), alternatively wood panel (28 mm x 120 mm)

Figure 2.5 Suggested new construction of exterior walls.

2.2.3 Basement walls

Basement walls were typically constructed by externally plastered hollow-concrete blocks, with added wood fiber insulation to the interior which provided a *U*-value of approximately 0.5 W/(m²·K). Adding insulation internally is not recommended due to capillary suction from the exterior walls. If performed internally, a maximum of 50 mm -100 mm EPS insulation is recommended, without the use of wood studs or vapor barrier (EPS-bygg, 2010).

When adding insulation externally, a draining material called Isodrän is commonly used in Sweden, which has the same thermal conductivity as EPS or XPS. Appling insulation externally requires full exposure of the basement walls, which is a costly operation and usually only performed when drainage work of the house is executed (Isodrän, 2023).

2.2.4 Slab on ground

Typical foundations in the 1960s were built as a 100 mm cast concrete slab onto gravel or crushed rocks, often with no insulation below the concrete. To reduce heat losses and obtain lower *U*-values, wood studs were added on top of the concrete or partly cast inside the concrete with an insulation layer between the wood studs. This construction provides a *U*-value of 0.45 W/(m²·K) - 0.6 W/(m²·K), depending on the insulation thickness (Polygongroup, 2024). From a moisture safety perspective, this is a critical construction due to capillary suction to the wood materials (Hagentoft & Sandin, 2017; Östman, 2017). In multiple simulations of these 1960s constructions, Östman (2017) found that the construction would result in microbiological growth on wood materials or in the remains of sawdust. Only when the flooring was done with leakages or air gaps, sufficient air movements and vapor diffusion led to lower moisture content.

When adding floor heating into a concrete slab, a minimum of 300 mm insulation is recommended in order to avoid heat losses to the ground. Redoing a concrete slab is a time-consuming work, and costly, often in the range of 500 000 SEK - 700 000 SEK for a single-family house. The benefit is that no room height is lost when digging out the old ground and recasting the slab.

Internal insulation could also be performed with a material called EPScrete, or sometimes referred to as "warm concrete." A mixture of lightweight concrete and EPS insulation, offers a thermal conductivity of 0.08 W/m²·K – 0.1 W/m²·K. A maximum thickness of 50 mm - 100 mm can be cast on top of the existing concrete slab.

2.2.5 Windows and Doors

The technical lifetime for windows and doors is considered to be 50 years, although cheaper and weaker frames made out of fast-growing wood in the 1960s were common, with a shorter expected lifetime (Nylander, 2018). Adding an isolating pane to the original windows could be considered as an option when the architectural characteristic of the window is worth saving or building regulations will not allow the change of windows. In these cases, windows with a total *U*-value of 2.0 W/(m²·K) are assumed for the calculations.

2.2.6 Ventilation and Infiltration

In order to comply with BBR requirements, the ventilation air flow must not fall short of 0.35 l/(s·m²) equivalent to 0.5 ACH when the ceiling height is 2.5 m. Cooling coils are generally not used in smaller ventilation systems for residential living, whereas cross ventilation, achieved by opening windows on different sides of the building could reduce overheating during heatwaves. Increasing the mechanical ventilation airflow during heat waves to reduce the indoor air temperature, as well as using a cooling coil would result in a higher demand for fan energy and larger duct sizes, which are not taken into consideration. Energy efficient MVHR-systems are needed to achieve a Specific Fan Power (SFP) under 1.5 kW/(m³/s) according to the requirements in BBR29.

Infiltration is defined as uncontrolled air leakages through the building envelope. Air tightness is highly dependent on the craftsmanship of the actual building. 90 % of all single-family houses built in the 1960s have natural draught ventilation (Boverket, 2009). Ventilation in the 1960s often relied on leakages in the building envelope, and supply air ducts were often neglected. When adding facade insulation, changing the facade material, or changing windows, the air tightness could be improved and reduces the natural ventilation. In a typical single-family house, infiltration, and ventilation combined account for 25 % - 45 % of all heat losses, depending on air tightness and wind profile of the location. For buildings located in open landscapes or closer to coastal areas, the wind profile often results in even higher infiltration losses. When adding insulation internally, it is important to investigate if the construction has a vapor barrier installed. Accelerated aging tests have proven that PE-foils last for 50 years. It is important to install the PE-foil with overlapped joints and to repair all rips and tears. Even a 1 mm - 5 mm gap around electrical outlets has shown increased infiltration rates up to 8 m^3/h, at 50 Pa pressure difference, which corresponds to 0.022 $l/(s \cdot m^2)$ for a 100 m^2 single-family house (Bankvall, 2013).

Improving airtightness as a stand-alone renovation measure is not presented as an option, although adding or improving the insulation between the window frame and the connected wall and adding sealing strips to old windows could significantly reduce infiltration (Björk et al., 2011). Instead, while renovating the building envelope, reduced infiltration follows as a positive consequence. Tombarević et al. (2023) performed blower door tests before and after the change of windows and doors in a multifamily house from the 1980s in Montenegro. Infiltration rates decreased from 6.25 ACH to 0.77 ACH after the installation.

Jokisalo et al. (2009) studied infiltration rates in 170 Finnish detached houses, built in the era of 1989 - 2007. Infiltration rates due to leakages were on average at 3.7 ACH at 50 Pa, and transmission losses due to infiltration and ventilation results in the range of 15 % - 30 % of the total heating demand. Energy demand due to increased infiltration rate has an almost linear relation. Increasing the infiltration by 1 ACH, results in a 7 % increased energy demand for space heating.

In a literature review by Kalamees (2007), air tightness of Scandinavian houses built in the 70s and 80s were assessed. The average ACH at 50 Pa for 205 houses in Sweden, 61 houses in Norway and 16 houses in Finland were 3.7 ACH, 4.7 ACH and 6.0 ACH respectively. Hasper et al. (2021) studied 2 934 passive house retrofit projects in Germany, where the average air tightness was found to be 0.41 ACH at 50 Pa pressure difference.

A ventilation system with rotary wheel heat exchanger is commonly used in residential buildings with an efficiency rate of 85 %. These heat exchangers recover both latent and sensible heat, while a small portion of the exhaust and supply air are being mixed. This could spread odors since exhaust air is commonly taken from kitchen and bathroom areas. Therefore, a separate kitchen enforced exhaust fan is needed while cocking for. A plate heat exchanger could be used to avoid mixing of the air streams, with the downside of slightly lower efficiency (Warfvinge & Dahlblom, 2010).

2.2.7 Thermal bridges

Sweden Green Building Council (2022), the issuing organization of the certification Miljöbyggnad, allows approximations for determining thermal bridges. In the bronze and silver category, thermal bridges are assumed to be 30 % of the total transmission losses for the envelope. For the gold level, only essential thermal bridges have to be calculated. It should be considered that this applies to new constructions, whereas the building code allows a total U_m value of 0.3 $W/(m^2 \cdot K)$. Šadauskienė et al. (2015) found similar results where thermal bridges account for 35 % of the building envelope transmissions.

2.2.8 Lighting

Indoor lighting is excluded from the EPCs for single-family houses. However, high internal gains from light sources would reduce the need for space heating. In 2008, the average household electricity for lighting was 800 kWh per year, which was estimated as 600 kWh / year in 2015 (The Swedish Energy Agency, 2018). A further decrease would be expected due to old lightbulbs being exchanged for new LED bulbs when broken down, although Schleich et al. (2014) found that the “rebound effect” results in more lighting and higher energy use when switching for highly efficient lightning or equipment. For this master thesis, it is assumed that households have already replaced old incandescent light bulbs with LEDs which require about 90 % less energy.

3 Methodology

3.1 Energy modelling

IDA ICE was used for all energy simulations, which is a commonly used building simulation software, developed by EQUA Solutions. The software is verified according to the standard CIBSE TM33 by Moosberger (2007) and according to the standard EN 15265 and EN 15255 for thermal performance of buildings (Equa Simulation AB, 2010).

3.1.1 Reference Buildings

Two commonly used archetypes from the 1960s according to Björk et al. (2015) were modeled in IDA ICE 5.0. Reference Building 1, see Figure 3.1 (left) was commonly known as a "Hultsfredshus". A catalogue house from a one of the most productive prefabrication factories in Sweden, from a town called Hultsfred in Småland, south of Sweden. Approximately 2 000 houses per year during The Million Program was produced in this factory (Visit Hultsfred, 2023). This one-story building entailed 135 m² living area with 4 bedrooms on the ground floor, with a full basement of 135 m² housing hobby rooms, food storage, and a boiler room. Reference Building 2, see Figure 3.1 (right) is a 100 m² single family-house with 3 bedrooms, where the gavel was partly connected to the garage.

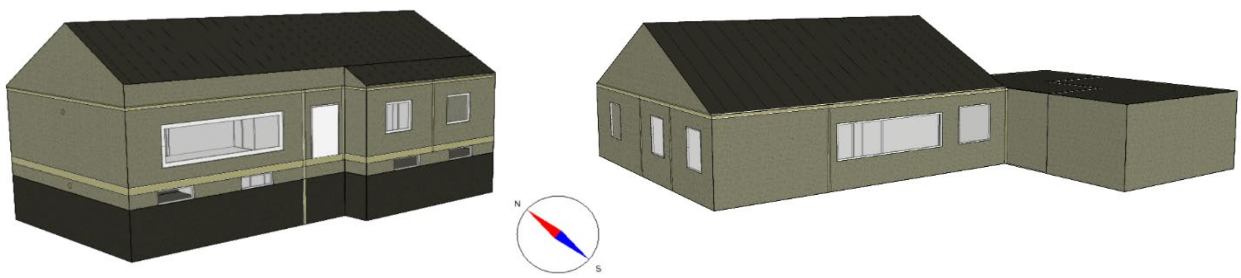


Figure 3.1 IDA ICE Energy model of Building 1 (left) and Building 2 (right).

Identical construction details for both reference buildings were assumed, both for the Base Cases, and in all renovation scenarios. Both buildings were modelled with the living room located to the south. The building lots were assumed to be 600 m² each, with each building placed in the center. To represent neighboring buildings and vegetation shading the low inclined solar heat gains during the year, a 4 m opaque object was modeled, surrounding the building lot. The building envelope was constructed according to the findings in the literature review. However, the formfactor, window-to-wall ratio and internal gains differed between the two models. Building 1 was assumed to house 3.51 occupants, and 2.79 occupants for Building 2, according to SVEBY standards. The heating set-point for the ground floor was decreased to 18 °C during June, July, and August. Table 3.A presents the general simulation input data for both archetypes, according to standards in BEN 2 (Boverket, 2017).

Table 3.A Simulation input data according to BEN2 and SVEBY standards.

Ground floor temperature	Basement temperature	Domestic Hot Water	Plug loads	Internal gains utilization	Occupancy Schedule	Internal gains people
21 °C	18 °C	20 kWh/m^2_{Atemp}	30 kWh/m^2_{Atemp}	70 %	14 h / day	80 W / person

3.1.1.1 Locations for the simulated buildings

Sweden is approximately 1600 km long and divided into three major provinces, visualized in Figure 3.2. The lower two provinces were chosen, due to containing 82 % of the total building stock, and 80 % of the final energy use in Swedish households (Energimyndigheten, 2021). The six biggest cities in these provinces were chosen, with the criteria of a distance exceeding 250 km in between, and half to be located at coastal-near area.

Figure 3.2 Map of Sweden, displaying the three major provinces and the six locations for the energy simulations.

3.1.1.2 Heat Transfer Equations

Heat transfer calculations were simplified, in order to combine heat losses due to radiation, convection and conduction. These calculations were later used to validate the Base Case energy simulations.

Thermal resistance:

$R = \frac{d}{\lambda}$ $\quad [R] = \frac{m^2 \times K}{W}$ *Equation 1*

U-value:

$U = \frac{1}{R_{tot}}$ $\quad [U] = \frac{W}{m^2 \times K}$ *Equation 2*

One dimensional stationary heat transfer through building component layers

$Q = UA \times \Delta T$ $\quad [Q] = W$ *Equation 3*

Where:

d = thickness in m

λ = lambda, thermal transmittance in W/(m·K)

R_{tot} = $R_{layer\ 1}+R_{layer\ 2}+R_{layer\ 3}...R_{layer\ N}$

ΔT = temperature difference between the interior and exterior side in K

A = area in m^2

3.1.2 Base Case Construction Details

Construction details are displayed in Table 3.B and will be further analyzed when presenting renovation solutions and obtained *U*-values, as well as when validating the Base Case simulations by hand calculations.

Table 3.B Base Case construction details for Building 1 and Building 2.

Building part	Construction (inside to outside)	Lambda / (W/(m·K))	*R*-value / ((m²·K)/W)	*U*-value / (W/(m²·K))	Building 1 area /m²	Building 2 area /m²
Ext. walls above ground	12.5 mm gypsum board 75 mm insulation (between wood studs). 3.5 mm wood fiber board 30 mm ventilated air gap 63 mm facade brick	0.22 0.044 0.07 0.11 0.58	0.057 1.705 0.050 0.273 0.109	0.42	130	111.7
Basement walls	10 mm chip board 50 mm fiber board 250 mm concrete 10 mm render 1 000 mm soil	0.14 0.07 1.7 0.8 2.0	0.071 0.714 0.147 0.013 0.500	0.48	112	-
Slab on ground	25 mm wood flooring 3.5 mm fiber board 120 mm concrete 1 000 mm soil	0.13 0.07 1.7 2.0	0.192 0.714 0.071 0.500	0.45	141	103
Roof	25 mm spruce	0.14	0.179	2.87	187	140
Attic floor	18 mm chip board 100 mm glass wool 18 mm wood panel	0.14 0.044 0.14	0.129 2.273 0.129	0.37	141	103
Windows Ground floor	2 pane windows (25 % frame factor)			3.0	19.3	17.5
Windows basement	2 pane windows (25 % frame factor)			3.0	6.3	N/A
Doors	30 mm oak wood, partially glazed			2.9	4.6	1.9

	Building 1	Building 2
A_{temp}	270 m²	100 m²
Volume	661.5 m³	260 m³
Total envelope area (roof excluded, attic floor calculated as envelope boundary)	552.2 m²	337.1 m²
Building envelope, geometric *U*-value	0.71 W/(m²·K)	0.76 W/(m²·K)
Building envelope total *UA*-value	394.2 W/K	255.8 W/K
Form factor	2.0	3.4

R-values for each construction include internal surface resistance (R_{si}) 0.13 ($m^2 \cdot K$)/W and external surface resistance (R_{se}) 0.04 ($m^2 \cdot K$)/W, except for basement walls and slab on ground, which only include R_{si}.

Note that the roof was modeled as a single layer of 25 mm groove and tongue spruce wood. Most attics were constructed as cold attics, whereas the attic floor functioned as the main envelope insulation layer in the roof construction, hence the roof was not considered nor calculated as part of the building envelope. Basement walls and concrete slab include 1 000 mm of soil in the *U*-value calculations, according to the ISO-13370 standard. Internal walls are modeled as 75 mm wood studs with intermediate insulation, covered with 13 mm gypsum board on both sides. Openings between all zones ensured sufficient air flows.

Infiltration was set as 2 ACH at 50 Pa. Natural ventilation was modeled with an Air Handling Unit (AHU) with supply and extract air flows set to 0.27 l/($s \cdot m^2$) which is equivalent to 0.4 ACH according to the measurements in BETSI. Electricity for the ventilation was neglected. Thermal bridges were set as 20 % of the *UA*-value.

3.1.3 Renovation Measures

Renovation measures for the building envelope and HVAC-installations are presented in Table 3.C, and further explained in the methods section. However, simulating the 29 renovation scenarios in a parametric mode would result in 22 500 combinations for each building archetype. Thereby, each renovation step was calculated and presented individually, in order to calculate costs and environmental impacts for each step. Ultimately, the proposed renovation passport offers the availability of displaying all combinations for each of the two buildings.

Table 3.C Renovation matrix explaining all renovation measures.

Building envelope	**Added insulation thickness / mm**				
	Step 1	**Step2**	**Step 3**	**Step 4**	**Step 5**
Attic insulation	100	200	300	400	500
Exterior walls	50	100	150	200	250
Basement walls	50	100	200	300	400
Slab on ground	50	100	200	300	400
			U-value / (W/($m^2 \cdot K$))		
Windows	2.0	1.2	0.8	N/A	N/A
Doors	1.2	0.8	-	-	-
HVAC					
Mechanical Ventilation with Heat Recovery	η = 85 %	-	-	-	-
Heat Pumps	Air-To-Air HP sCOP 3.5	Air-to-Water HP sCOP 3.0	Geothermal HP sCOP 4.0	-	-

3.1.4 Goal renovation packages according to building requirements

Two combined renovation packages in addition to the initial Base Case design are simulated for both buildings, referred to as BBR-standard and Passive House-standard, illustrated in Figure 3.3.

Figure 3.3 Illustration of the Base Case, and the renovation package BBR-standard and PH-standard.

Selecting renovation measures was an interactive procedure which considered LCA results, investment costs and the obtained final Energy Class after the renovation.

Firstly, an interactive Excel sheet was produced, which calculated and presented the final Energy Classes after each renovation. Secondly, the goal was for the BBR-s to meet energy class C, and for the PH-s to meet energy class A, while using district heating for space heating and DHW. The use of district heating as an energy source was determined in order not to overestimate the impact of installing a heat pump with a high sCOP. District heating is equivalent to an older heat pump with a sCOP of 2.6, in terms of primary energy. The primary energy number was calculated using Equation 4. Thirdly, different renovation measures were simulated, based on the findings for optimal thicknesses in the LCA and cost calculations. Lastly, the BBR-s and PH-s renovation package for both building types were defined.

The requirement for renovated single family houses, according to the current building code BBR29, is to reach Energy Prestanda <90 kWh/ for building 1, and <95 kWh/ for building 2. In addition, if possible, the goal is to reach the envelope *U*-values, explained in Table 3.D.

The PH-standard was not aiming to meet PH-criteria from the FEBY18 certification level. The objective was only to meet the requirements regarding *U*-values for the building envelope, air tightness and mechanical ventilation system with heat recovery in Table 3.D. The passive house building certification is one of the most recognized standards in northern Europe and represents a highly energy efficient building design, requirements taken from (Andrén & Tirén, 2012).

Table 3.D The goal U-values and ventilation details for the BBR-standard and PH-standard renovation packages.

Part	BBR29 Building code	PH-requirements
	U-value / (W/(m²·K))	*U*-value / (W/(m²·K))
Exterior wall	0.18	0.1
Roof/attic	0.13	0.1
Windows and doors	1.2	0.8
Slab on Ground / basement	0.15	0.1
Ventilation /ACH	0.5	0.5
MVHR	-	n = 85 %
Air tightness at 50 Pa / $l/(s \cdot m^2_{envelope\ area})$	-	0.3

$$EP_{pet} = \frac{\sum \frac{n}{i=1} \left(\frac{E_{uppv,i}}{F_{geo}} + E_{Kyl,i} + E_{tvv,i} + E_{f,i}\right) \times VF_i}{A_{temp}}$$ *Equation 4*

Where EP_{pet} is the primary energy number, E_{uppv} is space heating in kWh/year, E_{kyl} is cooling in kWh/year, E_{tvv} is domestic hot water in kWh/year, E_f is property electricity in kWh/year and VF_i is the energy carrier correction factor where 1.8 was used for electricity, 0.7 was used for district heating. F_{geo} is the geographical correction factor, with the following values: 0.8 – Malmö, 0.9 – Gothenburg, 1.0 – Stockholm and Växjö, 1.1 – Karlstad, 1.2 - Borlänge.

3.1.4.1 Insulation materials in general

The following sections present the obtained *U*-values after each renovation step. All the suggested insulation materials offer lambda values in the range of 0.030 W/(m·K) – 0.036 W/(m·K). All simulations were thereby run with a generic mineral wool insulation material, with lambda value of 0.033 W/(m·K), density 50 kg/m³ and heat capacity of 2000 J/kg. In all scenarios, the original insulation layer in the corresponding reference building was kept in the assembly except for the slab on ground construction due to moisture safety.

3.1.4.2 Attic insulation

Three variations of loose fill insulation are suggested as attic floor insulation: glass wool, rock wool and cellulose insulation. Thicknesses and *U*-values are displayed in Table 3.E.

Table 3.E Attic U-value after each renovation step.

Insulation	Base Case	+ 100 mm	+ 200 mm	+ 300 mm	+ 400 mm	+ 500 mm
U-value / (W/(m²·K))	0.370	0.180	0.119	0.089	0.070	0.059

3.1.4.3 Exterior walls

Three different types of insulation slab materials are investigated: mineral wool, rock wool and EPS. All of which could be used behind facade claddings such as wood panel, tiles, bricks or plastered. All constructions are recommended to include a minimum of 30 mm airgap (Hagentoft & Sandin, 2017). Regardless of the desired placement of the insulation layer, internally or externally, all simulations were run as externally placed, whereas the *U*-values did not change, and moisture assessment was out of scope for the simulations. Thicknesses and *U*-values are displayed in Table 3.F.

Table 3.F Exterior wall U-value after each renovation step.

Insulation	Base Case	+ 50 mm	+ 100 mm	+ 150 mm	+ 200 mm	+ 250 mm
U-value / (W/(m²·K))	0.423	0.258	0.185	0.145	0.119	0.101

3.1.4.4 Basement walls

All basement wall simulations were run with the insulation layer placed externally. Thicknesses and *U*-values are displayed in Table 3.G.

Table 3.G Basement walls U-value after each renovation step.

Insulation	Base Case	+ 50 mm	+ 100 mm	+ 200 mm	+ 300 mm	+ 400 mm
U-value / (W/(m²·K))	0.482	0.295	0.190	0.110	0.097	0.076

3.1.4.5 Slab on ground

Two materials were used in the slab on ground simulations. EPScrete was only simulated as 50 mm and 100 mm, following the recommended maximum thickness for this material.

The second material was regular EPS insulation below the slab, which was simulated for all steps. It should be noted that the calculated *U*-values for the slab differ from the output data in IDA ICE, with a probable explanation of the "warm-pillow effect," below the slab. IDA ICE calculates the heat transfer towards the ground according to the standards in ISO-13370. Table 3.H presents both the simulated and calculated *U*-values, whereas the IDA ICE output was used in this master thesis.

Table 3.H U-values for slab on ground.

Insulation	Source	Base Case	+ 50 mm	+ 100 mm	+ 200 mm	+ 300 mm	+ 400 mm
EPScrete *U*-value / (W/(m²·K))	IDA ICE output	0.45	0.36	0.29	-	-	-
EPS + Concrete *U*-value / (W/(m²·K))	IDA ICE output	0.45	0.27	0.20	0.13	0.09	0.07
EPS + Concrete *U*-value / (W/(m²·K))	Calculated	0.69	0.34	0.22	0.13	0.09	0.07

3.1.4.6 Windows and doors

Windows and doors were modeled in 3 steps. Oak wood was simulated for window frames and doors in all scenarios. Window placement was set with a sill height of 0.9 m above the internal floor level. Glazing and frame specifications are found in Table 3.I.

Table 3.I Window specifications.

Total construction *U*-value / (W/(m²·K))	**3.0** (Base Case)	**2.0**	**1.2**	**0.8**
Frame factor	25 %	25 %	30 %	30 %
Frame *U*-value / (W/(m²·K))	3.3	2.7	1.5	1.5
Glazing *U*-value / (W/(m²·K))	2.9	1.8	1.07	0.5
Glazing / *g*-value	0.76	0.68	0.59	0.49
Recess dept	0.05 m			
Shadings	Always drawn, multiplication factor for *g*-value was 0.71 (BEN3 standard).			

3.1.4.7 Thermal Bridges

Thermal bridges were modeled as 20 % of the Base Case *UA*-value, equivalent to 0.14 W/(m²·K). The absolute value in terms of heat losses in kWh, was later used for all individual renovation scenarios since it was assumed that a reduction of thermal bridges was not achievable by a single renovation measure. SGBC (2023) calculates thermal bridges as a 30 % addition of the average *UA*-value for new constructions. According to BBR29, the highest *UA*-value for new constructions is 0.3 W/(m²·K), which would yield a thermal bridge *U*-value of 0.09 W/(m²·K). This might not be representable for older buildings, hence the 20 % addition to the Base Case *UA*-values were estimated as better representable.

For the PH-standard, thermal bridges were calculated as half of the base case value, equivalent to 0.07 W/(m²·K) for the *UA* since the combined renovation measures were assumed to reduce the thermal bridges significantly.

3.1.4.8 Mechanical Ventilation with Heat Recovery

The BBR-standard simulations were run with 0.35 l/(s·m) for the occupied areas, and 0.1 l/(s·m²) for the basement, to follow the BBR requirements. As for the MVHR simulation, a recovery rate of 85 % was used. Electricity for the Air Handling Unit (AHU) was deducted from the energy demand savings in the result section. However, when calculating the Primary Energy need for energy classifications, the AHU electricity was calculated as property electricity and the full space heating savings were calculated.

3.1.4.9 Duct design sizing

HVAC design was performed using hand calculations. All quantitative data and dimensioning methods were taken from (Warfvinge & Dahlblom, 2010). The equal pressure method was used in order to achieve a pressure drop close to 1 Pa/m throughout the ventilation system. Air flow charts for circular steel ducts, originally by Swegon, were assessed to limit the pressure drops between >0.6 Pa to <1.1 Pa, to obtain a balanced and energy efficient system. Volume flow rates were limited to 1.5 m/s – 3.0 m/s, in order to keep duct noises to a minimum. Air flow rates were determined to be 61 l/s and 35 l/s for reference building 1 and 2 respectively, equal to 0.35 l/(s·m²) for occupied areas and 0.1 l/(s·m²) for occasionally occupied areas such as the basement in reference building 1. All ducts were estimated as mounted onto the interior side of the ceiling, fully visible without any covering materials or insulation. Supply air diffusers were taken from the Swegon database, with a suggested throw length equal to 75 % of the distance between the diffuser and neighboring wall in order to achieve a mixed ventilation without draughts. Generalized pressure drops for Diffusers (D), Tees (T) and Elbows (E) were set to 7 Pa, 5 Pa and 2 Pa respectively, calculated according to Swegon tables using an air flow rate of 3 m/s and a diameter of 100 mm. The 5DD approach was taken into consideration when designing the duct layout, where a minimum distance of 5 diameters has to be achieved before a fitting to avoid turbulent air flow. Supply air was distributed as 4 l/s per bed space, while the remaining was distributed into the living room. Exhaust air was taken from kitchen, laundry room, toilet, and bathroom, with a minimum volume flow rates of 10 l/s per zone. A separate kitchen exhaust fan with enforced air flow during cooking was assumed to be present, used to avoid grease and odors into the heat recovery system (Warfvinge & Dahlblom, 2010).

SFP, energy use and heating coil size were calculated using the online tool ProCASA from Swegon (2024), and compared to the IDA ICE results.

3.1.4.10 Power demand

Heat pumps were sized based on the peak power demand simulations in IDA ICE. Hand calculations were used to confirm these simulations using Equation 5. Dimensioned Winter Outdoor Temperatures (DVUT, in Swedish) were assessed for each city, displayed in Table 3.J. The indoor heating setpoint temperature was set to 17 °C for all calculations, assuming that internal gains and solar heat gains would further increase the temperature to 21 °C. The building time constant which corresponds to the time it takes for the indoor temperature to drop to 63 % of the desired temperature was not calculated. However, it was assumed that the base case models and BBR-standards were considered as light weight constructions with low thermal mass and insulation, with a two-day time constant, and for the PH-standard to achieve a five-day time constant (Warfvinge & Dahlblom, 2010).

$$Peak\ Power\ Demand = P_{transmission} + P_{Infiltration} + P_{Ventilation}$$ *Equation 5*

$$P_{Transmission} = UA \times (T_{Setpoint} - DVUT)$$ *Equation 6*

$$P_{Ventilation\,\&\,Infiltration} = p \times C_p \times q \times (T_{Setpoint} - DVUT)$$ *Equation 7*

Where:
P = Power demand in W, p = Density of air in 1.2 kg/m³, Cp = Heat capacity for air in 1000 J/(kg·K), q = volume air flow rate in m³/s, $T_{setpoint}$ = indoor heating temperature setpoint in °C, DVUT = Dimensioned Winter Outdoor Temperature in °C.

Table 3.J DVUT for all six locations (Warfvinge & Dahlblom, 2010).

City	Malmö	Växjö	Gothenburg	Stockholm	Karlstad	Borlänge
DVUT 2-days / °C	-7.1	-11.9	-9.3	-12.9	-15.3	-16.8
DVUT 5-days / °C	-6.1	-10.4	-8.0	-11.3	-14.2	-15.0

3.1.4.11 Heat Pumps

The energy use, which is the energy delivered to the heat pumps, was calculated in Excel by dividing the energy demand by the Seasonal Coefficient of Performance (sCOP) for each heat pump. An Air-To-Air heat pump with sCOP 3.5 was assumed to cover 50 % of the energy demand of each floor, due to internal walls obstruction the heated air flows from fully cover the whole building's heating demand. Air-to-water and geothermal heat pumps were assumed to have a sCOP 3, and sCOP 4 respectively, which represent the combined sCOP for both space heating and DHW. Both heat pumps were sized to cover 100 % of the peak power demand in order to follow the BBR-requirements for maximum installed power. Both heat pumps require a water-based radiator system.

3.1.4.12 Radiators

The Base Case buildings were considered lacking water-borne radiators and heated by electric radiators. Installing a heat pump, district heating or solar thermal for space heating, would require a water-borne radiator system. The power demand was calculated for Building 1 and 2 in the three design stages: Base Case, BBR-standard, and PH-standard. Radiators are generally designed with the same width, or 200 mm less as the windows width, and positioned 100 mm below the windowsill. Since 1985, it's not common to size radiators for higher supply temperatures than 55 °C and return temperatures of 45 °C (Warfvinge & Dahlblom, 2010). For both Buildings, one radiator was placed below each window, and the power demand was calculated on a building level.

Sizing of each radiator was simplified and calculated as:

$$P_{Radiators} = \frac{Total\ building\ heating\ demand}{total\ number\ of\ radiators}$$ *Equation 8*

Where P = Power demand in W.

(Purmo, 2024) was used for accessing the weight of radiators based on dimensions, power demand and supply water temperatures. Total pipe lengths were measured in AutoCAD according to floor plan drawings. 12 mm PEP pipes were considered, which could be exposed or integrated into internal walls.

3.2 Life Cycle Assessment

Green House Gasses (GHG) allow short wave radiation from the sun to surpass through, but block and absorb the long wave radiation that is emitted from earth, causing the greenhouse effect and hence global warming. GHG consists of approximately 80 % Carbon Dioxide, 11 % Methane, 6 % Nitrous Oxide and remaining parts from Fluorinated gases (EPA, 2024). For this thesis, GHG emissions are displayed as Carbon Dioxide equivalent (CO_2eq.), which is the summarized greenhouse effect for the emissions, presented as CO_2 as reference.

The climate impact category for Global Warming Potential fossil - Green House Gas emissions (GWP-GHG), was assessed for both operational energy, and the embodied emissions for building materials and HVAC installations. Figure 3.4 illustrates the process of selecting data for the underlying CO_2eq. emissions calculations. The climate database from (Boverket, 2024b) was used as the primary source, which is commonly used in Sweden for constructing climate declarations which is required by building regulations since 2022 for new constructions. The database contains data for generic building materials. The secondary source used for this thesis was the Emissions database by the The Finnish Environment Institute (2024), and lastly, published EPDs in accordance with the standards ISO 14025 and EN 15804 + A2.

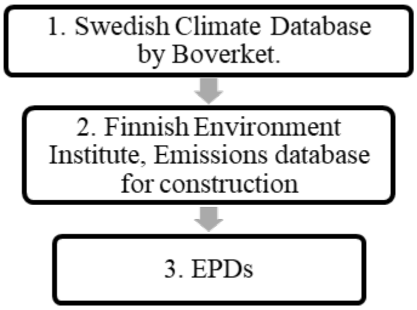


Figure 3.4 Methodology illustration for selecting data for the CO_2 emissions calculations.

The life span of the building material was set to 50 years, where materials with shorter lifetime were multiplied with a correction factor to achieve 50 years. The system boundary was set to A1-A3 (cradle-to-gate), B4 (replacement for all installations with less than 50 years lifetime), and B6 (operational energy). Functional unit was set to 1 m² of heated floor area.

Operational energy was assumed to be provided by electricity in all renovation scenarios, either by direct electricity or by Heat Pumps. The “Swedish electricity mix” from the climate database by Boverket was used where the emissions were declared as 0.037 kgCO_2eq. / kWh.

CO_2 emissions due to district heating vastly differs based on the municipality and electricity company in Sweden. Factors that influence the emissions are the efficiency of the waste-incineration plant unit and the amount of waste heat from the industry is used. Energiföretagen (2023) advises against the comparison of district heating emissions, due to the import and export of garbage between different municipalities, which might not provide the full picture. The average emissions value from the Boverket climate database of 0.056 kgCO_2eq. / kWh was used.

The embodied emissions for all renovations measures were calculated according to the input values in Appendix H. The volume for the added material in each renovation measure is presented in Appendix G for Building 1 and 2, respectively.

3.3 Investment costs

The online tool Wikells Sektionsfakta (2024) were assessed for all price estimations throughout this master thesis, which have been used extensively in the field of researching for renovation costs estimations. Since the current building archetypes are assumed in their original state, components such as wall and attic insulation, bricks and mortar joints, façade panel, doors and windows are outdated and have reached the end of its service life. Therefore, replacement is inevitable at some point and the energy efficient measures in this master thesis are assumed to be implemented simultaneously. Only the costs for the added insulation materials and labor work needed to achieve the goal *U*-values were calculated. This excluded the costs for demolition, recycling, landfill, scaffolding, transportation, digging, paint job and reassembly of façade materials or any indoor surfaces.

Windows and HVAC installations were calculated as the full installation since the base case used natural draught ventilation and direct electricity.

Building owners all over Sweden have different electricity rates and agreements with the electrical companies. Energy prices are not assumed or displayed, nor were LCC calculations performed.

Installation costs were calculated as:

$$Cost\ of\ savings = \frac{Installation\ cost}{Energy\ use\ savings_{50\ years}} \qquad [\frac{SEK}{kWh}] \qquad Equation\ 9$$

4 Results and Discussion

4.1 Energy modeling

4.1.1 Validation of the Base Case energy model

Table 4.A presents the simulated annual energy demand for Base Case, BBR-standard, and PH-standard, as well as the calculated energy demand for the Base Case buildings, to validate the energy modelling. The hand calculations overpredict the simulations by 7 % and 12 % for building 1 and 2 respectively. Warfvinge & Dahlblom (2010) emphasizes that hand calculations based on the degree hour method should only be used for approximations. Differences between the results might depend on numerous factors, such as modeling of window positions, ground properties for heat losses through basement walls and slab on ground. Degree hours were calculated based on 17 °C set point temperatures throughout the year, which might be higher than the actual building requirement for obtaining desired indoor temperature, and hence resulting in a higher energy demand. Simulations included a lower setpoint temperature in the basement throughout the entire year, and for the heating system to be shut off during June through September, which would result in less degree hours. Hand calculations are presented in Appendix Q and Appendix R.

Table 4.A Hand calculations and simulated energy demand results for the Base Case, BBR-standard and PH-standard.

	Hand calculations		**IDA ICE simulation results**					
	Base Case		**Base Case**		**BBR-standard**		**PH-standard**	
	/kWh	/(kWh/m²)	/kWh	/(kWh/m²)	/kWh	/(kWh/m²)	/kWh	/(kWh/m²)
Building 1	40 023	148	37 390	138	25 265	94	5 845	22
Building 2	22 985	230	20 526	205	11 442	114	4 485	45

4.1.2 Energy results for the renovation packages

Following the simulated results in

Table 4.B, building 2 indicates a higher energy demand than building 1 per A_{temp} throughout all renovation measures, which might be explained by the higher formfactor. Another explanation might be the lowered set point temperatures for the basement in building 1, while the area is still calculated as part of A_{temp}.

Compared to the Base Case, the BBR-standard renovation decreases the energy demand with 32 % and 44 % for Building 1 and 2 respectively, while for the PH-standard, energy demand is reduced by 84 % and 78 %, for Building 1 and 2, respectively. The higher energy demand reduction for building 2 in the BBR-standard scenario is explained by the use of MVHR in order to comply with the energy class C. On the other hand, when renovating towards the PH-standard, building 1 achieves higher energy reduction (percentage wise), due to the lowered air flows in the basement area, which ultimately leads to less ventilation losses.

4.1.3 Energy demand savings based on all individual measures.

Figure 4.1 presents the individual energy demand savings for each renovation measure, without the use of any heat pumps for the Stockholm location. All six locations are displayed in detail in Appendix A to Appendix F, where all locations achieved energy reduction (percentage wise), within 0.2 percentage points difference. While in absolute terms, the colder the climate, (Karlstad and Borlänge) the higher the heat losses and hence higher benefits of adding insulation. The opposite was true for warmer climates (Gothenburg and Malmö), while Växjö showed comparable results as Stockholm in general. To benchmark the two buildings, the energy savings are presented as kWh/(m²A_{temp}/year). Both buildings achieve similar reduction trends after each implemented measure; the buildings benefit the most reduction compared to the Base Case in the first renovation step, after which, each step entails less energy savings, in compliance with the phenomena "the law of diminishing marginal utility." As explained previously, building 2 has a higher form factor, (envelope-to-floor ratio), hence the generally higher savings in Figure 4.1.

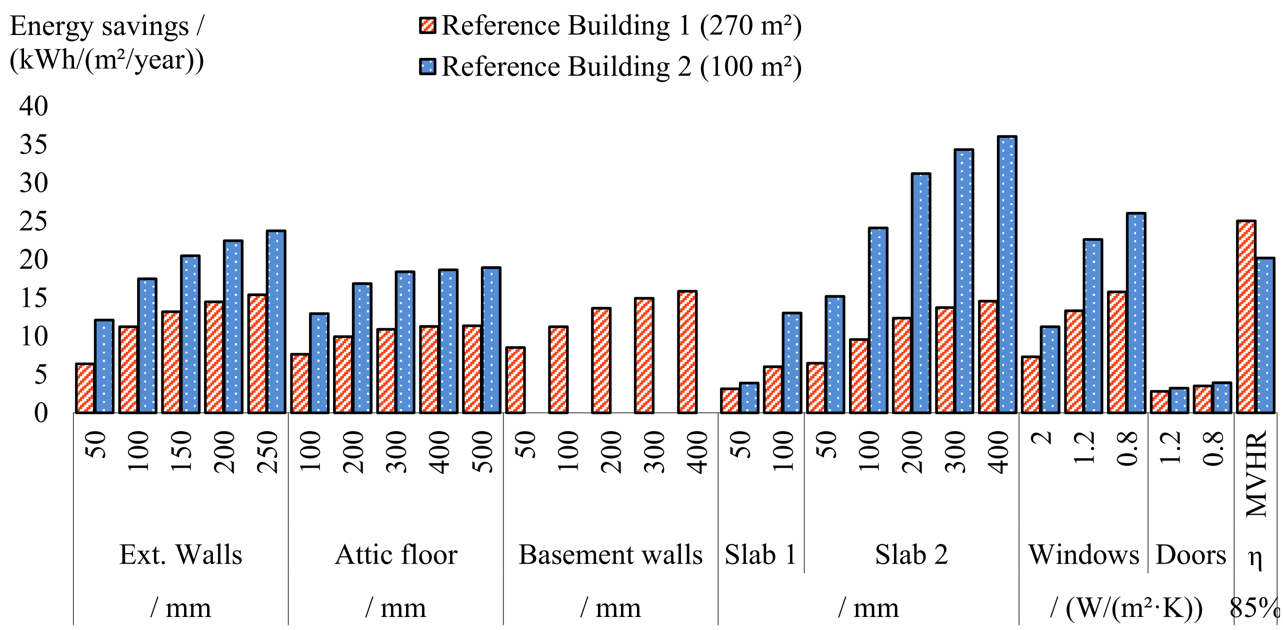


Figure 4.1 Energy demand reduction after each implemented renovation measure. Building 1 in red, Building 2 in blue, location Stockholm.

External walls show a continuing reduction in energy demand after each implemented renovation step, mainly due to lower increments in insulation thicknesses than for the remaining building envelope. The attic floor does not achieve significant reduction in energy demand after adding 300 mm of insulation.

The significantly higher benefits of insulating the slab in Building 2, could be explained by the same arguments as previously: lower set point temperatures in the basement for building 1, hence lower heat losses through the slab. "Slab 1" refers to EPScrete, while "Slab 2" refers to the more often used method of EPS insulation below the concrete slab. EPScrete offers more than twice as high lambda value as for EPS insulation, while the impact of adding EPScrete is less than for EPS insulation.

MVHR was more efficient in building 1 with larger area and airflows, explained by the possibility of a lowered air flow of 0.1 l/(s·m²) in the basement after installing MVHR, compared to the Base Case designs with a generalized air flow of 0.27 l/(s·m²) or 0.4 ACH.

Heat losses through windows are reduced noticeably when applying the energy glass with *U*-value 2.0 W/(m²·K), and BBR required windows with *U*-value 1.2 W/(m²·K). However, installing the more energy efficient windows with *U*-value 0.8 W/(m²·K) results in the highest energy demand savings after insulating the slab, for Building 2. Mechanical Ventilation with heat recovery yielded the highest reduction per square meter in Building 1.

4.1.4 BBR-standard and PH-standard renovation packages

To determine what renovation measures would yield energy class C for the renovation package BBR-s and energy class A for PH-s, the impact of different heating sources was first compared for the Base Case design. Originally, by using direct electricity the energy class G was reached, for both buildings. By changing the heat source to district heating, energy class D is obtained, which would exclude the building from the worst performing buildings, and no other measure would have to be taken, in compliance with the EPBD. By using a ground source heat pump with sCOP 4, energy class C, equivalent to the building practice for new constructions would be the outcome. However, following the Kyoto pyramid, the heat pump is the last step to improve, and changing the heat source would not improve thermal comfort or improve the indoor environment.

The resulting energy classes after changing the heat sources, are displayed in Figure 4.3 for Building 1 and in Figure 4.2 for Building 2.

Following renovation measures led to the BBR-standard for Building 1:

- Exterior walls: + 100 mm insulation
- Attic: + 200 mm insulation
- Windows and doors: *U*-value 1.2 W/(m²·K)
- ATW-HP sCOP 3
- Infiltration: 1 ACH.

For Building 2, it was not enough to incorporate the same measures as for Building 1 in the BBR-standard. When applying MVHR, energy class C was reached.

Following renovation measures led to the PH-standard for Building 1 and 2:

- Exterior walls: + 250 mm insulation.
- Attic: + 300 mm insulation
- Slab on ground and basement walls: + 300 mm insulation.
- Windows and doors: *U*-value 0.8 W/(m²·K)
- MVHR, 85 % efficiency
- ATW-HP sCOP 3
- Infiltration: 0.42 ACH
- Thermal bridges: 50 % of Base Case (0.07 W/(m²·K))

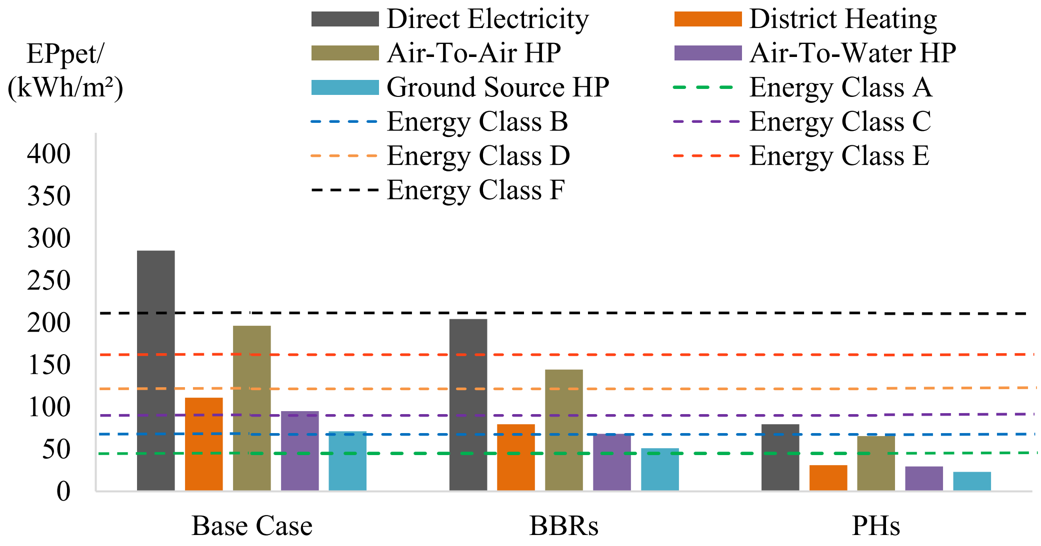


Figure 4.3 Energy Class for Building 1, for the Base Case design with different heat sources, location Stockholm.

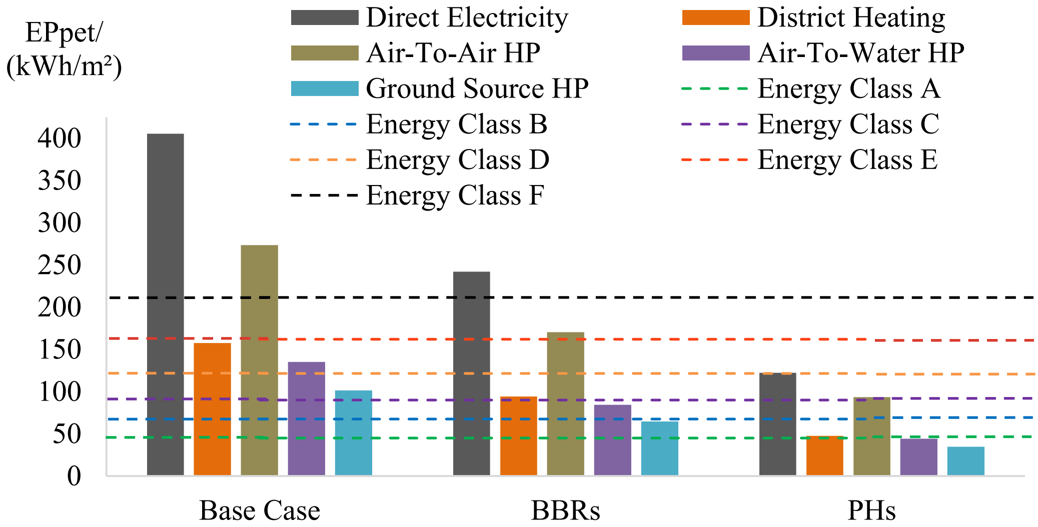


Figure 4.2 Energy Class for Building 2, for the Base Case design with different heat sources, location Stockholm.

4.2 HVAC design

As the Base Case design consisted of natural draught ventilation by grills and leakages, and heating was supplied by electric radiators, the following sections present the suggested layout for the new HVAC systems. Detailed description of materials and calculation are presented in Appendix J.

4.2.1 MVHR Building 1

A suggested duct layout for the mechanical ventilation system is provided in Figure 4.5 and Figure 4.4 for building 1, for the full pressure drop matrix Appendix O. The long and narrow hallway acts as the suitable placement for the main duct placement, where short connection ducts are placed with a Tee-fitting, connects the bedrooms, and living room for supply air, and the bathrooms and kitchen for exhaust air, at the ground floor. The main ducts are placed in the staircase to connect the basement, where supply air is distributed in the two rooms at each end, and exhaust air is taken from the food storage room. All ducts are fully visible and attached to the ceiling. Since the duct diameters range in the span of 160 mm – 63 mm, a false ceiling is applicable to hide the installations if desired on the ground floor. Since the basement has a lower ceiling height of 2.3 m, a false ceiling might not be suggested nor suitable. Regular steel ducts were considered, although white ducts that are suitable for visible installations usually in offices, are available on the market. The duct system was sized using the equal pressure method, which resulted in various duct dimensions throughout the system to keep the pressure losses close to 1 Pa/m. This resulted in supply ducts with the dimension of 63 mm, which is not available for supply and exhaust air diffusers with the desired throw length and low noise levels. For simplistic reasons, all supply and exhaust diffusers were assumed as 100 mm dimension for cost estimations and LCA calculations.

The total volume air flow that is needed to comply with the BBR requirements was set at 61 l/s. 47.5 l/s for the ground floor and 13.5 l/s for the basement due to the occasional occupancy. Exhaust ventilation might not be necessary in the basement since the staircase provides an open path to the ground floor. This would then result in higher exhaust air flow from the bathrooms and kitchen, which could affect the noise level.

The critical path for the supply air was calculated as AHU – E6, with a total pressure drop of 80 Pa, while the critical path for exhaust air was calculated as AHU – C4, with a total pressure drop of 49 Pa. The critical path determines the balancing needed for all supply or exhaust diffusers to attain the same pressure drop, in addition to the energy and SFP calculations for the AHU, which was completed using the online tool of Swegon. The Swegon report is presented in Appendix M, with an SFP of 1.25 kW / (m^3/s), and annual energy demand for both the fan energy and preheater of 667 kWh. The chosen AHU uses a plate heat recovery, of 80 % efficiency, which is slightly lower efficiency than the simulated scenarios (85 %). However, this AHU was chosen due to availability on the online calculation tool and based on the suitable airflows, in addition to available EPDs.

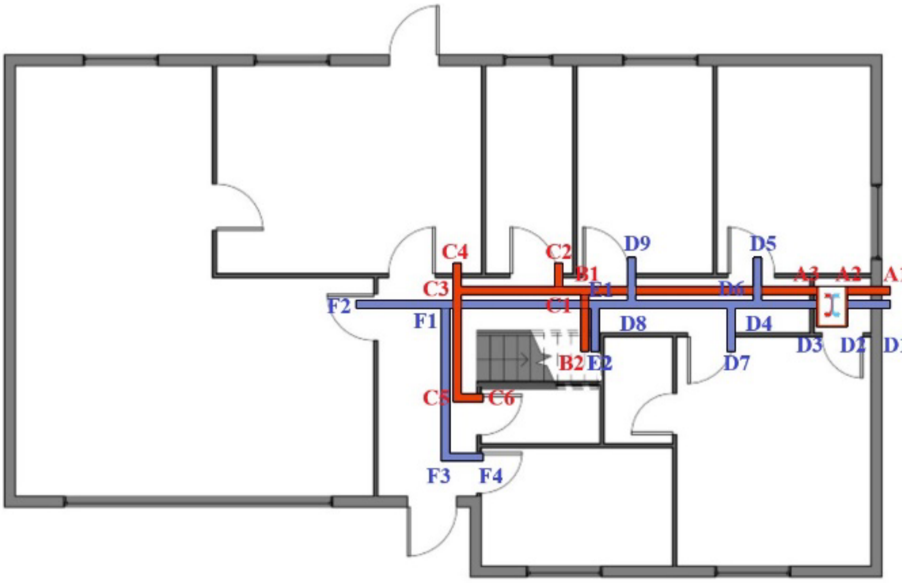


Figure 4.5 Ventilation duct design for Building 1, ground floor. Red lines are exhaust air, blue lines are supply air.

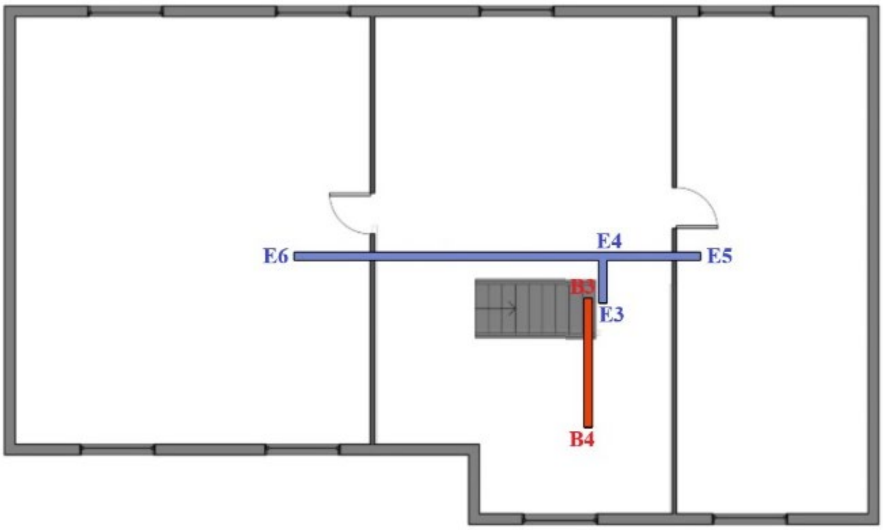


Figure 4.4 Ventilation duct design for Building 1, basement. Red lines are exhaust air, blue lines are supply air.

4.2.2 HVHR Building 2

As for Building 1, a full pressure drop matrix is found in Appendix P. The suggested layout of the ventilation system for building 2 is presented in Figure 4.6. The supply air ducts are placed in the kitchen area in order to reach the three bedrooms and the living room. The total airflow of 35 l/s resulted in a maximum duct size of 125 mm, which could rather easily be hidden below a false ceiling. The critical path was calculated as AHU – G4, with a pressure drop of 58 Pa. Exhaust air is taken from the two bathrooms, kitchen, and the laundry room, where AHU - B5 was determined as the critical path with 40 Pa pressure drop. The Swegon tool was assessed for calculating the SFP as 0.98 kW / (m^3/s) and 300 kWh for annual energy demand for both the fan energy and preheater. For the full Swegon report, see Appendix N.

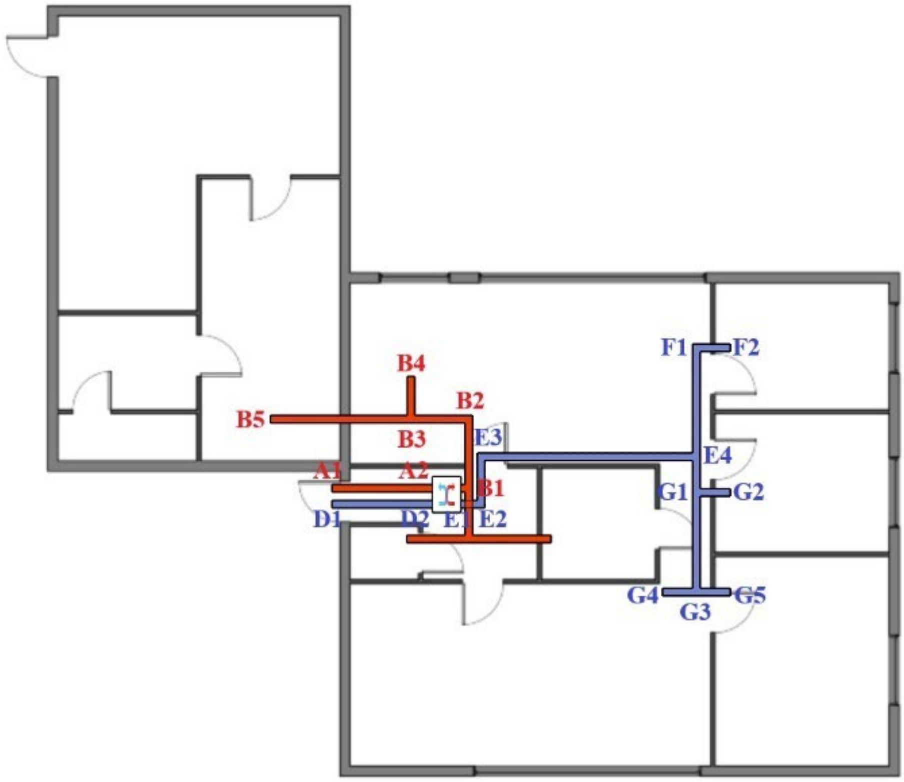


Figure 4.6 Ventilation duct design for Building 2. Red lines are exhaust air, blue lines are supply air.

4.2.3 Peak Power demand

The power demand changes in each zone and for the building level after each renovation measure. Separate zones were not considered. The peak power demand for all six locations is presented in

Table 4.B which show great variations, due to varying dimensioning outdoor temperatures (DVUT). This would later influence the size and hence costs for heat pumps and radiators. For this thesis, only the peak power demand for the Stockholm location is considered. It is noted that based on the location, investment costs might differ.

Table 4.B Calculated Peak Power Demand for all locations.

		Malmö	Växjö	Gothenburg	Stockholm	Karlstad	Borlänge
Building 1 Power demand /kW	Base Case	11.5	13.8	12.5	14.2	15.4	16.1
	BBRs	5.9	7.1	6.4	7.3	7.9	8.3
	PHs	3.2	3.8	3.4	3.9	4.3	4.4
Building 2 Power demand /kW	Base Case	7.5	9.0	8.2	9.3	10.0	10.5
	BBRs	3.5	4.3	3.9	4.4	4.8	5.0
	PHs	1.9	2.2	2.0	2.3	2.5	2.6

4.2.4 Sizing of Radiators

Figure 4.7 present the suggested layout of the radiators and piping for Building 1, and Figure 4.8 for Building 2. Generally, radiators were placed below each window on the ground floor in order to prevent cold draughts. In the basement of Building 1, fewer radiators were selected given the lower heat load due to lower setpoint temperatures and smaller windows. The radiator systems were constructed as 2-way systems in order to keep the same set point temperatures for each radiator. The basement allowed visible pipes in a circular formation, where raising pipes would connect the radiators on the ground floor without having visible pipes more than necessary. Building 2 included all visible piping. A total of 13 radiators and 103 m of piping is needed for building 1. A total of 5 radiators and 34 m of piping for building 2.

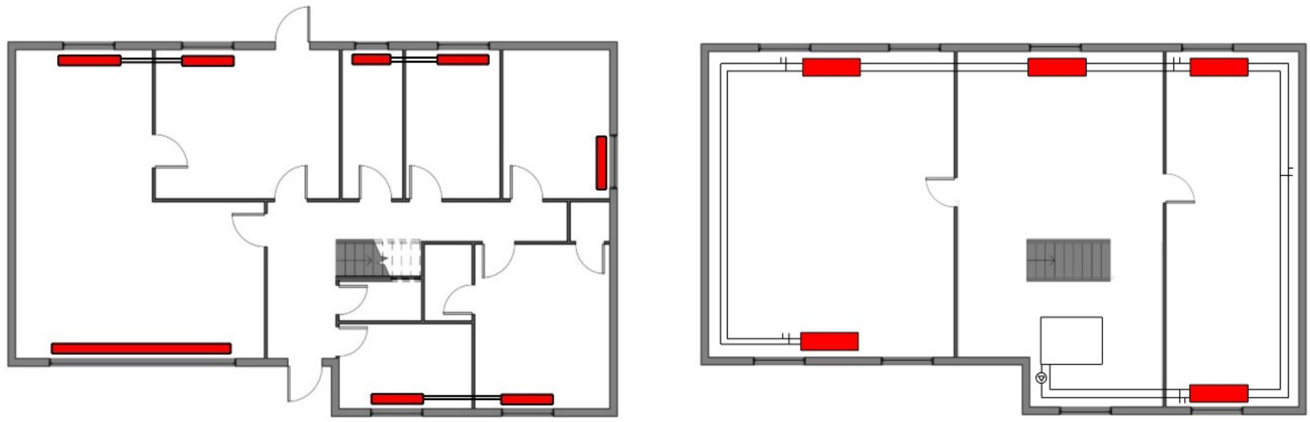


Figure 4.7 Layout of radiators and piping in Building 1, ground floor (left), basement (right). Rectangles marked in red are radiators, dual lines in between the radiators are the 2-way piping distribution.

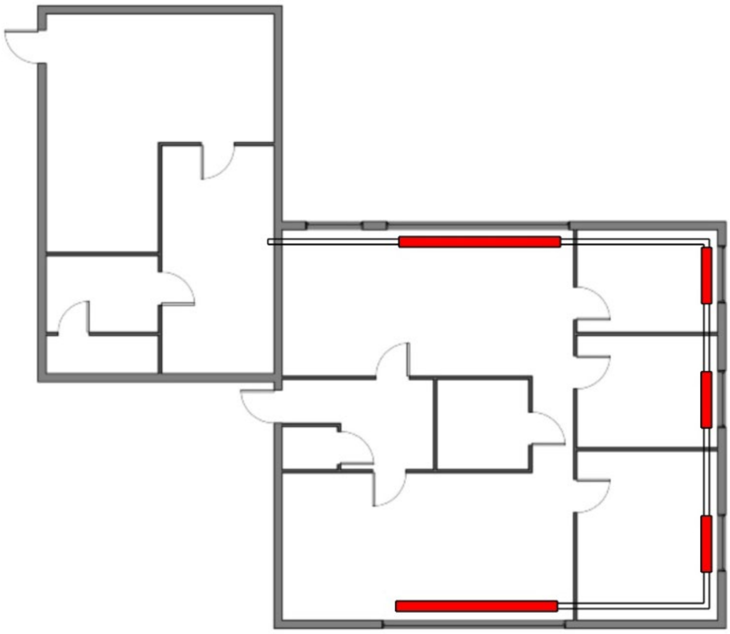


Figure 4.8 Layout of radiators and piping in Building 2. Rectangles marked in red are radiators, dual lines in between the radiators are the 2-way piping distribution.

4.3 Life Cycle Assessment

In this section, the environmental impact for each renovation measure will be presented in addition to a comparison between different insulation materials for the envelope. Lifetime emissions are calculated as both the embodied emissions for the materials, and the operational emissions for 50 years. This will aid in deciding the optimal thickness for each renovation measure.

Due to similar trends for lifetime emissions of building materials, only results from Building 1 are shown. For the renovation packages BBR-standard and PH-standard, both buildings are shown.

4.3.1 Heat Pumps

When considering a life cycle of 50 years, the installation of one sort of heat pumps were determined as reasonable. For that matter, a comparison of four different heat source scenarios is included: direct electricity (base case), district heating, Air-To-Air HP and Air-To-Water heat pump, presented in Figure 4.9, for the operation of Building 1.

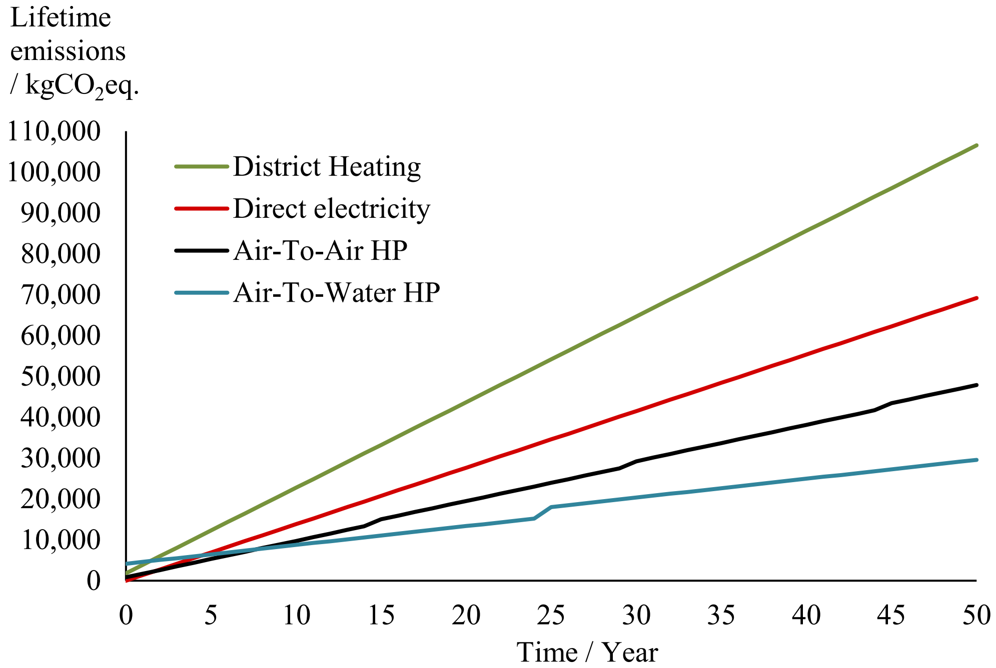


Figure 4.9 Life-time emissions for different heating systems.

The Base Case is assumed to be heated by direct electricity (red line), which is considered as the "business as usual" scenario. Environmental payback time for the other heat sources is readable by the intersection on the red line.

Both district heating and Air-To-Water Heat Pumps would require the installation of water-borne radiators, whereas the base case power demand of 14.2 kW was considered. Figure 4.9 includes the embodied emissions for radiators and piping.

The district heating heat exchanger has a service life of 25 years, after which it needs to be replaced. District heating results in the highest emissions over a 50-year period due to the generalized value of 0.056 $kgCO_2eq.$ per kWh. Installing district heating is not technically feasible in all single-family houses due to the availability of distribution network and is therefore not considered a suitable renovation option.

Due to its relatively low installation-weight of 50 kg, an ATA-HP has the lowest embodied emissions of the investigated heat pumps, 853 $kgCO_2eq.$, which provides an environmental payback time as short as two years. However, it could only cover half the energy demand of a building, and the replacement after each 15 year-period result in a 32 % emissions reduction compared to direct electricity.

An ATW-HP requires both an outdoor and an indoor unit with a total weight in the range of 200 kg - 300 kg. EPDs containing the refrigerant fluid R32 were selected for this master thesis, excluding the previously used refrigerant R407C, which resulted in 2-3 times higher embodied emissions than those available on the market today. The EPDs for the ATW-HP included leakages of the refrigerant, which is highly CO_2 intensive, however, this was declared in the B1-stage which was were excluded from this master thesis. A 57 % lifetime emissions reduction is attained by the installation of an ATW-HP, compared to the base case.

Geothermal heat pumps were not considered for the LCA calculations due to the technical constraints for the installation in various ground properties. Municipal permission is needed before installation as well as a minimum of 20 m between two neighboring boreholes. Generally, geothermal heat pumps have a slightly higher sCOP than the ATW-HP, and presumably higher embodied emissions due to higher weight and more components for the ground piping. By analyzing the general trend in Figure 4.9, the embodied emissions play an insignificant role in the long-term perspective, and a high sCOP is more crucial in the role of reducing the overall lifetime emissions.

For the remaining LCA calculations it will be assumed that an ATW-HP with sCOP of 3 is used for space heating and DHW, due to the feasibility and rather simplistic approach of the installation, with a total lifetime emission of 29 560 kgCO_2eq.

4.3.2 External walls

The general trend for exterior wall insulation show that glass wool provides the lowest climate impact in all thicknesses, as presented in Figure 4.10. However, the optimal thickness for glass wool is 150 mm, followed by 100 mm providing a reduction of 1 276 kgCO_2eq. and 1 257 kg over its lifetime, respectively. Rock wool and EPS perform the best in its own category, when choosing 100 mm thickness, providing a reduction of 530 kgCO_2eq. and 1 040 kgCO_2eq., respectively. Both mineral wool and EPS yield lower lifetime emissions than the base case, in all the investigated thicknesses, where Rock wool increases the lifetime emissions after adding 250 mm.

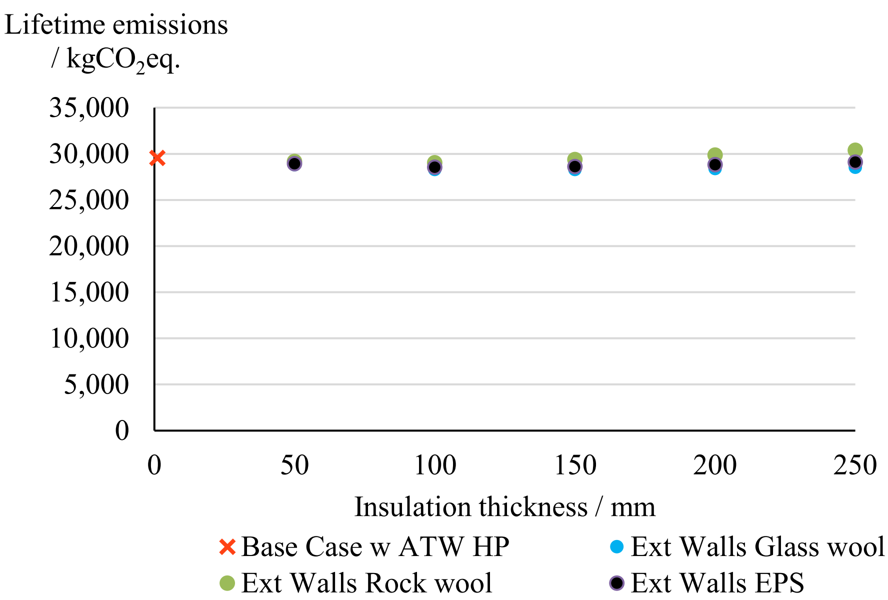


Figure 4.10 Life-time emissions for several types of exterior wall insulation.

4.3.3 Attic

Cellulose fiber insulation outperforms glass wool and rock wool in all thicknesses, see Figure 4.11. The optimal thickness for the lowest climate impact for attic insulation is achieved with 300 mm of cellulose insulation, resulting in a 1 509 kgCO_2eq. reduction over its lifetime. Both cellulose and mineral wool reduce the lifetime emissions in all thicknesses compared to the base case, while rock increases the emissions at 400 mm of insulation.

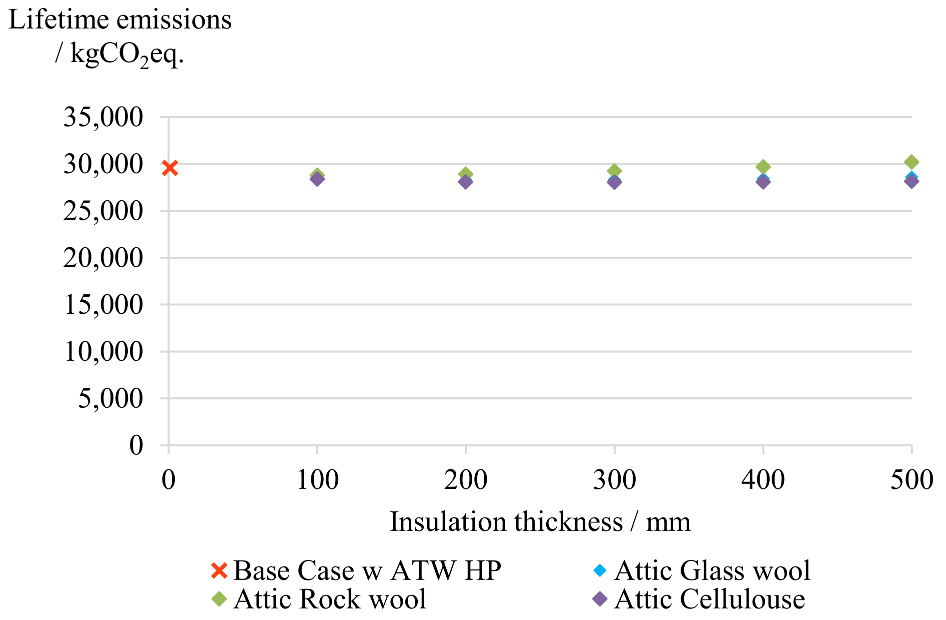


Figure 4.11 Life-time emissions for several types of attics insulation

4.3.4 Basement walls and slab on ground

Basement walls have lower environmental impact when insulated with 300 mm or less, whilst the optimal thickness is found to be 100 mm of EPS or Isodrän, providing a net saving of 1 154 $kgCO_2eq$. The high embodied emissions for EPS with concrete, and EPScrete result in a non-profitable environmental impact for insulating the concrete floor slab in any of the above-mentioned scenarios, see Figure 4.12.

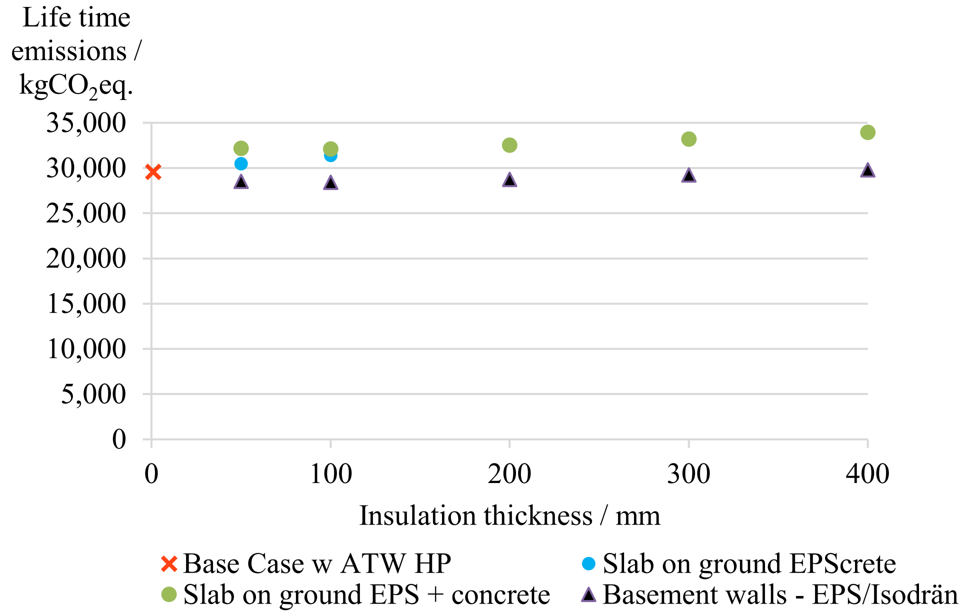


Figure 4.12 Life-time emissions for insulating basement walls and slab on ground.

4.3.5 Environmental payback time for the BBR-standard

Lifetime emissions savings are presented for Building 1 in Figure 4.13 (left) and Building 2 (right), which presents the building envelope materials that were needed to reach energy class C, after the use of an ATW-HP. The negative bars represent the embodied emissions for each material, where the environmental payback time is reached when positive values are shown. Note that the bars are accumulated values for all materials. Embodied emissions are similar for both buildings, with approximately 3 000 kgCO_2eq. each, while the net savings are higher for building 1 than building 2. Both buildings show similar trends for environmental payback time for all materials, where attic insulation has the lowest payback time, 5 years for building 1, and 14 years for building 2. MVHR was only used in building 2, which yields a 20-year payback time. Windows have the longest payback time for both buildings, 43 and 46 years for building 1 and 2, respectively.

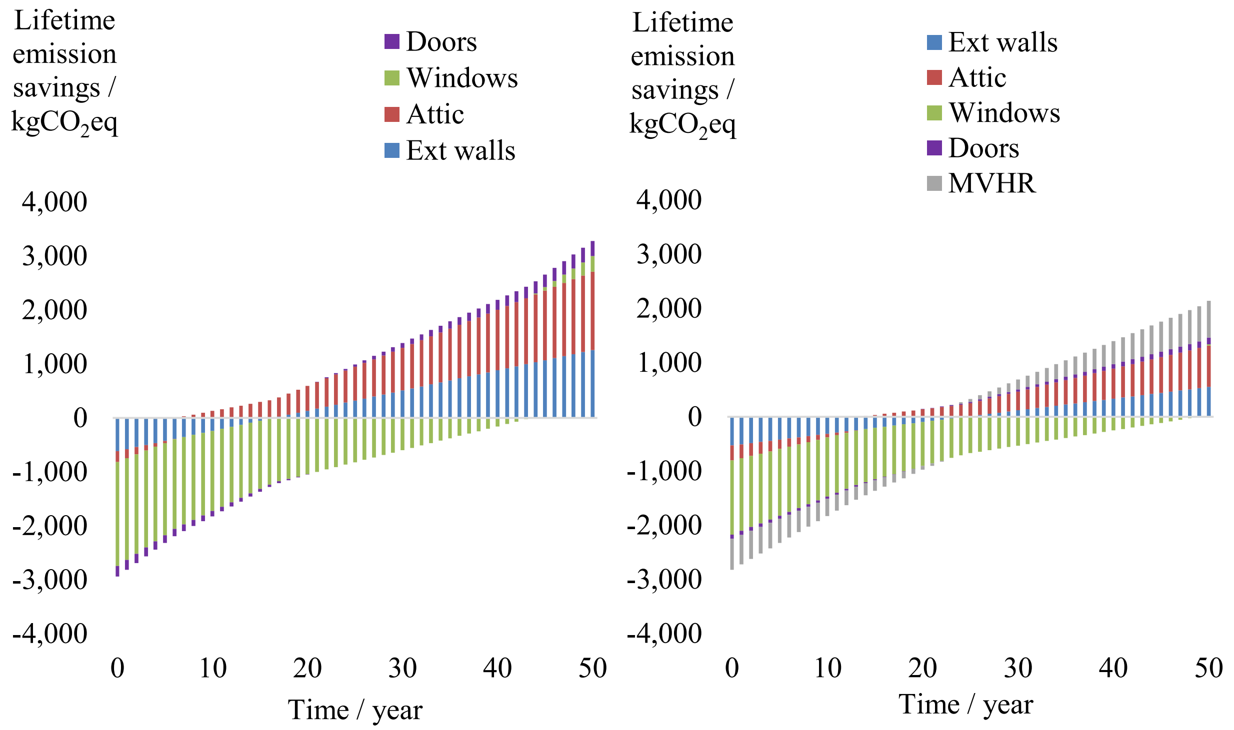


Figure 4.13 Accumulated environmental payback time for all building materials in the BBR-standard renovation package. Building 1 (left), Building 2 (right).

4.3.6 Environmental payback time for PH-standard

When renovating towards the PH-standard, the embodied emissions increase significantly for both buildings, see Figure 4.14. Embodied emissions are approximately 13 000 $kgCO_2eq$. for building 1, while 8 000 $kgCO_2eq$. for building 2. As presented in section 4.3.4, insulating the slab on ground with recast concrete resulted in increased emissions over the lifetime, where the slab on ground still remains negative after 50 years. MVHR has the shortest payback time of 9 years in Building 1 and offers the highest emissions savings of the proposed measures. The PH-standard package offers net savings of 6 000 $kgCO_2eq$. for building 1, which is twice the savings as in the BBR-s package. For building 2 the savings are lower in the PH-standard package (1 500 $kgCO_2eq$.) than for the BBR-standard (2 000 $kgCO_2eq$.) Note that the embodied emissions savings were only considering the building envelope and excluding the savings due to the heat pump. The combined emissions are discussed in the next section.

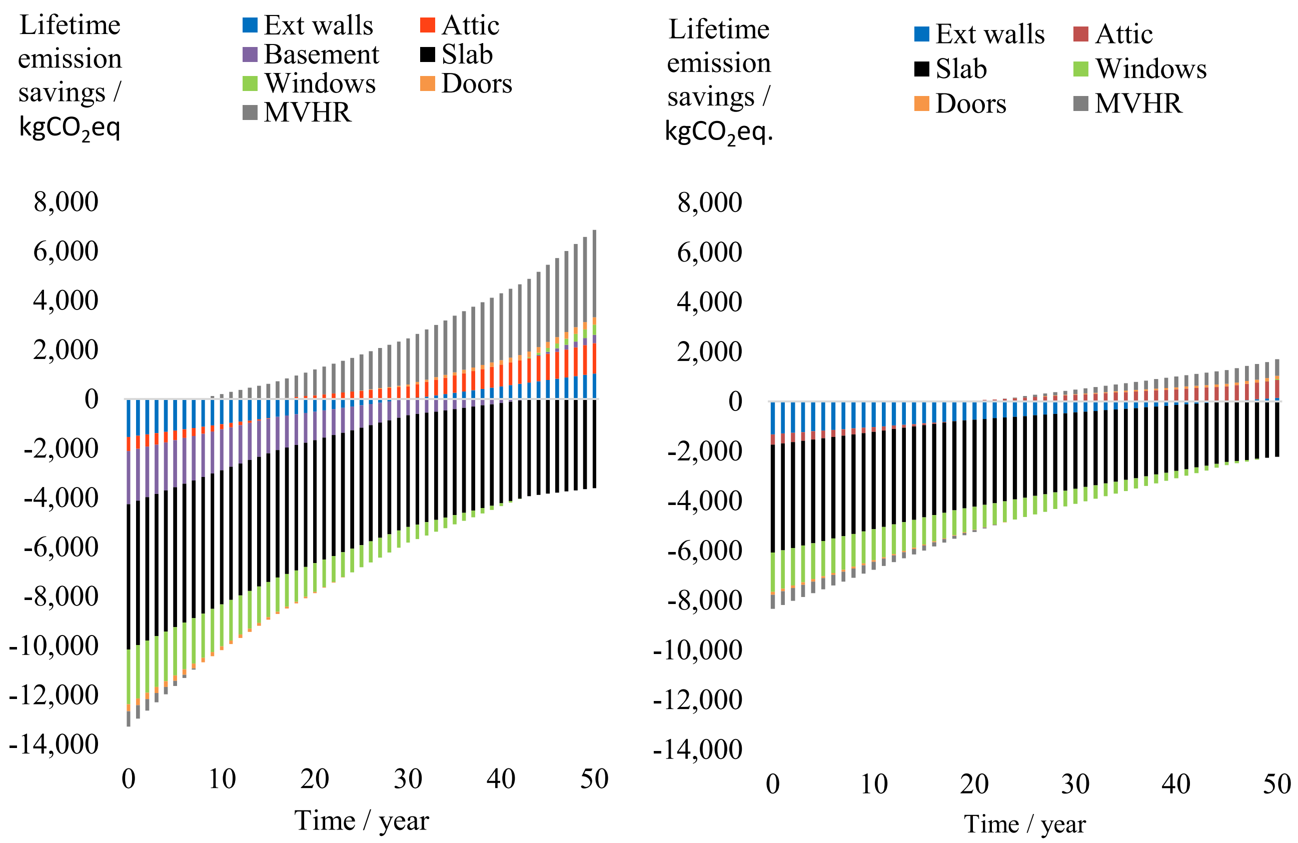


Figure 4.14 Accumulated environmental payback time for all building materials in the PH-standard renovation package. Building 1 (left), Building 2 (right).

4.3.7 Lifetime emissions: Base Case, BBRs and PHs

Lifetime emissions for both buildings are presented in Figure 4.15. In the initial Base Case, the lifetime emissions consist of operational energy only. When only adding an ATW-HP to the Base Case, carbon dioxide emissions are reduced with 57 % and 53 % over its lifetime, for building 1 and 2, respectively. Adding the BBRs renovation package yields a 66 % and 64 % emissions reduction for building 1 and 2 respectively, and the last step of the PHs renovation package results in a 70 % and 61 % decrease of emissions, for building 1 and 2, respectively. As discussed in the previous section, the PHs renovation for Building 2 offers more emissions during its lifetime than the BBRs renovation and is hence less effective in terms of reducing emissions.

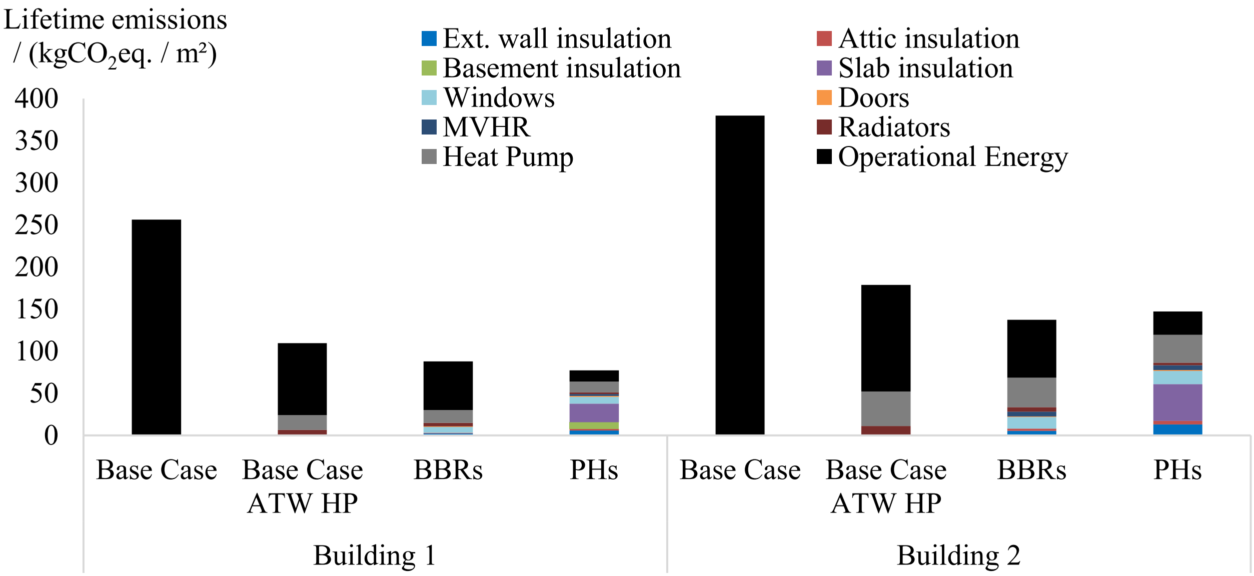


Figure 4.15 Comparison of lifetime emissions in the Base Case, Base Case with an Air-To-Water Heat Pump, BBR-standard and PH-standard. Building 1 (left) Building 2 (right).

4.4 Investment costs

As for the arguments in the LCA section, it is assumed that a heat pump will most likely be installed during the 50-year period. Therefore, an ATW-HP is considered, and the energy demand savings are divided by 3, in order to obtain the savings for bought energy (energy use). Figure 4.16 shows the investment cost divided by the energy use savings over 50 years, for insulating the building envelope in Building 1. Attic insulation is by far the most economically viable option, for all thicknesses, followed by 50 mm external wall insulation and 100 mm basement insulation. Insulating the slab has the highest investment cost per savings in general, although 200 mm EPS insulation when recasting the concrete slab facilitates the highest profitability. All prices exclude moms (VAT), and subsidies. For the full table of investment costs, see Table 4.C.

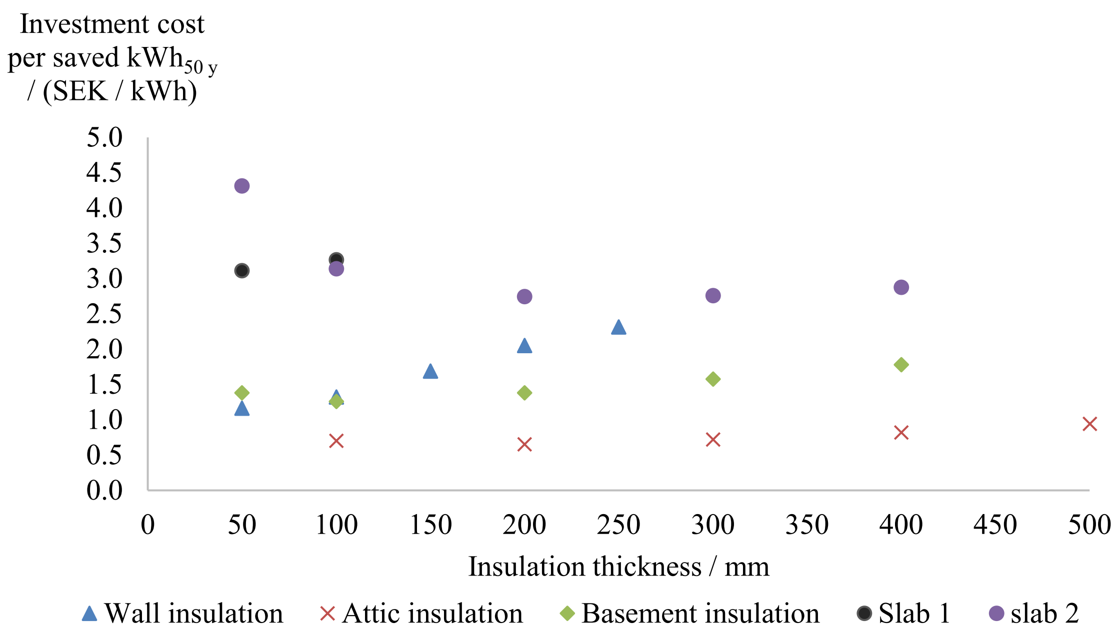


Figure 4.16 Investment cost based on energy use savings for 50 years, for all envelope renovation measures, for Building 1.

Figure 4.17 presents the investment costs for windows and doors. Adding an additional glass pane to the old windows is the most cost-efficient measure. However, original windows from the 1960s might not be possible to renovate and this option is mostly used when the building code prohibits the change of windows. Wiksell did not provide other door solutions than *U*-value 1.2 W/(m²·K), whereas the difference in prices for the highly insulated door was estimated as 20 %, which was true for windows in the database.

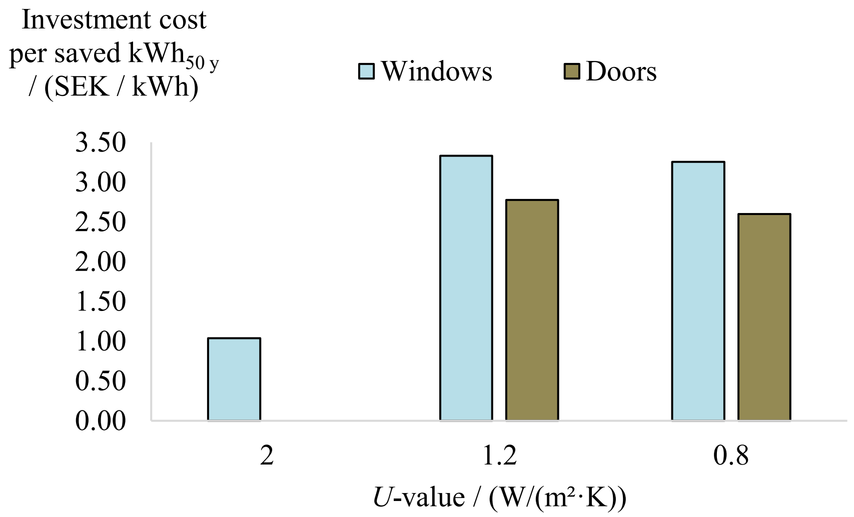


Figure 4.17 Investment cost based on energy use savings for 50 years, for windows in Building 1.

HVAC installations have generally higher savings potentials for Building 1 than Building 2, visualized in Figure 4.18. The higher difference in profitability for MVHR could be explained by the following arguments: Firstly, building 2 has 43 % lower air flow than in Building 1, (35 l/s compared to 61 l/s), meaning that the heat losses are lower. The basement in Building 1 allowed for a lowered air flow according to BBR29, which is attainable with a MVHR system. Therefore, the lower heat losses due to the lower ventilation air flow was accumulated in the overall savings when installing a MVHR system. Lastly, both buildings required the installation of the same air handling unit model, which accounts for the majority of the installation costs.

ATA-HP and ATW-HP in Building 2 were generalized and calculated as 80 % of the heat pump peak power in Building 1, since the Wikells database only included prices for two heat pump sizes: 7 kW ATA-HP, and 9 kW ATW-HP.

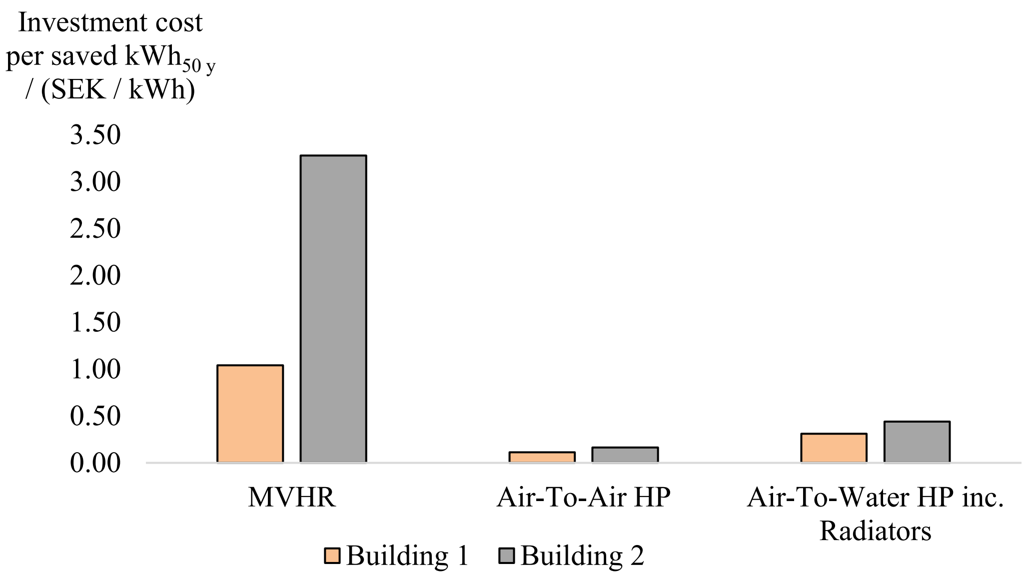


Figure 4.18 Investment cost based on energy use savings for 50 years, for HVAC-installations in Building 1.

Given the calculations in this section, the most profitable installations in each category in terms of investment cost per saved kWh, is listed below:

1. ATA-HP
2. ATW-HP
3. Attic insulation (200 mm)
4. MVHR (Building 1)
5. Ext. wall insulation (50 mm)
6. Basement insulation (100 mm)
7. Windows *U*-value 0.8 W/(m²·K) (Both Buildings)
8. EPScrete slab on ground insulation (50 mm)
9. MVHR (Building 2)

Table 4.C Total installation cost for each renovation measure.

	Thickness / mm	Price / (SEK / m²)	Building 1 Investment costs / SEK	Building 2 Investment costs / SEK
Wall insulation	50	257	33 394	28 693
	100	514	66 788	57 386
	150	771	100 181	86 079
	200	1 028	133 575	114 772
	250	1 233	160 290	137 726
Attic insulation	100	170	23 970	17 510
	200	207	29 187	21 321
	300	249	35 109	25 647
	400	295	41 595	30 385
	500	341	48 081	35 123
Basement insulation	50	473	52 920	-
	100	568	63 560	
	200	756	84 684	
	300	945	105 808	
	400	1 133	126 931	
Slab 1, EPScrete	50	315	44 067	32 421
	100	630	88 134	64 842
Slab 2, EPS + Concrete	50	899	125 860	92 597
	100	963	134 820	99 189
	200	1 091	152 740	112 373
	300	1 219	170 660	125 557
	400	1 347	188 580	138 741

	U-value / (W/(m²·K))	Building 1 Investment costs / SEK	Building 2 Investment costs / SEK
Windows	2	34 145	24 234
	1.2	199 429	96 184
	0.8	231 338	111 573
Doors	1.2	35 232	17 616
	0.8	40 869	20 435
	HVAC		
MVHR		81 523	74 472
ATA-HP		22 400	17 920
ATW-HP		136 418	109 134
Radiators, piping		113 938	55 251

Investment costs for Building 1:

- BBR-standard: 581 000 SEK
- PH-standard: 1 076 000 SEK

Investment costs for Building 2:

- BBR-standard: 431 000 SEK
- PH-standard: 660 000 SEK

It should be considered prices in this chapter are suggestive and generalized, based on the selection of materials in the Wiksell database. Prices for labor work is included in the presented data, which might differ depending on the location in Sweden and while some homeowners might be able to perform parts of the renovations themselves. The prices for external wall insulation and basement wall insulation might be misleading due to only taking the added insulation and labor into account. For windows and HVAC installations, the full installation costs were considered. The attic insulation costs are considered the most reliable price estimations, since the loose fill insulation is blown onto the attic floor, with no other measure required.

Demolition work was not considered in any scenario, which might be lower for the replacement of windows or doors, while the demolition of the previous concrete slab on ground would be substantially higher part of the total cost.

5 Renovation Passport

For the owner of a typical 1960s single family house, similar to the two archetypes presented in this master thesis, there are multiple combinations of Base Case starting points, and desired renovation measures. The suggested 29 steps of renovation measures could result in 22 500 different combinations per building. Energy savings, embodied emissions, and investment costs, for all of these 22 500 combinations are accessible through the suggested Renovation Passport, presented in this chapter. The logo and the graphic layout are created by Chat GPT-4 image generator. DHW is based on the SVEBY standard, 20 kWh / $m^2A_{temp.}$

The Renovation Passport is divided into three parts and a total of five easy-to-follow steps, described below. All the blue and green boxes next to the numbers 1-5 are drop-down menus with multiple choices, corresponding to the renovation matrix, previously presented in Table 3.C.

5.1 Proposed Renovation Passport

Part 1 is presented in Figure 5.1, where the 3 steps are explained:

1. Select the location (Malmö, Växjö, Gothenburg, Stockholm, Karlstad, Borlänge) and the archetype, Building 1 (270 m² with basement), Building 2 (100 m²). All subsequent result data in the drop-down menus are dependent on these variables.

2. Set up your Base Case building envelope, prior to the renovation. If no previous renovation work has been completed, select “1960s original”. The menu entails the options from the previously presented renovation matrix, Table 3.C.

3. Select your corresponding heating system. Direct electricity, District heating, ATA-HP, ATW-HP or GSHP. The energy use will be calculated based on the heating source.

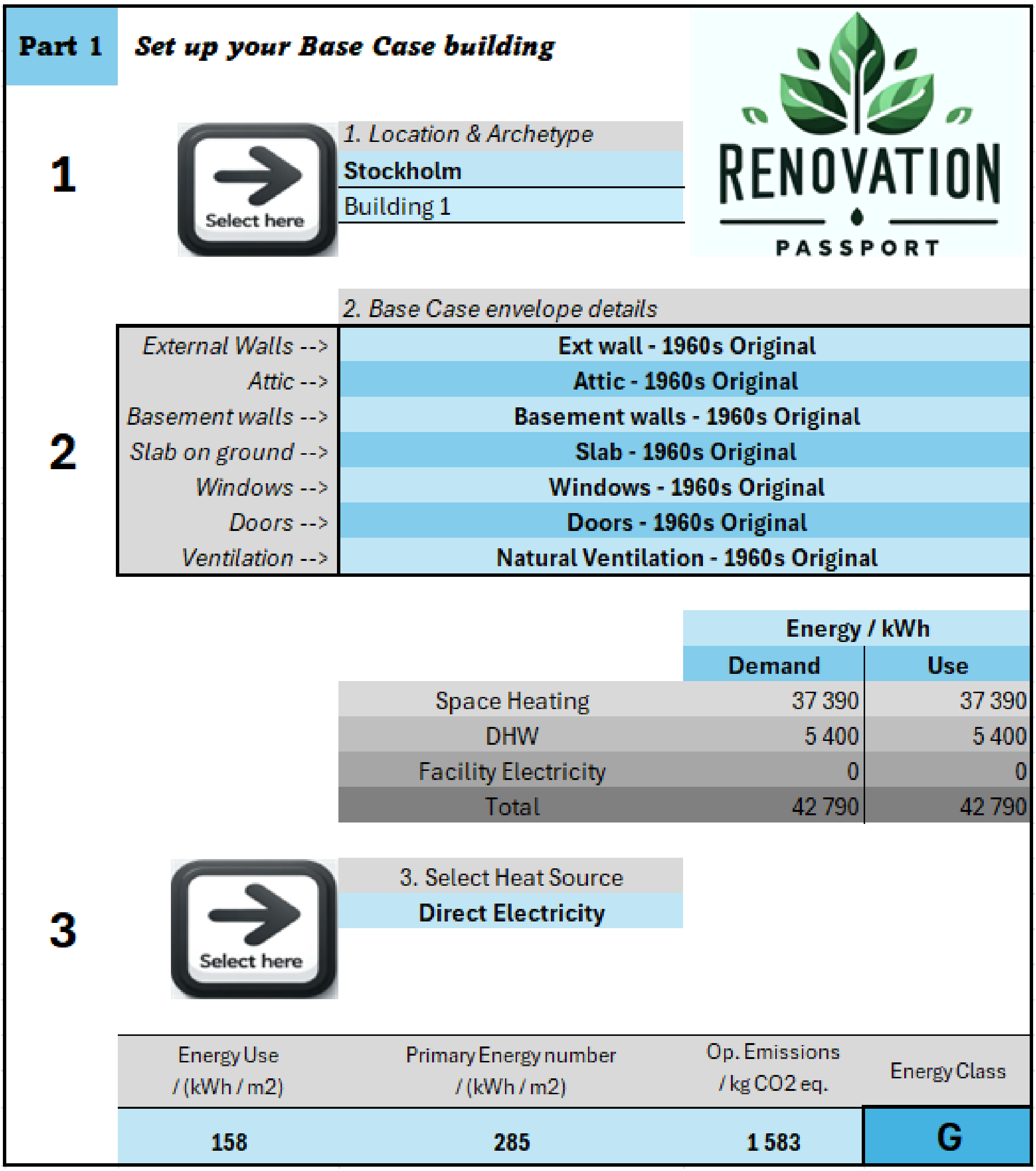


Figure 5.1 Renovation Passport, part 1 of 3.

Part 2 is presented in Figure 5.2. All options in the drop-down menus are equal to the options in Part 1.

Step nr:

4. Select the desired renovation measures.
5. Select the heating source. If water-borne radiators are needed in addition to the installation of district heating, ATW-HP or GSHP, select "Yes." This will then include the embodied emissions.

Part 2 will sum up all the energy demand savings, benefitted by the envelope measures chosen in step 4. The final energy demand for both space heating and DHW is divided by the sCOP for the selected heat source in step 5 and presented as total energy use, which is the annual required bought amount of energy. The renovation measures chosen in Part 2, correspond to the BBR-standard for Building 1. The energy demand data for each renovation measure is based on single-option simulations in IDA ICE, while the final output in the renovation passport adds up to all the individual savings. This was benchmarked in IDA ICE, where all the measures in BBR-s and PH-s were chosen and simulated as a combination. On average, when combining multiple renovation scenarios, the renovation passport underpredicts the savings by 4.7 % for the BBRs, and 9.2 % for the PHs, compared to the IDA ICE simulations. This might be explained by IDA ICE taking the added thermal mass, increased air tightness, lower heating demand, lower heating setpoints into account when simulating the combination of measures. This could be interpreted as a safety margin, where the output of the Renovation Passport underpredicts the savings rather than overpredicts.

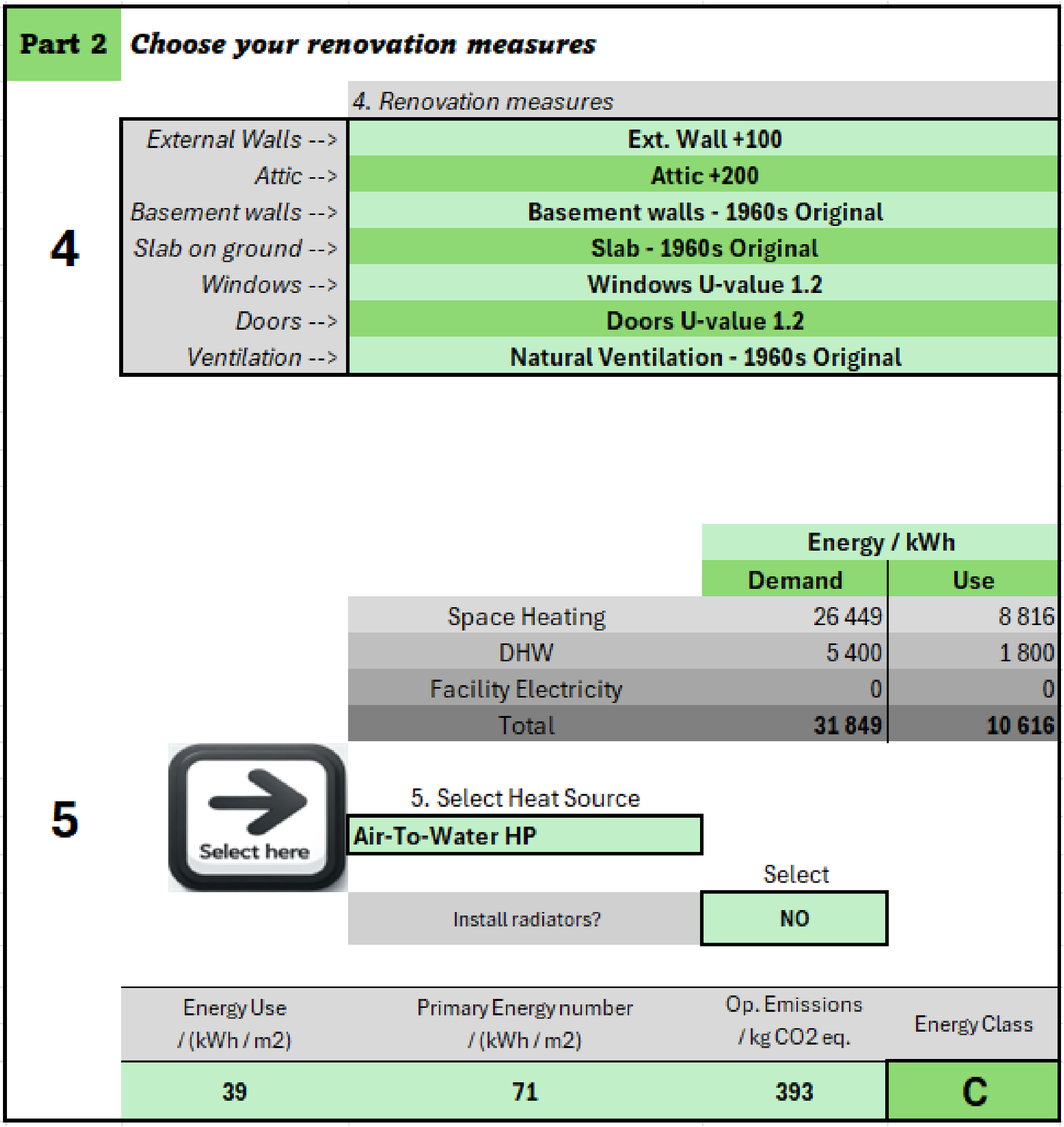


Figure 5.2 Renovation Passport, part 2 of 3. The input data corresponds to the BBR-standard.

Part 3 of the Renovation Passport provides a detailed description sheet for all the selected renovation measures, including embodied emissions for the applied building materials, investment costs, investment cost per saved kWh for 50 years, energy use savings, operational emissions savings, and finally the environmental payback time. All results are dependent on the selected heat source. Part 3 is displayed in Figure 5.3, Figure 5.4 and Figure 5.5.

Part 3 ***Detailed report***

Building 1
Stockholm

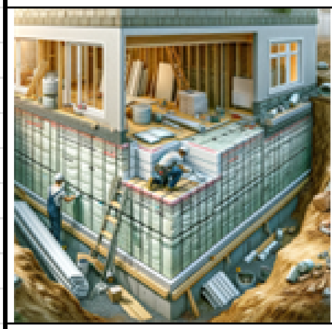
RENOVATION PASSPORT

Ext. Wall +100

Embodied emissions	615	kg CO2 eq.
Investment cost	66 788	SEK
Investment / saved kWh	1.32	SEK / kWh, 50y
Energy use savings	1 012	kWh / y
Op. Emissions savings	37	kg CO2 eq. /y
Environmental paybacktime	16.4	years

Attic +200

Embodied emissions	203	kg CO2 eq.
Investment cost	29 187	SEK
Investment / saved kWh	0.65	SEK / kWh, 50y
Energy use savings	896	kWh / y
Op. Emissions savings	33	kg CO2 eq. /y
Environmental paybacktime	6.1	years



Basement walls - 1960s Original

Embodied emissions	0	kg CO2 eq.
Investment cost	0	SEK
Investment / saved kWh	#DIV/0!	SEK / kWh, 50y
Energy use savings	0	kWh / y
Op. Emissions savings	0	kg CO2 eq. /y
Environmental paybacktime	#DIV/0!	years

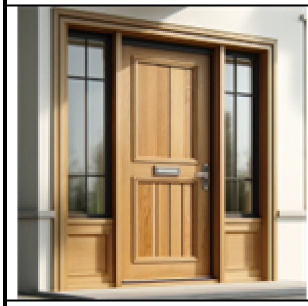
Figure 5.3 Renovation Passport, part 3 of 3.

Slab - 1960s Original

Embodied emissions	0	kg CO2 eq.
Investment cost	0	SEK
Investment / saved kWh	#DIV/0!	SEK / kWh, 50y
Energy use savings	0	kWh / y
Op. Emissions savings	0	kg CO2 eq. /y
Environmental paybacktime	#DIV/0!	years

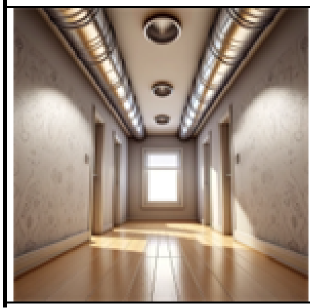
Windows U-value 1.2

Embodied emissions	1 929	kg CO2 eq.
Investment cost	199 429	SEK
Investment / saved kWh	3.33	SEK / kWh, 50y
Energy use savings	1 197	kWh / y
Op. Emissions savings	44	kg CO2 eq. /y
Environmental paybacktime	43.5	years



Doors U-value 1.2

Embodied emissions	191	kg CO2 eq.
Investment cost	35 232	SEK
Investment / saved kWh	2.78	SEK / kWh, 50y
Energy use savings	254	kWh / y
Op. Emissions savings	9	kg CO2 eq. /y
Environmental paybacktime	20.4	years

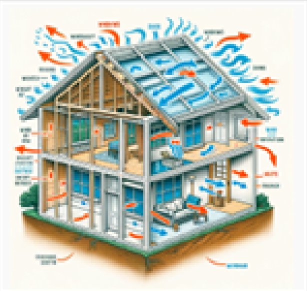


Natural Ventilation - 1960s Original

Embodied emissions	0	kg CO2 eq.
Investment cost	0	SEK
Investment / saved kWh	#DIV/0!	SEK / kWh, 50y
Energy use savings	0	kWh / y
Op. Emissions savings	0	kg CO2 eq. /y
Environmental paybacktime	#DIV/0!	years

Figure 5.4 Renovation Passport, continuation of part 3.

Air-To-Water HP		
Embodied emissions	2 059	kg CO2 eq.
Investment cost	136 418	SEK
Investment / saved kWh	0.25	SEK / kWh, 50y
Energy use savings	22 097	kWh / y
Op. Emissions savings	818	kg CO2 eq. /y
Environmental paybacktime	2.5	years
Financial Paybacktime		

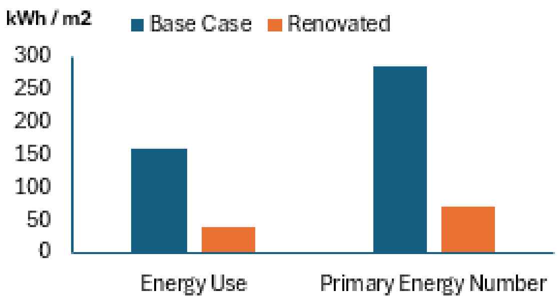


***Additional** embodied emissions due to previous selections*		
Raditors, embodied emissions	1 100	kg CO2 eq.
***Additional** - energy savings due to previous selections*		
Less infiltration	864	kWh / y
Reduced thermal bridges	0	kWh / y

Summarized

Total embodied emissions	**6 097**	kg CO2 eq.
Energy use savings	**32 174**	kWh / y
Total investment cost	**467 054**	SEK
Operational CO2 reductions	**1 190**	kg CO2 eq. /y
Environmental paybacktime	**5.1**	years

Energy use reduction	**75.2%**	
Emission reductions by 2050	**24 854**	**kg CO2 eq.**



Energy Class

C

Figure 5.5 Renovation Passport, continuation of part 3.

6 Answering the research questions

The main goal was to produce a Renovation Passport based on reliable data. The following research questions aided in the work, and each question is addressed below:

- **What renovation measures are practically, economically, and environmentally feasible when renovating towards Zero Emission Buildings?**

For the building envelope, attic insulation has the lowest investment cost and shortest environmental payback time. Insulating the attic floor is fairly simple, which can be performed by the homeowner him/herself. External wall insulation is an effective way of reducing heat losses and improving thermal comfort, although it requires a reconstruction of the façade, if not performed internally. Costs regarding demolition work or facades were not calculated since it was considered that the facades were outdated and in need of replacement anyway. While considering these costs, the economic feasibility might be altered. Insulating the basement walls and the slab on ground are costly procedures due to extensive digging and demolition work. While only the added insulation and concrete were considered in this master thesis with the same approach as for the external walls, that the building component was outdated and in need of replacement anyway, these estimated costs do not represent the full investment costs for the procedures.

High investment costs for window replacement, in addition to a 45-year environmental payback time, makes the renovation measure non-profitable. Although, when changing windows, the highly efficient windows with U-value 0.8 W/(m²·K) was the more favorable option.

Even though an Air-To-Water heat pump have a high investment cost and requires the installation of water-borne radiators, the investments yield a substantial energy use reduction, and is thereby the most profitable investment, both in financial and environmental terms. Mechanical Ventilation is more profitable with higher volume air flows due to the high investment costs.

- **What are the disadvantages and potential risks when renovating?**

Moisture safety is of highest importance when renovating, to ensure that no future mold issues will occur. This master thesis addressed some of the critical building techniques that were used in the 1960s, and how to improve the construction when renovating. However, moisture assessment was not the main scope in this thesis, and no moisture calculations nor mold calculations were performed. All presented renovation measures were considered to be moisture safe constructions due to the findings and suggestions in the literature review.

An additional disadvantage when adding insulation externally or changing windows, is changing the appearance of the building. After a deep-staged renovation, the building could potentially deviate from the building requirements or the general architecture in the neighborhood, if not performed with caution and in line with the building permits.

- **What is the environmental payback time for these measures?**

The renovation packages BBR-standard had an accumulated environmental payback time of 8 and 15 years, for building 1 and 2, respectively, while the renovation package PH-standard 20 and 23 years, for building 1 and 2, respectively. Although most individual measures had a longer environmental payback time, heat pumps aided in shortening the payback time for the combined measures, while heat pumps as an individual measure yielded an environmental payback time of 2 – 5 years. Attic insulation has the shortest individual environmental payback time of 8 years, followed by external wall insulation of 18 years, while windows resulted in a 45-year environmental payback time, and the concrete slab with EPS insulation resulted in a 70-year environmental payback time.

- **What is the most effective sequence of renovation measures to ensure the maximum benefits in the subsequent scenarios?**

Following the Kyoto-pyramid, the sequence of renovation measures should entail starting with improving the envelope, while changing the heat source is to be performed as the last step. It is important to have a long-term perspective in order to avoid lock-in effects. By improving the building envelope through multiple measures, thermal bridges and infiltration might decrease which improves the overall energy performance. Mechanical Ventilation with Heat Recovery is an effective way of reducing ventilation heat losses and ensure sufficient air flows, especially in regards of preventing moisture and mold issues. When supplying pre-heated air, the power demand for the building decreases, which is yet another reason for sizing and installing heat pumps or other heat sources as the last step.

6.1 Limitations

There are multiple variations of building types from the 1960s, while this master thesis only assessed two typical archetypes, with the same construction. While the results in this master thesis might not be representable for the majority of the Swedish building stock, one could use the drop-down menus in Part 1, to represent the total thickness or obtained *U*-value for the building of interest and generate potential savings in Part 2.

To comply with building regulations and architectural constraints, following suggested renovation measures might not be feasible: adding insulation to the external walls or basement, extending the roof overhang to cover the extended walls, changing windows or window placement. In these cases, the internal placement of insulation was assessed and presented. Adding an additional glass pane to the old windows were represented by the option of *U*-value 2.0 W/(m²·K).

The data used for the Renovation Passport is based on simulations for six locations in the mid and south of Sweden. Although these locations did not deviate much regarding potential energy savings (percentage wise) for the building envelope, differences based on location were found due to infiltration and ventilation heat losses. The peak power demand for heating varied vastly in the six locations bases on the DVUT for the location, making these calculations non-comparable to the northern part of Sweden, where temperatures are substantially lower. Additionally, each renovation measure influences the peak power demand of the heating system, which could not be included in this master thesis other than for the renovation packages BBR-standard and PH-standard for the Stockholm location.

Investment costs for labor work might differ depending on geographical location. The scarce variation of components in Wikells Sektionsfakta (especially for HVAC-components and windows), in addition to not including demolition work in this thesis, might not provide the full picture of price indications. Investment costs were only presented as a benchmark between the measures, while the focus of this master thesis was the environmental impact.

The comparison between district heating and electricity as heat source might not be applicable since emissions value for district heating varies dependent on municipality. The EPBD considers district heating and heat pumps as renewable energy, while the emissions data used for the Renovation Passport favors the use of electricity over district heating, which could provide misleading conclusions on potential emissions savings.

7 Conclusions

In this master thesis, the impact of several renovation measures for the building envelope, and HVAC-installations of two typical single-family houses from the 1960s were assessed. Firstly, energy simulations were performed in IDA ICE, where data for energy demand reduction was gathered for the six separate locations. Secondly, installation costs and CO_2 emission were calculated based on the proposed renovation measures, and finally, all data were made accessible in numerous iterations through the proposed interactive Renovation Passport, following the guidelines in the latest EPBD.

Heat pumps were the most economically and environmentally feasible measure, due to the high provided sCOP, which offers a substantial energy use reduction and hence reduced operational emissions. A 57 % lifetime emissions reduction can be attained when installing an Air-To-Water heat pump, compared to using direct electricity. However, by renovating the envelope first, and considering heat pumps as the final renovation measure, a 70 % lifetime emissions reduction is possible. Additional benefits of renovating the envelope before selecting the heat source includes improved thermal comfort, and a decreased power demand which facilitates a smaller heat source and radiators, and thereby less embodied emissions and lower investment costs.

Since many homeowners might have invested in heat pumps already, the impact of renovating the building envelope was studied while a heat pump with a sCOP of 3 was present. In terms of life-time emissions, cellulose insulation for attics, and mineral wool insulation for external walls were profitable in all investigated thicknesses, although the optimal thicknesses were 300 mm and 150 mm, respectively. Basement walls were profitable up to 300 mm of thickness, while insulating the concrete slab was not profitable in any scenario, due to the embodied emissions for the concrete. MVHR was highly beneficial for both building archetypes, although most profitable when the building has a higher volume air flow, due to the high investment costs. Following the concrete slab, windows yielded the longest environmental payback time of 45 years.

LCA calculations for all renovation measures aided in identifying two suitable renovation packages named BBR-standard and PH-standard, with the aim of reaching energy class C and A, respectively. At this point, there is no quantitative definition of a ZEB on a national level, other than the building should have a very low energy demand which is covered by renewable energy sources. On the other hand, the EPBD suggests that both heat pumps and district heating are considered as renewable energy. Both renovation packages yielded substantial energy and emissions savings, although the investment cost the PH-standard was 55 % - 85 % more expensive than for the BBR-standard. The BBR-standard resulted in 66 % and 64 % life-time emissions reductions compared to the base case, and PH-s offered 70 % and 61 % emissions reduction for Building 1 and 2, respectively. For building 2, the PH-standard thus resulted in higher lifetime emissions, which was explained by the high form factor for the building. The added costs for building 1 might not be economically justifiable.

Investment costs should be seen as approximated and are not considered as fully representable. The building envelope only took the added amount of insulation and labor work into account, while HVAC-installations and windows took all installation costs into account.

The presented Renovation Passport should be used as a guidance tool to determine which renovation measures could lower energy demand and energy use, as well as decrease lifetime emissions. Following the guidelines in the EPBD, an energy expert should perform an on-site audit of the building to accurately present the potential energy savings and investment costs.

7.1 Further research

The Renovation Passport suggested in this master thesis could be further developed by expanding the number of different archetypes and include a greater span of construction years. A further study could be conducted while including the north of Sweden, and a higher number of locations. Photovoltaics, solar thermal and LCC-calculations were excluded in this master thesis, which could be of high interest for many homeowners. The implementation of LCC-calculations could be further developed to include a financial investment plan for the homeowner, along with a customized future schedule for implementing each measure.

Future energy mix-scenarios could be investigated, while also including more alternative materials in the renovation scenarios when conducting LCA calculations.

8 References

Andrén, L., & Tirén, L. M.-G. (2012). *Passivhus: En handbok om energieffektivt byggande* (2. utg). Svensk Byggtjänst.

Attia, S., Kurnitski, J., Kosiński, P., Borodiņecs, A., Deme Belafi, Z., István, K., Krstić, H., Moldovan, M., Visa, I., Mihailov, N., Evstatiev, B., Banionis, K., Čekon, M., Vilčeková, S., Struhala, K., Brzoň, R., & Laurent, O. (2022). Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe. *Energy and Buildings*, *267*, 112165. https://doi.org/10.1016/j.enbuild.2022.112165

Bankvall, C. G. (2013). *Luftboken: Luftrörelser och täthet i byggnader*. Studentlitteratur.

Björk, C., Nilsson, H., Sandberg, M., Adolfi, B., Leijonhufvud, G., Laila, R., Broström, T., Ohlén, B., Fickler, S., Bokalderd, V., Hansson, P., Söderström Rosén, M., Franzén, A., & Holmberg, J. (2011). *Energiboken: Energieffektivisering för småhusägare*. Svenska byggnadsvårdsföreningen.

Björk, C., Nordling, L., & Reppen, L. (2015). *Så byggdes villan: Svensk villaarkitektur från 1890 till 2010* ([Ny utg.]). Svensk Byggtjänst.

Björk, C., Reppen, L., & Nordling, L. (2012). *Så byggdes staden: [Stadsbyggnad, arkitektur, husbyggnad]* (3., uppdaterade och utök. uppl). Svensk byggtjänst.

Boverket. (2009). *Så mår våra hus: Redovisning av regeringsuppdrag beträffande byggnaders tekniska utformning m.m* [Elektronisk resurs]. Boverket.

Boverket. (2016). *Byggregler – en historisk översikt*. https://www.boverket.se/contentassets/ba75fc25915f4a79bad02ff6e9a5eb02/aldre-byggregler-2016-08-12.pdf

Boverket. (2017). *BFS 2017:6 BEN 2*. https://rinfo.boverket.se/BFS2016-12/pdf/BFS2017-6.pdf

Boverket. (2024a). *Bidrag för energieffektivisering i småhus*. https://www.boverket.se/sv/bidrag--garantier/bidrag-for-energieffektivisering-i-smahus/ [Accessed: 15 May 2024]

Boverket. (2024b). *Boverkets klimatdatabas*. https://klimatdatabasen.boverket.se/ [Accessed: 15 May 2024]

Boverket. (2024c). *Utsläpp av växthusgaser från bygg- och fastighetssektorn*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/vaxthusgaser/ [Accessed: 15 May 2024]

Energiföretagen. (2023). *Miljövärdering av fjärrvärme*. https://www.energiforetagen.se/statistik/fjarrvarmestatistik/miljovardering-av-fjarrvarme/ [Accessed: 15 May 2024]

Energimyndigheten. (2021). *The Swedish Energy Agency*. https://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/energistatistik-for-smahus/ [Accessed: 15 May 2024]

EPA. (2024). *Overview of Greenhouse Gases*. https://www.epa.gov/ghgemissions/overview-greenhouse-gases [Accessed: 15 May 2024]

EPS-bygg. (2010). *Grundboken—EPS i grund och mark*. https://www.ikem.se/globalassets/media-eps-sverige/eps-dokument/informationsmaterial/grundboken.pdf

Equa Simulation AB. (2010). *Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standards EN 15255-2007 and EN 15265-2007*. https://www.equaonline.com/iceuser/validation/CEN_VALIDATION_EN_15255_AND_15265.pdf

European Climate Foundation. (2022). *Building Europe's net-zero future*. https://europeanclimate.org/wp-content/uploads/2022/03/ecf-building-emissions-problem-march2022.pdf

European Commission. (2023). *Energy Performance of Buildings Directive*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en [Accessed: 15 May 2024]

European Commission. (2024). *BSO - Building Stock Observarory*. https://building-stock-observatory.energy.ec.europa.eu/database/ [Accessed: 15 May 2024]

European Commission. Joint Research Centre. (2021). *EU challenges of reducing fossil fuel use in buildings.* Publications Office. https://data.europa.eu/doi/10.2760/85088

European Environment Agency. (2022). *Modelling the Renovation of Buildings in Europe from a Circular Economy and Climate Perspective*. https://www.eea.europa.eu/publications/building-renovation-where-circular-economy/modelling-the-renovation-of-buildings [Accessed: 15 May 2024]

Fabbri, M. (2017). *Understanding building renovation passports: Customised solutions to boost deep renovation and increase comfort in a decarbonised Europe*. https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2017/6-buildings-policies-directives-and-programmes/understanding-building-renovation-passports-customised-solutions-to-boost-deep-renovation-and-increase-comfort-in-a-decarbonised-europe/ [Accessed: 15 May 2024]

Fabbri, M., De Groote, M., & Rapf, O. (2016). *BUILDING RENOVATION PASSPORTS: Customised roadmaps towards deep renovation and better homes*. Buildings Performance Institute Europe (BPIE). https://bpie.eu/wp-content/uploads/2016/10/Building-Passport-Report_v4.pdf

Formas. (2012). *Miljonprogrammet—Utveckla eller avveckla?* Forskningsrådet Formas.

Hagentoft, C.-E. (2003). *Vandrande fukt, strålande värme: Så fungerar hus*. Studentlitteratur.

Hagentoft, C.-E., & Sandin, K. (2017). *Byggnadsfysik: Så fungerar hus* (Upplaga 1). Studentlitteratur.

Hasper, W., Kirtschig, T., Siddall, M., Johnston, D., Vallentin, G., & Harvie-Clark, J. (2021). Long-term performance of Passive House buildings. *Energy Efficiency*, *14*(1), 5. https://doi.org/10.1007/s12053-020-09913-0

HI-SMART. (n.d.). *nZEB definition*. https://ec.europa.eu/programmes/erasmus-plus/project-result-content/48ff898e-a503-414a-b112-fba01dd2976e/HI-SMART_1.2_nZEB_definition_presentation.pdf

Holm, F., Wahlström, Å., Persson, A., Gråd, E., Andersson, P. A., Malinen, F., Engdahl, N., Gräås, C., Sharif, M., & Guldbrand, M. (2023). Länsförsäkringar. https://citrenergy.se/app/uploads/2023/11/Svenska-allmanhetens-energikunskaper-230929.pdf

International Energy Agency. (2023). *Final energy consumption of buildings relative to other sectors*. https://www.iea.org/energy-system/buildings [Accessed: 15 May 2024]

Isodrän. (2023). *Tekniken bakom*. https://www.isodran.se/tekniken-bakom [Accessed: 15 May 2024]

Jokisalo, J., Kurnitski, J., Korpi, M., Kalamees, T., & Vinha, J. (2009). Building leakage, infiltration, and energy performance analyses for Finnish detached houses. *Building and Environment*, *44*(2), 377–387. https://doi.org/10.1016/j.buildenv.2008.03.014

Jonsson, L. (1990). *1960-talets enplansvilla*. https://byggnadsvard.se/enfamiljshuset-i-sverige-efter-1950/ [Accessed: 15 May 2024]

Kalamees, T. (2007). Air tightness and air leakages of new lightweight single-family detached houses in Estonia. *Building and Environment*, *42*(6), 2369–2377. https://doi.org/10.1016/j.buildenv.2006.06.001

Maduta, C., D'Agostino, D., Tsemekidi-Tzeiranaki, S., Castellazzi, L., Melica, G., & Bertoldi, P. (2023). Towards climate neutrality within the European Union: Assessment of the Energy Performance of Buildings Directive implementation in Member States. *Energy and Buildings*, *301*, 113716. https://doi.org/10.1016/j.enbuild.2023.113716

Moosberger, S. (2007). *IDA ICE CIBSE-Validation Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3*. https://www.equaonline.com/iceuser/validation/ICE-Validation-CIBSE_TM33.pdf

Nik, V. M., Sasic Kalagasidis, A., & Kjellström, E. (2012). Assessment of hygrothermal performance and mould growth risk in ventilated attics in respect to possible climate changes in Sweden. *Building and Environment*, *55*, 96–109. https://doi.org/10.1016/j.buildenv.2012.01.024

Nylander, O. (2018). *Svensk bostads arkitektur: Utveckling från 1800-tal till 2000-tal* (2:1). Studentlitteratur AB, Lund.

Östman, R. (2017). *Byggnadsteknik hos villor byggda på 1960-talet*. [Examensarbete inom samhällsbyggnad, advancerad nivå, 30 HP] Kungliga Tekniska Högskolan (KTH).

Purmo. (2024). *Produktdimensionering*. https://www.purmo.com/sv-se/verktyg-och-tjanster/produktdimensionering [Accessed: 15 May 2024]

Šadauskienė, J., Ramanauskas, J., Šeduikytė, L., Daukšys, M., & Vasylius, A. (2015). A Simplified Methodology for Evaluating the Impact of Point Thermal Bridges on the High-Energy Performance of a Passive House. *Sustainability*, *7*(12), 16687–16702. https://doi.org/10.3390/su71215840

Schleich, J., Mills, B., & Dütschke, E. (2014). A brighter future? Quantifying the rebound effect in energy efficient lighting. *Energy Policy*, *72*, 35–42. https://doi.org/10.1016/j.enpol.2014.04.028

Sesana, M. M., & Salvalai, G. (2018). A review on Building Renovation Passport: Potentialities and barriers on current initiatives. *Energy and Buildings*, *173*, 195–205. https://doi.org/10.1016/j.enbuild.2018.05.027

Sesana, M. M., Salvalai, G., Greslou, O., Rivallain, M., & Zirngibl, J. (2019). Long - Term Renovation Strategies, Energy Voluntary Certification Scheme and Building Renovation Passport: An overview on Energy Performance Certification tools for the European Building stock. *IOP Conference Series: Earth and Environmental Science*, *296*(1), 012029. https://doi.org/10.1088/1755-1315/296/1/012029

Sveriges Allmännytta. (2024). *Kommande energirenoveringskrav En konsekvensanalys från Sveriges Allmännytta*. https://www.sverigesallmannytta.se/wp/wp-admin/admin-ajax.php?action=sabo_download_secure_file&id=95864 [Accessed: 15 May 2024]

Sweden Green Building Council. (2022). *Miljöbyggnad 4.0*. https://www.sgbc.se/app/uploads/2022/12/Manual_MB_4.0_1.pdf

Swegon. (2024). *ProCASA Energikalkylator*. https://procasa.swegon.com/sv/procasa-e [Accessed: 15 May 2024]

The European Parliament. (2024). *DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024 on the energy performance of buildings*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401275'

The Finnish Environment Institute. (2024). *Emissions database for construction*. https://co2data.fi/rakentaminen/ [Accessed: 15 May 2024]

The Swedish Energy Agency. (2018). *Belysningsel i bostäder och lokaler*. https://www.energimyndigheten.se/globalassets/belysningsutmaningen---portal/rapporter/belysningsel-i-bostader-och-lokaler-statisticon-2018-underlagsrapport-belysningsutmaningen.pdf

The Swedish Energy Agency. (2022a). *Energiklassning på svenska småhus*. https://www.energimyndigheten.se/energieffektivisering/husguiden---for-dig-som-vill-energieffektivisera-ditt/gor-en-husesyn/ [Accessed: 15 May 2024]

The Swedish Energy Agency. (2022b). *Husguiden – för dig som vill energieffektivisera ditt hus*. https://www.energimyndigheten.se/energieffektivisering/husguiden---for-dig-som-vill-energieffektivisera-ditt/ [Accessed: 15 May 2024]

Tombarević, E., Vušanović, I., & Šekularac, M. (2023). The Impact of Windows Replacement on Airtightness and Energy Consumption of a Single Apartment in a Multi-Family Residential Building in Montenegro: A Case Study. *Energies*, *16*(5), 2208. https://doi.org/10.3390/en16052208

U.S. Department of energy. (2023). *National Definition of a Zero Emissions Building: Part 1 Operating Emissions Version 1.00, Draft Criteria*. https://www.energy.gov/sites/default/files/2024-01/bto-national-definition-zero-emissions-building-122023.pdf

Visit Hultsfred. (2023). https://visithultsfred.se/hultsfreds-hus-museum/ [Accessed: 15 May 2024]

Warfvinge, C., & Dahlblom, M. (2010). *Projektering av VVS-installationer* (1:10). Studentlitteratur AB, Lund.

WHO. (2023). *Climate Change*. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health [Accessed: 15 May 2024]

Wikells Sektionsfakta. (2024). *Wikells byggberäkningar*. https://wikells.se/ [Accessed: 15 May 2024]

9 Appendix

Appendix A. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, location: Malmö.

Location: Malmö							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings /(kWh/year)**	**/(kWh/m²)**	**Ratio**	**Reference Building 2 Savings /(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls	50	1 434	5.3	3.8 %	1 075	10.7	5.2 %
	100	2 599	9.6	6.9 %	1 550	15.5	7.6 %
	150	3 052	11.3	8.2 %	1 820	18.2	8.9 %
	200	3 348	12.4	9.0 %	1 991	19.9	9.7 %
	250	3 557	13.2	9.5 %	2 110	21.1	10.3 %
Attic	100	1 805	6.7	4.8 %	1 160	11.6	5.7 %
	200	2 354	8.7	6.3 %	1 515	15.2	7.4 %
	300	2 576	9.5	6.9 %	1 655	16.6	8.1 %
	400	2 668	9.9	7.1 %	1 698	17.0	8.3 %
	500	2 688	10.0	7.2 %	1 708	17.1	8.3 %
Basement walls	50	1 972	7.3	5.3 %			
	100	2 587	9.6	6.9 %			
	200	3 135	11.6	8.4 %	-	-	-
	300	3 424	12.7	9.2 %			
	400	3 641	13.5	9.7 %			
Slab EPS-crete	50	755	2.8	2.0 %	341	3.4	1.7 %
	100						
Regular EPS + casted concrete	50	1 384	5.1	3.7 %	1 150	11.5	5.6 %
	100	1 462	5.4	3.9 %	1 348	13.5	6.6 %
	200	2 143	7.9	5.7 %	2 139	21.4	10.4 %
	300	2 777	10.3	7.4 %	2 764	27.6	13.5 %
	400	3 085	11.4	8.2 %	3 042	30.4	14.8 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	1 716	6.4	4.6 %	1 047	10.5	5.1 %
	1.2	3 119	11.6	8.3 %	2 125	21.3	10.4 %
	0.8	3 697	13.7	9.9 %	2 458	24.6	12.0 %
Doors	1.2	662	2.5	1.8 %	298	3.0	1.5 %
	0.8	810	3.0	2.2 %	356	3.6	1.7 %
MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	5 500	20.4	14.7 %	1 669	16.7	8.1 %

Appendix B. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, location: Växjö.

Location: Växjö							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings**			**Reference Building 2 Savings**		
		/(kWh/year)	**/(kWh/m²)**	**Ratio**	**/(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls							
	50	1 706	6.3	4.6 %	1 207	12.1	5.9 %
	100	3 011	11.2	8.1 %	1 740	17.4	8.5 %
	150	3 536	13.1	9.5 %	2 040	20.4	9.9 %
	200	3 883	14.4	10.4 %	2 231	22.3	10.9 %
	250	4 121	15.3	11.0 %	2 362	23.6	11.5 %
Attic	100	2 040	7.6	5.5 %	1 283	12.8	6.3 %
	200	2 661	9.9	7.1 %	1 668	16.7	8.1 %
	300	2 910	10.8	7.8 %	1 820	18.2	8.9 %
	400	3 010	11.1	8.1 %	1 860	18.6	9.1 %
	500	3 034	11.2	8.1 %	1 873	18.7	9.1 %
Basement walls	50	2 278	8.4	6.1 %			
	100	3 010	11.1	8.1 %			
	200	3 663	13.6	9.8 %	-	-	-
	300	4 011	14.9	10.7 %			
	400	4 263	15.8	11.4 %			
Slab EPS-crete	50	842	3.1	2.3 %	386	3.9	1.9 %
	100						
Regular EPS + casted concrete	50	1 599	5.9	4.3 %	1 304	13.0	6.4 %
	100	1 725	6.4	4.6 %	1 523	15.2	7.4 %
	200	2 542	9.4	6.8 %	2 414	24.1	11.8 %
	300	3 299	12.2	8.8 %	3 123	31.2	15.2 %
	400	3 667	13.6	9.8 %	3 434	34.3	16.7 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	1 967	7.3	5.3 %	1 106	11.1	5.4 %
	1.2	3 579	13.3	9.6 %	2 245	22.4	10.9 %
	0.8	4 258	15.8	11.4 %	2 599	26.0	12.7 %
Doors	1.2	750	2.8	2.0 %	307	3.1	1.5 %
	0.8	930	3.4	2.5 %	372	3.7	1.8 %

MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	6 735	24.9	18.0 %	2 021	20.2	9.8 %

Appendix C. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, location: Gothenburg.

Location: Gothenburg							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings**			**Reference Building 2 Savings**		
		/(kWh/year)	**/(kWh/m²)**	**Ratio**	**/(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls							
	50	1 511	5.6	4.0 %	1 119	11.2	5.5 %
	100	2 732	10.1	7.3 %	1 617	16.2	7.9 %
	150	3 207	11.9	8.6 %	1 896	19.0	9.2 %
	200	3 521	13.0	9.4 %	2 074	20.7	10.1 %
	250	3 737	13.8	10.0 %	2 199	22.0	10.7 %
Attic	100	1 878	7.0	5.0 %	1 202	12.0	5.9 %
	200	2 455	9.1	6.6 %	1 568	15.7	7.6 %
	300	2 690	10.0	7.2 %	1 712	17.1	8.3 %
	400	2 785	10.3	7.4 %	1 724	17.2	8.4 %
	500	2 805	10.4	7.5 %	1 763	17.6	8.6 %
Basement walls	50	2 060	7.6	5.5 %			
	100	2 709	10.0	7.2 %			
	200	3 284	12.2	8.8 %	-	-	-
	300	3 590	13.3	9.6 %			
	400	3 818	14.1	10.2 %			
Slab EPS-crete	50 100	783	2.9	2.1 %	358	3.6	1.7 %
Regular EPS + casted concrete	50	1 447	5.4	3.9 %	1 197	12.0	5.8 %
	100	1 537	5.7	4.1 %	1 393	13.9	6.8 %
	200	2 256	8.4	6.0 %	2 206	22.1	10.7 %
	300	2 918	10.8	7.8 %	2 851	28.5	13.9 %
	400	3 244	12.0	8.7 %	3 132	31.3	15.3 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	1 797	6.7	4.8 %	1 052	10.5	5.1 %
	1.2	3 268	12.1	8.7 %	2 138	21.4	10.4 %
	0.8	3 884	14.4	10.4 %	2 481	24.8	12.1 %
Doors	1.2	685	2.5	1.8 %	292	2.9	1.4 %
	0.8	849	3.1	2.3 %	355	3.5	1.7 %

MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	5 907	21.9	15.8 %	1 766	17.7	8.6 %

Appendix D. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, Stockholm location.

Location: Stockholm							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings**			**Reference Building 2 Savings**		
		/(kWh/year)	**/(kWh/m²)**	**Ratio**	**/(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls							
	50	2 316	8.6	6.2 %	1 213	12.1	5.6 %
	100	3 349	12.4	9.0 %	1 750	17.5	8.1 %
	150	3 942	14.6	10.5 %	2 051	20.5	9.5 %
	200	4 326	16.0	11.6 %	2 246	22.5	10.3 %
	250	4 598	17.0	12.3 %	2 377	23.8	10.9 %
Attic	100	2 061	7.6	5.5 %	1 295	13.0	6.0 %
	200	2 689	10.0	7.2 %	1 688	16.9	7.8 %
	300	2 941	10.9	7.9 %	1 841	18.4	8.5 %
	400	3 047	11.3	8.1 %	1 867	18.7	8.6 %
	500	3 070	11.4	8.2 %	1 896	19.0	8.7 %
Basement walls	50	1 907	7.1	5.1 %			
	100	2 593	9.6	6.9 %			
	200	3 216	11.9	8.6 %	-	-	-
	300	3 544	13.1	9.5 %			
	400	3 765	13.9	10.1 %			
Slab EPS-crete	50	850	3.1	2.3 %	1 156	11.6	5.3 %
	100	1619	6.0	4.3 %	2 054	20.5	10.3 %
Regular EPS + casted concrete	50	1 751	6.5	4.7 %	2 703	27.0	12.5 %
	100	2 578	9.5	6.9 %	3 596	36.0	16.6 %
	200	3 343	12.4	8.9 %	4 305	43.1	19.8 %
	300	3 714	13.8	9.9 %	4 614	46.1	21.3 %
	400	3 935	14.6	10.5 %	4 787	47.9	22.1 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	1 972	7.3	5.3 %	1 124	11.2	5.2 %
	1.2	3 592	13.3	9.6 %	2 265	22.6	10.4 %
	0.8	4 263	15.8	11.4 %	2 607	26.1	12.0 %
Doors	1.2	761	2.8	2.0 %	324	3.2	1.5 %
	0.8	944	3.5	2.5 %	393	3.9	1.8 %

MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	5 558	20.6	14.9%	1 822	18.2	8.4%

Appendix E. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, location: Karlstad.

Location: Karlstad							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings**			**Reference Building 2 Savings**		
		/(kWh/year)	**/(kWh/m²)**	**Ratio**	**/(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls	50	1 815	6.7	4.9 %	1 258	12.6	6.1 %
	100	3 173	11.8	8.5 %	1 815	18.1	8.8 %
	150	3 724	13.8	10.0 %	2 127	21.3	10.4 %
	200	4 086	15.1	10.9 %	2 327	23.3	11.3 %
	250	4 340	16.1	11.6 %	2 463	24.6	12.0 %
Attic	100	2 130	7.9	5.7 %	1 333	13.3	6.5 %
	200	2 778	10.3	7.4 %	1 733	17.3	8.4 %
	300	3 040	11.3	8.1 %	1 891	18.9	9.2 %
	400	3 147	11.7	8.4 %	1 930	19.3	9.4 %
	500	3 171	11.7	8.5 %	1 947	19.5	9.5 %
Basement walls	50	2 434	9.0	6.5 %			
	100	3 222	11.9	8.6 %			
	200	3 926	14.5	10.5 %	-	-	-
	300	4 299	15.9	11.5 %			
	400	4 572	16.9	12.2 %			
Slab EPS-crete	50	887	3.3	2.4 %	411	4.1	2.0 %
	100						
Regular EPS + casted concrete	50	1 709	6.3	4.6 %	1 375	13.8	6.7 %
	100	1 860	6.9	5.0 %	1 607	16.1	7.8 %
	200	2 745	10.2	7.3 %	2 548	25.5	12.4 %
	300	3 568	13.2	9.5 %	3 294	32.9	16.0 %
	400	3 969	14.7	10.6 %	3 621	36.2	17.6 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	2 050	7.6	5.5 %	1 141	11.4	5.6 %
	1.2	3 736	13.8	10.0 %	2 316	23.2	11.3 %
	0.8	4 443	16.5	11.9 %	2 678	26.8	13.0 %
Doors	1.2	803	3.0	2.1 %	318	3.2	1.5 %
	0.8	995	3.7	2.7 %	387	3.9	1.9 %
MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	7 064	26.2	18.9 %	2 081	20.8	10.1 %

Appendix F. Energy demand savings for all renovation measures, in comparison to the Base Case of the reference buildings, location: Borlänge.

Location: Borlänge							
Insulation construction	**Thickness / mm**	**Reference Building 1 Savings**			**Reference Building 2 Savings**		
		/(kWh/year)	**/(kWh/m²)**	**Ratio**	**/(kWh/year)**	**/(kWh/m²)**	**Ratio**
Ext. walls	50	2 050	7.6	5.5 %	1 357	13.6	6.6 %
	100	3 511	13.0	9.4 %	1 958	19.6	9.5 %
	150	4 121	15.3	11.0 %	2 295	23.0	11.2 %
	200	4 522	16.7	12.1 %	2 511	25.1	12.2 %
	250	4 800	17.8	12.8 %	2 660	26.6	13.0 %
Attic	100	2 333	8.6	6.2 %	1 440	14.4	7.0 %
	200	3 040	11.3	8.1 %	1 875	18.7	9.1 %
	300	3 327	12.3	8.9 %	2 045	20.4	10.0 %
	400	3 441	12.7	9.2 %	2 065	20.7	10.1 %
	500	3 467	12.8	9.3 %	2 105	21.0	10.3 %
Basement walls	50	2 616	9.7	7.0 %			
	100	3 470	12.9	9.3 %			
	200	4 233	15.7	11.3 %	-	-	-
	300	4 637	17.2	12.4 %			
	400	4 931	18.3	13.2 %			
Slab EPS-crete	50 100	940	3.5	2.5 %	436	4.4	2.1 %
Regular EPS + casted concrete	50	1 834	6.8	4.9 %	1 469	14.7	7.2 %
	100	2 019	7.5	5.4 %	1 725	17.2	8.4 %
	200	2 978	11.0	8.0 %	2 743	27.4	13.4 %
	300	3 870	14.3	10.4 %	3 556	35.6	17.3 %
	400	4 303	15.9	11.5 %	3 913	39.1	19.1 %
		Reference Building 1 Savings			**Reference Building 1 Savings**		
	***U*-value / (W/(m²·K))**	**/ (kWh/y)**	**/(kWh/m²)**	**Ratio**	**/(kWh/y)**	**/(kWh/m²)**	**Ratio**
Windows	2.0	2 265	8.4	6.1 %	1 212	12.1	5.9 %
	1.2	4 130	15.3	11.0 %	2 445	24.5	11.9 %
	0.8	4 933	18.3	13.2 %	2 828	28.3	13.8 %
Doors	1.2	877	3.2	2.3 %	340	3.4	1.7 %
	0.8	1 087	4.0	2.9 %	417	4.2	2.0 %

MVHR	Efficiency	/(kWh/year)	/(kWh/m²)	Ratio	/(kWh/year)	/(kWh/m²)	Ratio
Rotary	85 %	7 864	29.1	21.0 %	2 308	23.1	11.2 %

Appendix G. Insulation thickness and volume for both buildings.

	Material thickness	**Material volume / m³**	
	/ mm	**Building 1**	**Building 2**
Wall insulation	50	6.5	5.6
	100	13	11.2
	150	19.5	16.8
	200	26	22.3
	250	32.5	27.9
Attic insulation	100	14.1	10.3
	200	28.2	20.6
	300	42.3	30.9
	400	56.4	41.2
	500	70.5	51.5
Basement insulation	50	5.6	N/A
	100	11.2	N/A
	200	22.4	N/A
	300	33.6	N/A
	400	44.8	N/A
Slab insulation	50	7	5.2
	100	14	10.3
	200	28	20.6
	300	42	30.9
	400	56	41.2

Appendix H. Embodied emissions input variables for LCA calculations.

Building envelope input values by Boverket climate database			
	Material	**Embodied emissions / ($kgCO_2$eq. / kg material)**	**Density / (kg/m^3)**
Ext. walls	Glass wool facade slabs	0.86	55
	Rockwool facade slabs	1.29	80
	EPS	3.20	20
Attic floor	Mineral wool loose fill	0.90	15
	Rockwool loose fill	1.28	28
	Cellulose loose fill	0.16	45
Basement walls	EPS / Isodrän	3.2	20
Slab on ground	EPScrete	1.01	200
	EPS	3.2	20
	Concrete	0.0977	2 350
			Weight / (kg/m^2)
Windows	Wood frame	2.0	39.2
Doors	Wood	1.5	27.7

HVAC installations, input values by the Finnish Environment Institute			
	Material	Embodied emissions / ($kgCO_2$eq. / kg material)	Weight per assembly
Ventilation fittings	Steel	3.59	Variable value. Specified in Appendix J.
Ventilation ducts	Steel	2.6	Variable value. Specified in Appendix J.
Radiator pipes	PEX	2.53	2 kg / m
Radiators	Steel	3.4	35.5 kg / kW Peak Power

Appendix I. Embodied emissions for the building envelope.

		Embodied emissions / kgCO$_2$eq.					
		Building 1			**Building 2**		
	Thickness / mm	Glass wool	Rock wool	EPS	Glass wool	Rock wool	EPS
Wall Insulation	50	307	671	416	264	576	357
	100	615	1 342	832	528	1 153	715
	150	922	2 012	1 248	793	1 729	1 072
	200	1 230	2 683	1 664	1 057	2 305	1 430
	250	1 537	3 354	2 080	1 321	2 882	1 787
	Thickness / mm	Glass wool	Rock wool	Cellulose	Glass wool	Rock wool	Cellulose
Attic Insulation	100	190	505	102	139	369	74
	200	381	1 011	203	278	738	148
	300	571	1 516	305	417	1 107	222
	400	761	2 021	406	556	1 477	297
	500	952	2 527	508	695	1 846	371
	Thickness / mm	EPS / Isodrän	-	-	-	-	-
Basement Insulation	50	358					
	100	717					
	200	1 434					
	300	2 150					
	400	2 867					
	Thickness / mm	EPS + 100 mm concrete	EPScrete		EPS + 100 mm concrete	EPScrete	
Slab Insulation	50	3 662	1 414		2 694	1 040	
	100	4 110	2 828		3 024	2 081	
	200	5 006	-		3 683	-	
	300	5 902	-		4 342	-	
	400	6 798	-		5 002	-	
	U-value / (W/(m²·K))	Wood frame			Wood frame		
Windows	2	1 929			1 369		
	1.2	1 929			1 369		
	0.8	2 218			1 574		
	U-value / (W/(m²·K))	Wood			Wood		
Doors	1.2	191			78		
	0.8	220			101		

Appendix J. Emissions for ventilation systems, including all components.

		Building 1			Building 2		
Duct dimension / mm	**Weight /(kg/m)**	**Duct length / m**	**Total weight / kg**	**Emissions / kgCO_2eq.**	**Total duct length / m**	**Total weight / kg**	**Emissions / kgCO_2eq.**
200	2.56	6.8	17.4	45.3	0	0	0
160	2.02	2.2	4.4	11.6	0	0	0
125	1.41	5.9	8.3	21.6	12.2	17.2	44.7
100	1.14	1.0	1.1	3.0	2.9	3.2	8.4
80	0.91	16.4	14.9	38.8	6.7	6.1	15.9
63	0.75	5.0	3.8	9.8	4.5	3.4	8.8
Total		37.3	50.0	130.0	26.3	29.9	77.8
Fittings	Weight per fitting / kg	Pieces	Total weight / kg	kgCO_2eq.	Pieces	Total weight / kg	kgCO_2eq.
D_Supply (100 mm)	0.28	7	2.0	7.0	4	1.1	4.0
D_Exhaust (100 mm)	0.18	4	0.7	2.6	4	0.7	2.6
T (125 mm)	0.44	8	3.5	12.6	5	2.2	7.9
E (125 mm)	0.31	6	1.9	6.7	4	1.2	4.5
Total		25	8.1	28.9	17	5.3	19.0
AHU, Casa W3xs (2 per 50 years)			44.86	236		44.86	236
Total emissions 50 years		631 kgCO_2eq.			569 kgCO_2eq.		

Appendix K. Embodied emissions for radiators and piping.

	Location Stockholm	Peak Power demand / kW	Total radiator weight / kg	Radiator emissions / kgCO_2eq.	Piping weight / kg	Total emissions / kgCO_2eq.
Building 1	Base Case	14.2	505	1 717	55	1 773
	BBRs	8.7	309	1 049	55	1 104
	PHs	3.9	138	469	55	524
Building 2	Base Case	9.3	330	1 121	18	1 139
	BBRs	4.4	156	530	18	548
	PHs	2.3	81	277	18	295

Appendix L. Embodied emissions for Heat Pumps.

Model	Peak Power / kW	Total weight / kg	Embodied emissions / $kgCO_2eq.$	Source
Air-to-Air HP, generic	3 - 5	50	862	EPD Finland
Air to water HP, outdoor + indoor unit for both space heating and DHW				
Panasonic Aquarea	3	159	1 664	Calculated
Mitsubishi PUZ	5	192	1 735	EPD
Mitsubishi PUZ	6	192	1 971	EPD
Mitsubishi PUZ	8.5	213	2 059	EPD
Mitsubishi PUZ	14	226	2 365	Calculated
Termix VVX 22-22 Heat exchanger (District Heating)	22	10	37	EPD

Appendix M. Swegon report for the Air Handling Unit, Building 1.

ProCASA v9.0
2024-03-27

Projektdata

Projekt	**Master Thesis**		
Kund			
Konstruerat av	**Jens Lundgren**		
Placering			
Tilluftsflöde		**61 l/s**	**220 m³/h**
Total tryckförlust i tilluftskanalen		**80 Pa**	
Frånluftsflöde		**61 l/s**	**220 m³/h**
Total tryckförlust i avluftskanalen		**49 Pa**	
Luftflöde via spiskåpa		**0 l/s**	**0 m³/h**
användningstid per dag		**0 h/d**	

Specifikation för aggregat

Aggregattyp	**W3 xs Smart**		
		Tilluft	**Frånluft**
Fläktar, effektförbrukning		**41 W**	**35 W**
SFP		**1.25 kW / (m³/s)**	
Fläktar, årlig energianvändning		**667 kWh**	
SPI		**0.35 W / (m³/h)**	

Akustikdata

Oktavband (Hz)	**63, Lw**	**125, Lw**	**250, Lw**	**500, Lw**	**1k, Lw**	**2k, Lw**	**4k, Lw**	**8k, Lw**	**Lwa**
Ljud emitterat till:	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB**	**dB(A)**
Ljud emitterat till tilluftskanal	**74**	**74**	**68**	**62**	**57**	**55**	**50**	**46**	**65**
Ljud emitterat till frånluftskanal	**64**	**56**	**52**	**48**	**38**	**35**	**27**	**24**	**49**
table.outdoor	**64**	**61**	**57**	**51**	**41**	**37**	**29**	**24**	**53**
table.exhaust	**73**	**70**	**66**	**59**	**53**	**50**	**46**	**40**	**62**
Ljud emitterat till förbigångskanal för kök	**76**	**61**	**54**	**47**	**46**	**39**	**31**	**26**	**54**
emitterat till omgivningen	**54**	**49**	**45**	**33**	**26**	**16**	**16**	**15**	**39**
omgivningen vid -4 dB ljuddämpning									**35**

Aggregatet monterat mellan köksskåp minskar emitterat ljud med 2 dB

Tekniska specifikationer

Vikt	**47 kg**	
Värmeväxlare	**Plattvärmeväxlare**	
Filter	Tilluft	Frånluft
Filterklass	**ISO ePM1 50% (F7)**	**ISO Coarse > 50% (G3)**
Mått, mm, mm	**344*200*24**	**344*275*10**
Förvärme	**1000 W**	
Eftervärme till	**El**	**500 W**

Appendix N. Swegon report for the Air Handling Unit, Building 2.

ProCASA v9.0
2024-03-27

Swegon

Projektdata

Projekt	Master Thesis	
Kund		
Konstruerat av	Jens Lundgren	
Placering		
Tilluftsflöde	35 l/s	126 m³/h
Total tryckförlust i tilluftskanalen	58 Pa	
Frånluftsflöde	35 l/s	126 m³/h
Total tryckförlust i avluftskanalen	40 Pa	
Luftflöde via spiskåpa	0 l/s	0 m³/h
användningstid per dag	0 h/d	

Specifikation för aggregat

Aggregattyp	W3 xs Smart	
	Tilluft	Frånluft
Fläktar, effektförbrukning	18 W	16 W
SFP	0.98 kW / (m³/s)	
Fläktar, årlig energianvändning	300 kWh	
SPI	0.27 W / (m³/h)	

Akustikdata

Oktavband (Hz)	63, L_W	125, L_W	250, L_W	500, L_W	1k, L_W	2k, L_W	4k, L_W	8k, L_W	L_{wa}
Ljud emitterat till:	dB	dB	dB	dB	dB	dB	dB	dB	dB(A)
Ljud emitterat till tilluftskanal	69	67	61	56	50	46	40	33	58
Ljud emitterat till frånluftskanal	59	50	46	43	31	26	20	23	43
table.outdoor	61	54	50	44	34	29	21	23	46
table.exhaust	68	63	58	52	45	41	35	27	54
Ljud emitterat till förbigångskanal för kök	72	55	47	43	37	30	21	18	48
emitterat till omgivningen	48	44	38	27	21	12	8	7	33
omgivningen vid -4 dB ljuddämpning									29

Aggregatet monterat mellan köksskåp minskar emitterat ljud med 2 dB

Tekniska specifikationer

Vikt	47 kg	
Värmeväxlare	Plattvärmeväxlare	
Filter	Tilluft	Frånluft
Filterklass	ISO ePM1 50% (F7)	ISO Coarse > 50% (G3)
Mått, mm, mm	344*200*24	344*275*10
Förvärme	1000 W	
Eftervärme till	El	500 W

Appendix O. Duct sizing Building 2.

Section	Volume flow rate	Velocity	Dim	Pressure drop	Length	Duct loss	Fitting type	Fitting loss	Total friction loss
	/ (l/s)	/ (m/s)	/ mm	/ (Pa/m)	/ m	/ Pa		/ Pa	/ Pa
Exhaust air									
A1-A2	61	3.0	200	0.6	0.8	0.5			
A3-B1	61	3.0	200	0.6	4.2	2.5			
B1-B2	13.5	2.1	80	1.1	1	1.1	T	10	
B2-B3	13.5	2.1	80	1.1	0.5	0.6	E	5	
B3-B4	13.5	2.1	80	1.1	2.4	2.6	E+D	10	
AHU-B4									**31.8**
B1-C1	47	2.5	160	0.5	0.5	0.3	T	10	
C1-C2	15	2	100	0.6	0.5	0.3	T+D	20	
AHU-C2						0.0			**33.6**
C1-C3	32	2.7	125	0.8	1.7	1.4	T	10	
C3-C4	22	2.5	100	1	0.5	0.5	T+D	20	
AHU-C4						0.0			**45.1**
C3-C5	10	2	80	0.9	1.8	1.6	T	10	
C5-C6	10	2	80	0.9	0.5	0.5	E+D	10	
AHU-C6									**48.7**
Supply air									
D1-D2	61	3	200	0.6	0.8	0.5			
D3-D4	61	3	200	0.6	1	0.6			
D4-D5	4	1.8	63	0.7	0.8	0.6	T+D	20	
AHU-D5									**21.6**
D4-D6	57	3	160	8	0.4	3.2	T	10	
D6-D7	8	1.8	80	0.6	0.8	0.5	T+D	20	
AHU-D7									**34.8**
D6-D8	49	2.5	160	0.5	0.8	0.4	T	10	
D8-D9	4	1.8	63	0.7	0.8	0.6	T+D	20	
AHU-D9									**45.2**
D8-E1	45	2.5	160	0.5	0.5	0.3	T	10	
E1-E2	13.5	2.1	80	1.1	0.8	0.9	T	10	
E2-E3	13.5	2.1	80	1.1	0.5	0.6	E	5	
E3-E4	13.5	2.1	80	1.1	0.8	0.9	E	5	
E4-E5	6.75	1.2	80	0.5	1.7	0.9	T+D	20	
AHU-E5									**78.1**
E4-E6	6.75	1.2	80	0.5	5.6	2.8	T+D	20	
AHU-E6									**80.0**
E1-F1	31.5	2.7	125	0.8	2.6	2.1	T	10	
F1-F2	27.5	2.3	125	0.6	1.6	1.0	T+D	20	
AHU-F2									**68.0**
F1-F3	4	1.8	63	0.7	2.8	2.0	T	10	
F3-F4	4	1.8	63	0.7	0.6	0.4	E+D	10	
AHU-F4									**69.4**

Appendix P. Duct sizing Building 2.

Section	Volume flow rate	Velocity	Dim	Pressure drop	Length	Duct loss	Fitting type	Fitting loss	Total friction loss
	/ (l/s)	/ (m/s)	/ mm	/ (Pa/m)	/ m	/ Pa		/ Pa	/ Pa
Exhaust air									
A1-A2	35	3.0	125	1.0	2.0	2.0			
B1-B2	20	2.5	100	1.0	1.3	1.3	T	10	
B2-B3	20	2.5	100	1.0	1.0	1.0	E	5	
B3-B4	10	2.0	80	0.8	0.8	0.6	T+D	15	
AHU-B4									**32.9**
B3-B5	10	2.0	80	0.8	2.8	2.2	T+D	20	
AHU-B5									**39.5**
B1-C1	15	2.0	80	0.7	0.9	0.6	T	10	
C1-C2	5	1.8	63	0.7	1.2	0.8	T+D	20	
AHU-C2									**31.5**
C1-C3	10	2.0	80	0.8	1.6	1.3	T+D	20	
AHU-C3									**31.9**
Supply air									
D1-D2	35	3.0	125	1.0	2.0	2.0			
E1-E2	35	3.0	125	1.0	0.5	0.5			
E2-E3	35	3.0	125	1.0	1.0	1.0	E	5	
E3-E4	35	3.0	125	1.0	4.2	4.2	E	5	
E4-F1	4	1.8	63	0.7	2.2	1.5	T	10	
F1-F2	4	1.8	63	0.7	0.5	0.4	E+D	20	
AHU-F2									**47.6**
E4-G1	31	2.5	125	0.7	0.6	0.4	T	10	
G1-G2	4	1.8	63	0.7	0.6	0.4	T+D	20	
AHU-G2									**46.54**
G1-G3	27	2.3	125	0.6	1.9	1.1	T	10	
G3-G4	19	2.5	100	0.9	0.6	0.5	T+D	20	
	AHU-G4							**57.8**	
G3-G5	8	1.8	80	0.6	0.6	0.4	T+D	20	
AHU-G5									**57.6**

Transmission losses using Equation 5, *UA*-value from Table 3.B.

$$Q_{transmission} = 394.2 \frac{W}{K} \times (17\,°C - 6.4\,°C) \times 8760\ h = 36\,608\ kWh$$

Ventilation air flows calculated:

$$q_{airflow,\ ventilation} = 0.4\ ACH \times 270\ m^2 \times 2.5\ m = \frac{0.075\ m^3}{s}$$

$$q_{airflow,\ infiltration} = \frac{2\ ACH}{20} \times 270\ m^2 \times 2.5m = \frac{0.019\ m^3}{s}$$

Ventilation and infiltration losses calculated using equation Y:

$$Q_{ventilation+infiltration} = \frac{1.2\ kg}{m^3} \times \frac{1000\ J}{\frac{kg}{K}} \times 0.094 \frac{m^3}{s} \times (17\,°C - 6.4\,°C) \times 8760\ h = 10\,446\ kWh$$

Internal gains calculated:

$$Internal\ gains_{equipment+DHW} = 8\,000\ kWh \times 70\ \% = 5\,600\ kWh$$

$$Internal\ gains_{people} = 3.51\ person \times \frac{80\ W}{person} \times \frac{14\ h}{day} \times 365\ day = 1\,431\ kWh$$

Total annual energy demand = 40 023 kWh

Appendix R. Building 2, Base Case hand calculations.

Transmission losses using equation 5, *UA*-values from Table 3.B:

$$Q_{transmission} = 255.8\frac{W}{K} \times (17\,°C - 6.4\,°C) \times 8760\ h = 23\,756\ kWh$$

Ventilation air flows calculated:

$$q_{airflow,\ ventilation} = 0.4\ ACH \times 100\ m^2 \times 2.5\ m = \frac{0.028\ m^3}{s}$$

$$q_{airflow,\ infiltration} = \frac{2\ ACH}{20} \times 100\ m^2 \times 2.5m = \frac{0.007m^3}{s}$$

Ventilation and infiltration losses calculated using equation Y:

$$Q_{ventilation+infiltration} = \frac{1.2\ kg}{m^3} \times \frac{1000\ J}{\frac{kg}{K}} \times 0.035\frac{m^3}{s} \times (17\,°C - 6.4\,°C) \times 8760\ h = 3\,869\ kWh$$

Internal gains calculated:

$$Internal\ gains_{equipment+DHW} = 5\,000\ kWh \times 70\,\% = 3\,500\ kWh$$

$$Internal\ gains_{people} = 2.79\ person\ \times \frac{80\ W}{person} \times \frac{14\ h}{day} \times 365\ day = 1\,141\ kWh$$

Total annual energy demand = 22 985 kWh

Appendix S. Power demand hand calculations for Building 1, Base Case model.

DVUT-temperatures from Table 3.J were used in all power demand calculations. All Base Case and BBRs calculations used a 2-day time constant, while the PHs used a 5-day time constant.

$$P_{transmission} = 394.2\frac{W}{K} \times (17\,°C - (-12.9\,°C)) = 11.8\,KW$$

$$P_{ventilation+infiltration} = \frac{1.2\,kg}{m^3} \times \frac{1000\,J}{\frac{kg}{K}} \times 0.094\frac{m^3}{s} \times (17\,°C - (-12.9\,°C)) = 3.4\,kW$$

Total power demand = 15.2 kW

Appendix T. Power demand hand calculations for Building 2, Base Case model.

$$P_{transmission} = 255.8\frac{W}{K} \times (17\,°C - (-12.9\,°C)) = 7.6\,kW$$

$$P_{ventilation+infiltration} = \frac{1.2\,kg}{m^3} \times \frac{1000\,J}{\frac{kg}{K}} \times 0.035\frac{m^3}{s} \times (17\,°C - (-12.9\,°C)) = 1.2\,kW$$

Total power demand = 8.8 kW

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