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Increasing the Benefits of Renovation:

Exploring the potential of increased floor area for financial and environmental benefits in existing multi-family residential buildings

Master's thesis in Design and Construction Project Management

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Abstract

Property owners are under significant pressure to carry out energy-efficient renovations due to the urgent requirement to meet EU climate goals. Nevertheless, substantial initial investment outlays and a perceived absence of immediate advantages frequently result in the delay of such renovations.

This study investigates the potential financial and environmental advantages of expanding the floor(s) when renovating multi-family residential buildings in Sweden.

The study employs a comprehensive approach that combines Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) methodologies to assess different renovation strategies across multiple lifespans (10, 15, 20, 35, and 50 years). The research centres around two specific case studies: Blåsutgatan 8 and Byalagsgatan 8, both located in Gothenburg.

The main goals are to evaluate the current state of the building, develop renovation scenarios, simulate and optimise energy efficiency, and conduct thorough economic and environmental assessments. The renovation measures under consideration encompass enhancements to walls and roofs, replacement of windows, improved ventilation systems, and installation of photovoltaic panels. The viability of incorporating additional level(s) into an existing building is also examined as a tactic to augment property value and diminish environmental impact.

The findings suggest that incorporating extra floors into renovation projects can effectively decrease energy demand, increase property worth, and minimise carbon emissions, thus aligning with the sustainability objectives of the European Union. The best renovation scenario entails implementing both energy-saving measures and vertical expansion, which can yield significant financial gains and environmental advantages.

The thesis emphasises the significance of integrating financial and environmental factors into the decision-making processes for renovations. Additionally, it highlights the necessity of implementing supportive policy measures and providing financial incentives to encourage prompt and sustainable renovations. The research offers valuable insights for property owners, housing companies, and policymakers, thereby contributing to the overarching objectives of enhancing energy efficiency and sustainability in the Swedish residential sector.

Key words: Energy-efficient Renovation Strategies, Life Cycle Cost (LCC), Life Cycle Assessment (LCA), Vertical Expansion, Multi-family Buildings

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ABBREVATIONS & TERMINOLOGY

Abbreviation	Full Term	Description
CO_2	Carbon dioxide	
DH	District heating	
LCA	Life cycle assessment	A method for calculating the accumulated environmental impact over a building's lifetime.
LCC	Life cycle cost	A method for calculating the total costs over a building's lifetime.
NPV	Net present value	
PV	Photovoltaic	
EPS	Expanded Polystyrene	
PVC	Polyvinyl chloride	
GWP	Global Warming Potential	A measurement of environmental impact by translating emissions to carbon dioxide equivalents.
EPD	Environmental Product Declarations	Describes the environmental impact from a product over its lifetime.
Airtightness		The air exchange rate of a building at 50 Pa pressure difference from the inside to the outside.
BOA	Gross housing area	Usable apartment area including room dividing walls thinner than 30 cm.
CCI	Construction cost index	Representation of the entire private domestic consumption, in Sweden the CCI is the standard measure for inflation.
CPI	Consumer price index	Representation of the price trend for production in the housing sector such as costs for material, equipment, and salaries.
GFA	Gross floor area	The full building floor area including external walls.
NFA	Net floor area	The building's heated usable floor area without including external walls and internal walls thicker than 15 cm.
NOI	Net operational income	Difference between the operational costs and the operational incomes.
Primary energy demand		The energy demand of a building as taken from different energy sources such as oil, coal, or hydropower.
Thermal bridges		Parts of the building envelope that cause higher heat loss compared to the rest of the building surfaces.
U-value	Thermal transmittance of a construction part [W/m²K]	
VAT	Value added tax	Governmental tax added to the price of a product.
λ-value	Thermal conductivity of a material [W/m. K]	
BSAB	Byggsektorns Samordnade Anläggnings- och ByggnadsKlassifikation	
SEK, Kr	Swedish Currency	

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1. Introduction

Sweden possesses a total of approximate 4.7 million residential properties, and the Swedish National Board of Housing, Building, and Planning (Boverket) predicts that 75% of these homes will require renovation by the year 2050. In 2017, an estimated 800,000 buildings in Sweden required renovation, with 300,000 of them situated in million programme areas and needing urgent renovation. Renovating these buildings offers a chance to decrease their energy usage and, as a result, their impact on the environment (Olin, 2023). The residential sector in Sweden accounts for 21% of the overall final energy consumption. The figure falls slightly below the EU-27 average of 26%, highlighting the persistent challenges and the urgent requirement for strategies to comply with the European Union's energy efficiency and consumption regulations. Recent research and evaluations highlight the significance of improving energy efficiency in residential buildings as a crucial element in fulfilling EU directives and attaining sustainability objectives. Significant progress has been made in energy-saving technologies, the adoption of real-time feedback systems, and the incorporation of renewable energy sources. These factors have been recognized as crucial in decreasing energy usage and addressing environmental consequences. These endeavours align with the European Union's overarching goals of reducing energy consumption, expanding the proportion of renewable energy, and enhancing overall energy efficiency throughout its member states (SUHÁNYIOVÁ et al., 2023, Dolge and Blumberga, 2023). Boverket concluded that existing building renovation must accelerate to mitigate climate change. Several studies have shown that upgrading building envelopes and technical installations can significantly reduce energy demand in existing buildings (Berggren and Wall, 2019, Christis Z et al., 2023, Axon and Darton, 2023, Hartmann et al., 2023). However, the actual implementation of energy-efficient improvements is typically hindered by various barriers such as lack of information about the possibilities and benefits of the efficient use of energy (Dolšak et al., 2018). Moreover, one of the main barriers to renovation is the cost of renovation, which can be a significant challenge for companies (Berggren and Wall, 2019).

In addition, the European Union has committed to reducing its overall greenhouse gas (GHG) emissions by a minimum of 40% from 1990 levels by 2030. This aligns with its ambitious goals of becoming the first climate-neutral continent by the mid-21st century, as stated in the European Green Deal (Savickis et al., 2020). Out of all the sectors assessed, the building sector remains a substantial prospect for reducing carbon dioxide (CO_2) emissions through both technical and nature-based solutions. This sector is accountable for almost 40% of the total global CO_2 emissions, both directly and indirectly (Xiao et al., 2023). Although the building sector has the potential to reduce energy consumption and associated CO_2 emissions, it faces challenges due to the slow replacement of buildings in developed countries. Hence, the primary prospects for enhancing energy efficiency and mitigating greenhouse gas emissions are centred around retrofitting current buildings, as emphasized by the European Commission's plan to increase the annual rate of energy renovations by two-fold (Chersoni et al.). This shift highlights the significance of implementing retrofitting and energy efficiency measures in already existing buildings, rather than solely concentrating on the efficiency of new constructions. This reflects a more comprehensive approach towards attaining the European Union's energy efficiency and climate goals (Peeters and Athanasiadou, 2020).

It's critical to consider the energy utilized and the carbon emissions of the materials being used while renovating existing buildings. Renovations to buildings improve energy efficiency and reduce carbon emissions, but they often come with higher investment costs and environmental consequences since they use new materials (Almeida and Ferreira, 2018).

In the case of rental apartments, incentive mechanisms may be affected by the contract between landlord and tenant, which in turn may influence decisions about renovations. The most prominent problem is perhaps the so-called landlord-tenant dilemma, which occurs, for instance, when the renter pays the energy costs, and the landlord is thus not incentivized to use energy-saving measures (Mangold et al., 2023).

Therefore, there is a need to explore potential strategies to increase the benefits of renovation and incentivize timely renovation efforts. One such strategy is to add floors to existing buildings during renovation, which could offer several advantages. These include the potential for higher income for property owners, immediate revenue for housing companies from the sale of building rights or additional floor areas, an increase in gross floor area and a lower carbon footprint compared to new constructions. Recent policy incentives, such as Italy's "Superbonus" scheme, which offers up to 110% of investment costs for energy upgrades, demonstrate the effectiveness of financial incentives in promoting timely renovations (Ruggieri et al., 2023). Additionally, life cycle frameworks that identify optimal renovation strategies considering economic and environmental impacts can guide decision-making to maximise the benefits of building renovations (Caruso et al., 2020).

1.1. Research questions and objectives.

The aim of this thesis is to investigate the most viable measures renovation approaches for Swedish multi-family houses from LCA & LCC perspective.

<u>To be more specific</u>:

Analysing financial cost, carbon emission and energy consumption of Swedish multi-family houses after applying selected renovation strategies and adding floors scenario during a renovation.

<u>**Specific objectives:**</u>

1. To measure the current energy efficiency and environmental consequences of the buildings to establish a reference point for evaluating potential renovation scenarios.
2. To formulate and assess renovation scenarios that have the potential to greatly enhance the energy efficiency and sustainability of the building.
3. Investigate the potential energy savings for different renovation scenarios, with the goal of identifying scenarios that can achieve a minimum of 50% reduction in energy demand.
4. Evaluation of the economic feasibility of each renovation option, finding the scenarios that have a payback period of less than 10 years and a positive Net Present Value (NPV) with an Internal Rate of Return (IRR) higher than the interest rate.
5. To assess the environmental consequences of each renovation scenario in order to achieve a minimum 30% reduction in greenhouse gas emissions throughout the entire lifespan of the building.
6. Assessing the viability and consequences of implementing vertical expansion as a renovation approach, specifically examining its impact on energy efficiency, expenses, and environmental footprint in comparison to alternative renovation scenarios.
7. To integrate the results from BES (Building Energy Simulation), LCC (Life Cycle Costing), and LCA (Life Cycle Assessment) in order to propose an ideal renovation approach that achieves a harmonious balance between energy efficiency, cost-effectiveness, and environmental sustainability. The proposed strategy should deliver measurable enhancements in all three aspects.

1.2. Justification

- Adding extra floors to existing buildings could be an effective method, allowing companies to profit from renovations.
- This motivates more renovations, resulting in greater energy savings and environmental benefits.
- Adding a floor to an existing building emits less carbon dioxide and costs far less than demolishing and building a new.

1.3 Scope and goal

The renovation scenarios entail the addition of extra insulation on the outer walls and roof and the substitution of outdated windows with more efficient ones. All three measures aim to lower the average U-value of the building envelopes and diminish energy demand. In addition, a ventilation system incorporating heat recovery was implemented with the objective of enhancing the quality of indoor air. In addition, the installation of solar panels on rooftops, are also encompassed within the scope of the project, thereby incorporating new energy sources and renewable energy. Each of the measures were individually designed and simulated, and subsequently integrated into various scenarios. An additional analysis is conducted to determine the economic viability of the project by examining the life cycle costs. Ultimately, a Life Cycle Assessment (LCA) evaluation will be conducted for all possible scenarios.

2. Background

2.1. The European building stocks.

The EU member states agreed on a climate and energy framework known as the Europe 2020 Strategy, which included three quantifiable targets, often referred to as the "3x20" package. These targets were set to be achieved by the year 2020 and included:

- Reduction of CO_2 emissions by at least 20% compared to the level of 1990. If possible, the aim was to reduce emissions by as much as 30%.
- Increasing the share of renewable energy sources (RES) in total energy consumption to 20%.
- Increasing energy efficiency, which was closely tied to the reduction of CO_2 emissions and the increase in the use of renewable energy sources (Landwehr, 2013).

These targets were set with the aim of transforming the EU into a low-carbon and resource-efficient economy. The progress of the member states in achieving these targets was monitored and evaluated using a set of indicators. The targets were also part of the EU's commitment under the Paris Agreement, which was adopted in 2015 to accelerate efforts to limit global warming.

The implementation of these targets varied among the member states, with some countries achieving better results than others. For instance, Greece, Romania, and Estonia were among the countries that achieved the optima results, while France, Ireland, Austria, and Belgium did not meet the targets.

The Europe 2020 Strategy has now expired, and the focus has shifted to the 2030 Agenda, which continues and develops the long-term targets in the field of climate and energy challenges through the sustainable development goals (SDGs) (Gontkovičová and Spišáková, 2023).

The EU has pledged to cut its total emissions of greenhouse gases (GHGs) from 1990 levels by at least 20% by 2020. Among all the sectors evaluated, the building sector now has the highest potential for low-cost carbon dioxide (CO_2) abatement in the short- to medium term through the implementation of technical solutions, according to calculations and evidence presented by the IPCC (2007). The EU's building stock's energy consumption and related CO_2 emissions are rising despite their enormous potential (Mata et al., 2013).

EU buildings are crucial in the energy debate, accounting for 40% of energy use and 36% of greenhouse gas emissions. This data includes the entire lifecycle of a building, from construction and occupancy to repairs and eventual demolition. Around 75% of these EU structures lack energy efficiency. The European Commission has set an ambitious goal for the EU to become carbon-neutral by 2050 and transition to a sustainable, environmentally friendly economy. To achieve this goal, emissions from buildings must be reduced by 60% and their energy consumption for heating and cooling by 18% (SG, 2021).

Energy efficiency wasn't a priority during the construction boom in post-World War II. In the 1970s and 1980s, rising energy costs and environmental concerns led to new energy policies. While new buildings now have better energy standards, the rate of new construction is only around 1%/year of the total building stock, and many post-war buildings still lack energy efficiency (Meijer et al., 2009). Figure 1 shows a decreasing U-value in external walls, while older residential buildings (over 40 years) have higher U-values than newer homes. This aligns with the European Energy Efficiency Directive's assertion that energy savings potential lies in renovating existing buildings. However, the current renovation rate, around 1% per year, must be increased to meet these goals (Commission, 2010).

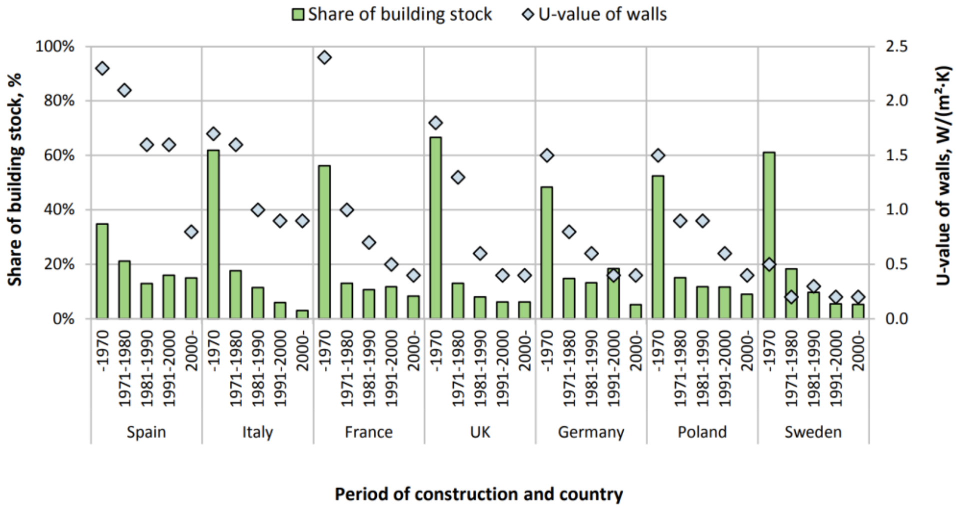

Figure 1- Building stock share and wall U-value of European residential building by age and nation (Gustafsson et al., 2017).

Both building envelopes and their energy systems are considered as reasons for energy waste in existing buildings. It is also worth mentioning that most EU states still rely on natural gas for heating, alongside coal and petroleum-based fuels (Rehfeldt et al., 2018) which can lead to large amount of CO_2 emission (Schneising et al., 2020). Approximately 50% of the overall energy consumption in residential comes from direct fossil fuel use. Adding the fact that 70% of electricity and district heating sources are non-renewable, makes the share of fossil fuels over 75% (Persson and Münster, 2016). Furthermore, out-of-date buildings' poor envelopes, energy systems, and high energy costs relative to income lead to insufficiently heated and ventilated, endangering residents' health and well-being. This underscores the importance of improving their energy efficiency (Adl-Zarrabi et al., 2020). European residential buildings use an average of 234 kWh/(m²·y) for heating, cooling, ventilation, domestic hot water (DHW), electrical appliances, and lighting. 65% of this energy is used for heating. It is worth to consider that 80–90% of Europeans' time is spent indoors (Gustafsson et al., 2017). Figure 2 illustrates share of different energy sources for total energy consumption of eight European countries.

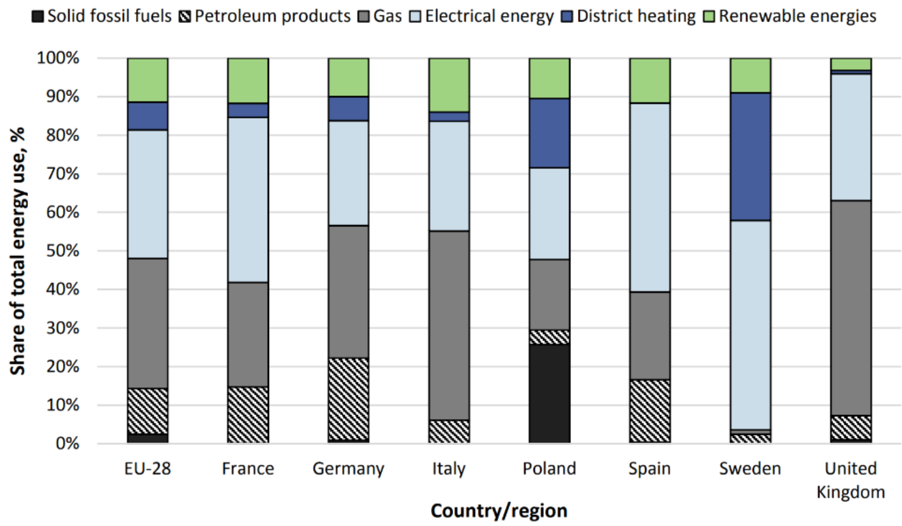

Figure 2- Share of total energy use in 8 European countries.

The inefficiency that the buildings hold highlights the necessity for targeted strategies in the construction sector, they also hold the most significant potential for energy conservation. While the focus has often been on minimising LC (Life Cycle) emissions in new buildings, the existing buildings represent a great potential for emission reductions across Europe (Ramírez-Villegas et al., 2019). Renovating these structures can lead to a 5-6% reduction in the EU's energy consumption and a similar decrease in carbon dioxide emissions. Yet, only about 1% of the total building stock is renovated each year, with rates varying between 0.4% to 1.2% across member states. To meet stringent climate and energy objectives, these renovation rates must see a significant grow (SG, 2020).

In industrialised countries, the building sector contributes for 36% of energy-related CO_2 emissions.

These emissions are mostly associated with building use, whereas emissions from the manufacture of building materials such as concrete and steel are assigned to the industry sector. Building material production accounts for 8-12% of total CO_2 emissions in Western Europe. (Nässén et al., 2007).

Classification of residential building (TABULA):

TABULA, a project implemented in 13 European countries, including Germany (as the coordinator), Greece, Slovenia, Italy, France, Ireland, Belgium, Poland, Austria, Bulgaria, Sweden, Czech Republic, and Denmark, aimed to develop and implement a Typology Approach for Building Stock Energy Assessment. The primary objective of TABULA was to establish a standardized framework for residential building typologies, specifically designed for energy analysis in the residential sector. Each typology is clearly delineated by building types that have distinct parameters, such as the construction period, which is indicative of the building's age and the construction principles and materials used.

• The size of buildings can vary depending on their type, which includes single-family houses, multi-family houses, terraced houses, and apartment blocks.

Additional factors of a building also impact energy consumption and must be taken into account in the classification:

• Description of the type and age of the supply system.

• Geographical position within a specific region.

The four "Building Size categories" as defined in TABULA were also taken into account, with a specific focus on building geometry, number of apartments and floors etc., as follows:

- A single-family house is a standalone or semi-attached residence consisting of one or two floors.
- A terraced house is a single residential building with one or two floors attached to other dwellings.
- Multi-family house, small dimension building with a limited number of apartments (up to 15 apartments and 2–5 floors, or 16–20 apartments and 2–4 floors).
- Apartment block, big dimension building with a higher number of apartments.

In section 2.2 this classification will be applied for Swedish building stock.

2.2. The Swedish building stocks.

Sweden is a country known for its sustainability initiatives. Nevertheless, the persistence of high energy consumption, evidenced by the residential and commercial sectors in Sweden accounting for nearly 39% of the country's total energy in 2016, highlights the pressing need and difficulties in complying with these EU regulations (Swedish Energy Agency, 2018).

Sweden has 5.2 million homes (centralbyrån(SCB), 2023), and the Swedish National Board of Housing, Building, and Planning (Boverket) estimates that **75%** of them must be renovated before 2050. It worth mentioning 21% of the total final energy use is accounted for by the residential sector in Sweden, which is somewhat less than the average of 26% for the EU-27, but still highlights the pressing need and difficulties in complying with European Union (EU) regulations (Mata et al., 2013). Boverket concluded that existing building renovation must accelerate to mitigate climate change. Several studies have shown that upgrading building envelopes and technical installations can significantly reduce energy demand in existing buildings (Berggren and Wall, 2019). However, the actual implementation of energy-efficient improvements is typically hindered by various barriers such as high initial costs for investment and a lack of information about the possibilities and benefits of the efficient use of energy (Dolšak et al., 2018). Moreover, one of the main barriers to renovation is the cost of renovation, which can be a significant challenge for companies (Berggren and Wall, 2019). Also, the reduction in tax deduction from 50% to 30% in 2016 for labor costs related to house renovations, although intended to curb undeclared work, raises concerns. This decision may act as a barrier for homeowners and property managers who want to undertake renovations that improve their homes' energy efficiency (SG, 2021).

Sweden, like other European nations, underwent intensive construction in the mid-20th century. Many of From Sweden's 5.2 million buildings are from "The Million Program" –(aimed to build one million homes in ten years) constructed from 1965 to 1974 (Boverket, 2014). Compared to other European countries, Swedish buildings from this period had lower external wall U-values (Figure 1). However, low Swedish temperatures require higher standards for energy-efficient constructions, thus development is possible.

In the long term, the main global environmental concerns for sustainable development are the reduction of energy consumption and CO_2 emissions in the building sector (Coma et al., 2019). According to (Mata et al., 2013) the main sources of CO_2 emissions in Swedish residential buildings are related to space heating and domestic hot water. These two applications have higher energy requirements in the residential building sector and are responsible for the majority of CO_2 emissions. However, since the use of fossil fuels in Swedish residential heating is relatively low, the production phase may often account for a greater percentage of the life cycle CO_2 emissions than the life cycle energy use (Nässén et al., 2007). Furthermore, Sweden has advantageous circumstances for generating electricity with low CO_2 emissions, primarily through water and nuclear power (Coma et al., 2019, La Fleur et al., 2017)

Furthermore, it's critical to notice the energy utilized and the carbon emissions of the materials being used while renovating existing buildings. In other words, whether the embedded energy and carbon emissions from renovation materials have a significant impact on the total amount of primary energy used and embodied carbon is a major concern. Renovations to buildings improve energy efficiency and reduce carbon emissions, but they often come with higher investment costs and environmental consequences since they use new materials. In nearly zero buildings, this question becomes even more important. Embodied energy has a trivial effect on cost-optimal solutions, as many life-cycle cost evaluations of renovation scenarios indicate, but the equation changes when energy performance approaches nearly-zero energy or carbon emissions. In such scenarios, the contribution of embodied energy or carbon emissions can become significant. Therefore, a life-cycle perspective that takes embedded impacts into account is crucial for obtaining optimal primary energy and carbon emissions in existing buildings. As nearly-zero energy and carbon emissions renovations become more feasible, Life Cycle Impact Assessment (LCIA) is advised for upcoming renovation projects (Almeida and Ferreira, 2018).

Classification of the residential building stock in Sweden:

In the context of implementing the TABULA system in a Swedish stock, it is imperative to establish parameters for classification. These parameters encompass the age, size, and geographical location (climate zones) of buildings (Mälardalen, 2013).

According to the national TABULA residential building typology, Sweden primarily has two types of residential building stock: single-family houses (SFH) and multi-family houses (MFH). Single-family homes (SFH) make up 46% of the total housing stock, with approximately 2 million units. Meanwhile, multi-family homes (MFH) account for around 2.3 million units. The average heated area per dwelling in Single-Family Homes (SFH) and Multi-Family Homes (MFH) is 146 and 76 square meters, respectively. This results in a total heated area of 292 and 175 million square meters, respectively. Based on data from (Boverket) up to 2005, a detailed study of the building typology in Sweden divides the building stock into five age categories and three climatic zones (Boverket, 2010). Around 70% of the existing buildings were constructed prior to 1975, with more than 80% located in a single climatic region in southern Sweden. representing a climate similar to that of Stockholm. The average number of people per household is 2.12 (Savvidou and Nykvist, 2020, Mälardalen, 2013).

Between 2000 and 2015, the average SFH construction rate was 0.4%, while the MFH rate was 0.7% (Nilsson et al., 2020). Demolition data was exclusively found for MFH, indicating a demolition activity rate of only 0.1%. The Boverket has set forth energy requirements for passive houses that are specifically tailored to the conditions in Sweden. The requirements vary between northern and southern Sweden. Renovating, especially in the context of multi-family housing (MFH), offers significant prospects for energy conservation (Brown et al., 2013). Buildings constructed between 1965 and 1975 as part of the Million Programme, an initiative designed to address the housing shortage, are particularly in need of refurbishment (Åberg and Henning, 2011). By 2050, it is projected that the rate of building renovation will be three times higher than that of new construction, leading to the renovation of approximately 1.5-2 million apartments (Mangold et al., 2015, Mälardalen, 2013, Savvidou and Nykvist, 2020).

After the studies carried out in the work, it can be concluded that the existing concrete frame offers good opportunities for storey addition, as the capacity of the concrete walls is only used to about 20 percent, with the condition that wall elements with door holes are not significantly loaded (Friberg and Karlin, 2015).

2.3. Renovation of buildings

2.3.1. Renovation in Europe

The need for more dwellings is more important in countries with higher population growth. Sweden ranks third in terms of population growth rate among European Union countries, according to Eurostat (Savvidou and Nykvist, 2020). Due to the fact that turnover of the building stock is low in developed countries, the main opportunities for optimising energy consumption and GHG emission reduction arise from retrofitting the existing buildings (Dineen and Gallachóir, 2011). Consequently, the emphasis has shifted from maximising the efficiency of newly constructed buildings to efficiency techniques that are relevant to the refurbishing process (Erik Bradley and Kohler, 2007).

Despite the growing emphasis on sustainability in the building sector, significant energy consumption persists, posing challenges to meeting the environmental goals. The EU has set forth the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive as foundational guidelines to propel the sector towards greater energy efficiency. Specifically, the EED calls for a more rapid pace in renovation activities to enhance building energy performance (European Parliament, 2012). Unfortunately, the challenges facing renovations are complex and cost remains the primary barrier to renovation. Emphasizing cost effective rehabilitation and the integration of energy efficient strategies during building upgrades is central to these directives (European Parliament, 2018). Owners, designers, and contractors agree that change-related renovation is expensive and time-consuming (Slaughter, 2001). In larger housing portfolios, property managers manage the arrangement of maintenance and renovations. However, during financial pressures, necessary maintenance often gets reduced or postponed. Factors like internal demands and current market conditions majorly influence these decisions. In addition, many property managers don't have knowledge about long-term expenses that arise from delays. As a result, deferred maintenance often leads to higher lifecycle expenses for building components, a fact overlooked in most simulations (Farahani et al., 2019).

2.3.2. Renovation in Sweden

The renovation of buildings in Sweden is a topic of significant importance due to the country's commitment to energy efficiency and sustainability. As mentioned, buildings worldwide are responsible for one-third of the total final energy consumption and are among the main emitters of carbon dioxide. In Sweden, as in other countries, there is an increasing emphasis on discovering energy-efficient solutions and exploiting renewable energy sources for the renovation of buildings (Anu and Kimmo, 2015). Sweden is currently facing a period where thousands of buildings built during the "Million Program" period will need facade and interior renovation. These buildings often have a large energy-saving potential as they are typically poorly insulated and often have a poor ventilation system without heat recovery. Nevertheless, performing energy-efficient renovation measures can be expensive, which can deter property owners or companies from undertaking the renovation. This can lead to the deterioration of the facades, insulation, and ventilation systems, resulting in energy wasting and more CO_2 emission (Adolfsson and Andersson, 2016).

The renovation planning process is often filled with uncertainties and subjective decisions, making the decision on what and when to renovate complex. Renovation measures related to the building envelope are often far from optimal as decisions are usually made based on visual inspections, which are prone to subjective assessment (Mandinec and Johansson, 2022).

To address these challenges, there are ongoing efforts to develop more objective and automated assessment methods for building inspections. For instance, Unmanned Aerial Vehicles (UAVs) and image recognition algorithms are being explored for their potential to identify imperfections and store the position and extent of such deviations into the building's digital assessment database(Mandinec and Johansson, 2022).

Moreover, there are studies exploring the potential of multi-active facade systems as a more energy and cost-efficient solution compared to traditional renovation measures. These systems are being integrated into typical "Million Program" houses for deeper investigation of their energy performance and Life Cycle Cost (Adolfsson and Andersson, 2016).

Without national regulations or incentive schemes, local governments are also investigating methods to encourage private owners of post-war mass-housing to invest in ambitious retrofitting projects aimed at improving energy efficiency. The Bygga om Dialogen project in Malmö, Sweden, is reevaluating the way investments in energy efficiency are approached by considering a wider socio-economic perspective. The project aims to identify new incentives that will encourage property owners to undertake the necessary investments (Landwehr, 2013).

Sweden aims to decrease the overall energy consumption per heated area in residential and commercial buildings by 50% by 2050, as stated in the program of the Swedish Environmental Objectives Council (Miljomålsrådet). This target is in comparison to the energy consumption levels recorded in 1995 (Regeringskansliet, 2010).

It is vital to consider this note that any renovation measures decrease heat demand while increasing electricity consumption. For example, when installing a more complex ventilation system. The effects of renovations on the energy system must therefore be considered. (La Fleur et al., 2017).

In the case of rental apartments, incentive mechanisms may be affected by the contract between landlord and tenant, which in turn may influence decisions about renovations. The most prominent problem is perhaps the so-called landlord-tenant dilemma, which occurs, for instance, when the renter pays the energy costs, and the landlord is thus not incentivized to use energy-saving measures (Mangold et al., 2023).

Therefore, there is a need to explore potential strategies to increase the benefits of renovation and incentivise companies to renovate their buildings at the right time and not postpone it. One such strategy is to add a floor to an existing building during renovation. Adding floors offers advantages and opportunities, including higher owner income, revenue in the short term for housing companies from the sale of building rights or areas of additional floors, a comparatively lower carbon footprint, and more gross floor area (Karjalainen et al., 2022, Bojić et al., 2012).

2.4. LCC in Buildings

Life Cycle Cost (LCC) is a method used in building construction to estimate the total cost of a building over its entire lifespan. This encompasses the initial investment costs, maintenance expenses, operating costs, and the remaining value of the asset at the end of its life (Alasmari et al., 2022). LCC is widely used in the construction sector to indicate the overall expenses associated with the ownership of a building over its entire lifespan. (Shamsuddin et al., 2017).

2.4.1. LCC in building's renovation

Within the realm of building renovation LCC analysis is employed to determine the most favourable scenario by taking into account energy consumption and LCA. This approach offers a highly effective strategy for managing a constrained budget for renovations. A variety of scenarios can be compared in a building renovation strategy with the aim of enhancing energy efficiency (Sharif and Hammad, 2019).

2.4.2. Renovation's Financial Impact: A Dual Perspective – Companies and Tenants

When exploring the potential of increased floor area for financial and environmental benefits in existing buildings, it is important to consider the perspectives of different stakeholders including investors (mostly companies or homeowners) and end-users (mostly tenants). Based on the Swedish rent-setting system value-enhancing renovations are a valid justification for rent increases, while maintenance-based renovations are not, as upkeep ought to be covered by current rents. The theory is that, in exchange for improved quality, municipalities could have to provide housing for households that might not be able to pay higher rent (and the municipality might have to pay if the household is on welfare). In this situation, local housing corporations need to have less incentive to carry out upgrades that raise rents—particularly in impoverished or low-income neighbourhoods (Mangold et al., 2023). Prior research on renovations in million programme areas in Sweden has revealed a deficiency in effective communication between tenants and the housing company. Within the million programme areas, there is typically a lower income rate and a significant rise in apartment standard, which increases the risk of people having to relocate due to high rents (Stenberg, 2020).

2.4.3. The Financial Benefits of Adding Floors During Building's Renovation

Renovating and increasing the floor area of existing buildings is a multifaceted strategy that can yield financial benefits. Below are some aspects of financial gains associated with building renovation.

Property Value Enhancement

One of the primary financial benefits of building renovation is the potential increase in property value. adding floors to a building through renovations can significantly increase its market value.

This is especially noticeable in densely populated urban areas where there is limited space available. The example of Florence, Italy, illustrates how density bonuses, which permit an increase in floor area, can greatly enhance the economic viability of renovation projects (Battisti and Campo, 2021). The model developed in this study suggests that the financial viability of renovations is context-dependent, with urban, landscape, and environmental impacts being critical factors.

Increase Rental Income

Additional rental space created through renovation can result in higher rental income. This is especially relevant for landlords who can capitalize on the increased leasable area. However, the landlord-tenant dilemma, as discussed in a recent study, highlights the conflict of interest where landlords bear the renovation costs while tenants benefit from reduced energy costs (Kühn et al., 2024).

Sale Price Elevation

Renovation can also influence sale prices. Additional floors increase the usable space of a building, which can directly translate into higher sale prices, especially in urban areas where space is at a premium. Renovations that include adding floors often incorporate modern design and technology, which can make the property more attractive to potential buyers and thereby increase its market value. In densely populated areas, the ability to expand upwards rather than outwards is often restricted by zoning laws, making vertically expanded properties particularly valuable (Yao and Hu, 2023).

Maintenance Cost Reduction

The installation of new and more efficient building systems during renovation can lead to a reduction in maintenance costs. A study on the energy renovation of a multi-residential pre-war building showed that while the financial viability of the renovation was not favourable, the improved thermal comfort and aesthetics were highly valued by tenants (Jerome et al., 2021). This suggests that although there may not be immediate cost savings from maintenance, there can be substantial long-term advantages and tenant contentment.

Energy Efficiency Improvements

Enhancing energy efficiency is a crucial factor in renovations, resulting in reduced energy expenses for heating, cooling, and lighting. The EEnvest calculation method, as outlined in a recent paper, assesses the financial consequences of technical risks associated with energy-efficient refurbishment of buildings (Andaloro et al., 2021). The objective of this approach is to enhance investor trust and stimulate investments in energy-efficient renovations by emphasizing the financial advantages of decreased energy consumption.

Marketability Improvement

Expanding the floor area through renovations can enhance the market appeal of a property, increasing its desirability for potential tenants or buyers. Research conducted on the financial advantages of constructing environmentally sustainable buildings in New York City revealed that implementing high-performance building design can result in cost savings and a reduced payback period. This, in turn, increases the attractiveness of the property to stakeholders who prioritize environmental concerns (Pereira Sanches, 2004).

2.5. LCA in building

The construction industry is a major contributor to global energy-related CO_2 emissions, accounting for 40% of total emissions worldwide (Huang et al., 2018). Given this sector's significant environmental impact, reducing its emissions is a priority for the Swedish construction industry to meet Sweden's climate goals for 2045. To achieve this goal, various methods can be used to analyse the environmental impact of infrastructure and buildings, and Life Cycle Analysis (LCA) is a commonly utilized method to investigate the total environmental impact of a building (Trafikverket, 2021). By utilizing data from LCA analyses, the largest contributors to environmental damage can be identified. LCA can comprehensively demonstrate the environmental and economic effects of a building throughout its lifespan. It is most effective when employed at the beginning of the design process to explore various design alternatives (Hollberg et al., 2016). LCA in building construction involves a thorough assessment of the environmental effects of a building from the extraction of raw materials to its eventual disposal. This encompasses the various phases of material production, construction, utilisation, and end-of-life management, such as recycling or disposal.

2.5.1. LCA in building's renovation

The goal of LCA in building renovation is to identify the most sustainable and environmentally friendly practices that can be implemented during the renovation process. This can involve assessing various strategies, materials, and technologies to determine their overall environmental impact and to find ways to minimise negative effects such as energy consumption, greenhouse gas emissions, and waste (Almeida et al., 2023). The building industry in Sweden accounts for approximately 20% of the country's overall environmental impact. Approximately 50% of the impact comes from maintenance, renovation, and reconstruction, as shown in the Figure 3 (Boverket, 2023).

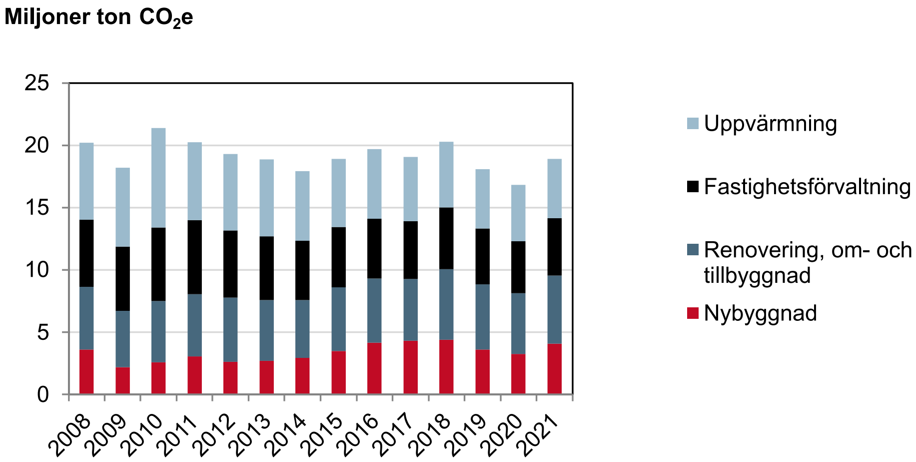

Figure 3-Total greenhouse gas emissions from the construction and property sector, broken down by industry.

The environmental impact of a building over its lifespan can be categorised into embodied carbon, representing the carbon from materials used in construction and demolition, and operational carbon, released during the building's use (Olin, 2023). Initially, LCA was used in residential buildings to reduce the primary energy demand. As buildings have become more energy efficient due to improved insulation, there is a growing emphasis on the impact of embodied carbon. Wooden construction, environmental impact reduction, and energy efficiency are the primary factors driving LCA in Sweden (Beemsterboer, 2019). Figure 4 and illustrate the changes in greenhouse gas emissions portions from the past to the present (Adalberth, 2000, Larsson et al., 2016).

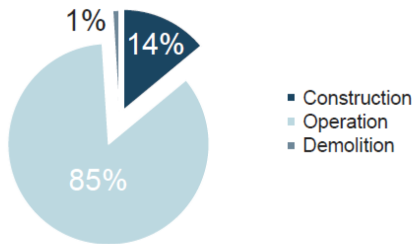

Figure 4-Previous division of greenhouse gas emission for a building(Adalberth, 2000).

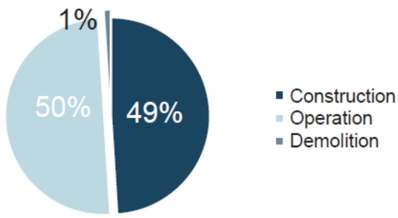

Figure 5-Updated Division of greenhouse gas emissions for a building (Larsson et al., 2016).

45% of the environmental impact comes from the foundation and loadbearing structure, 30% from the façade, 15% from the roof, and 10% from installations (Boverket, 2019). Considering that the foundation and loadbearing structure are typically preserved during renovations, it is important to incorporate the use stage in Life Cycle Assessment (LCA) for renovation projects. However, in this study the LCA of adding floors should be considered.

A life cycle assessment for a renovation is conducted in a similar manner as it would be for new production and marks the beginning of a new life cycle. Promoting the reuse of existing materials has significant environmental benefits by minimising the impact caused by constructing new buildings. Renovations have not been incorporated into the climate declaration yet (Boverket, 2019).

2.6. The Swedish residential heat energy system

In the past three decades, the Swedish residential heating system has transitioned away from using oil as a significant source of fuel. This change can be attributed to various factors, including the oil crisis that occurred in the 1970s and 1980s. The utilization of oil and other fossil fuels for heating purposes, which currently represents less than 3% of the overall energy consumption, has predominantly been substituted by two alternative energy systems: district heating (DH) and electricity through resistive heating and heat pumps (HP). These two systems fulfil over 75% of the energy requirements for heating households. District heating (DH) is responsible for around 50% of heat production in buildings, while the EU has a share of approximately 6%. Resistive electricity and heat pumps contribute approximately 21% and 8% respectively (Savvidou and Nykvist, 2020). More precisely, over 90% of all residences in multi-family buildings are linked to district heating (Selvakkumaran et al., 2021). According to the Swedish Energy Agency, district heating constitutes approximately 90% of the energy consumption in residential buildings. This underscores the substantial dependence of the residential and service sector in Sweden on district heating systems to fulfil their heating and hot water requirements (Energimyndigheten, 2021).

Sweden played a key role in promoting the widespread adoption of heat pumps (HP) by fostering research, supporting technology development, engaging key stakeholders, and providing subsidies. This strategy successfully incentivized the shift from oil boilers and resistive heating, making heat pumps cost-competitive with fossil-fuel systems. The combination of Sweden's climate policy and the population's inclination to stay in one place led to substantial long-term investments, resulting in one of the highest per capita installations of heat pumps. Currently, both district heating (DH) and electricity generation in Sweden are almost entirely decarbonized. The country leads the EU in renewable energy sources for heating, reaching around 70%, with some variations based on annual average temperatures (Savvidou and Nykvist, 2020).

Residential housing constitutes 15% of Sweden's overall final energy demand, with the predominant share, approximately 66%, allocated to space heating and domestic hot water (DHW) requirements. Within this category, one-third pertains to space heating, while the remaining portion is dedicated to DHW (Energimyndigheten, 2021). In 2014, single-family homes (SFH) consumed approximately 31.5 terawatt-hours (TWh), while multi-family homes (MFH) utilized about 24.1 TWh. These figures mark a notable decrease from the 1995 levels of 45.6 TWh for SFH and 30 TWh for MFH (Swedish Energy Agency, 2017).

Shifting towards a heat energy system that is more efficient needs consideration of drivers including behavioural change, building stock upgrades, and technology substitution or improvement (Savvidou and Nykvist, 2020).

The dominant energy carriers, electricity and district heating (DH) are key for single-family homes (SFH) and multi-family homes (MFH) in Sweden, respectively. The prevalence of DH in MFH has led to a technological lock-in (Savvidou and Nykvist, 2020). (Sartori et al., 2009) It is noted that the profitability of this supply-oriented approach, especially in areas with high energy intensity, could face challenges due to the promotion of energy efficiency measures. This could result in conflicts with investments in energy efficiency. The use of electric heating has decreased by 19% since 1995, primarily because of the transition from resistive heating to heat pumps (HP) and advancements in HP technology efficiency. The coefficient of performance (COP) has been increasing by 2% each year since 1995 (Swedish Energy Agency, 2015). Biomass is efficient in both single-family homes (using pellet boilers) and multi-family homes (as the primary fuel in district heating systems).

Globally, desired indoor temperatures vary based on lifestyle and income. In Sweden, there has been a longstanding tradition of maintaining high indoor temperatures, which is supported by informal social practices. As a result, the average indoor temperature in apartment buildings can reach as high as 22.4 degrees Celsius, a practice that is not commonly observed in many other countries. Multi-Family Homes (MFH) in Sweden tend to have higher indoor temperatures, with an average of 22.4 °C, compared to Single-Family Homes (SFH), which have an average of 21.2 °C. This can be attributed to the absence of individual measurement of heating consumption in multi-family housing (MFH) units. Additionally, heating expenses are included as a fixed component of the rent, which results in limited motivation for MFH residents to conserve heat energy. (Savvidou and Nykvist, 2020).

2.7. Common Renovation Strategies

Energy-efficient renovation strategies for a residential building can involve several key aspects including adding more efficient insulation, changing windows, heating, and cooling systems, improving ventilation system, changing the roof, and renewable energy. Here is a detailed approach for each:

2.7.1. Building Envelope Improvement

2.7.1.1. Wall improvement

Improving insulation is a crucial step in energy-efficient renovation. It reduces heat transfer, thus lowering the need for heating and cooling. The payback period for investments in insulation can be long, but it's a worthwhile investment for long-term energy savings (Gamayunova et al., 2019). A study conducted in France has demonstrated that the implementation of external wall insulation leads to a significant reduction in energy consumption for space heating in various types of buildings, with an average decrease of approximately 29% (Belaïd et al., 2021). This process involves several methods and technologies, each with its own benefits and considerations.

External Wall Insulation**:** This method involves adding insulation to the exterior of the building. It is often used in energy-saving renovations because it can significantly reduce heat loss through the walls. A "Modified Mortar Anchor Fastening Method" suited for exterior wall reinforcement and a "Functionally Graded Plate" based on fabricated external thermal insulation system are proposed methods for improving insulation (MY et al., 2015). Approximately 40% of the heat loss from the building fabric can be attributed to insufficient airtightness, which is caused by the temperature difference between the indoor and outdoor environments. Enhancing airtightness can be achieved by incorporating a vapor barrier or utilizing insulation with an integrated wind-stop layer during the installation of insulation materials on exterior walls (Cuce, 2017).

2.7.1.2. Windows

Windows play a significant role in a building's overall energy efficiency. Installing energy-efficient windows can significantly reduce energy consumption. Residential buildings typically lose 47% of their total heat through windows, which have higher U-values compared to other parts of the building. Airtight windows can achieve a 33% reduction in heat losses (Cuce, 2017).

To comply with the current building regulations, it is necessary to decrease the U-value of windows to less than 1.2 (W/m^2K). Triple-pane windows, which are more advanced than double-pane windows, feature low-emissivity coating and are filled with heavier gases. As a result, they have a lower U-value (Boverket, 2019).

2.7.1.3. Changing Roof

Energy efficiency can also be increased by replacing the roof. Including building-integrated photovoltaic (BIPV) systems in the roof's architecture is one strategy. These systems can reduce greenhouse gas emissions and overall energy consumption. The efficiency of BIPV systems installed on roofs can have a big impact on how much energy buildings use for heating and cooling (Maghrabie et al., 2021).

Enhancing the roof's insulation is another strategy. This could be a component of a larger plan to increase the building envelope's insulation, which can drastically lower energy usage (Baginski, 2019).

2.7.2. Building Ventilation Upgrades

Ventilation systems are essential for preserving indoor air quality and managing energy usage in residential buildings, particularly those that are well-sealed. The energy usage of the ventilation system constitutes a substantial portion of the total energy consumption in a low-energy residential building. The impact of the building's airtightness on the energy consumption of the ventilation system is a crucial factor to consider. An energy recovery ventilation system can effectively offset the energy saved from recovering heat from exhausted air with the extra energy consumed by the mechanical ventilation system. The control strategy of the ventilation system is also a major factor in its energy efficiency (Liu et al., 2019).

A study conducted in Sweden demonstrates that the implementation of ventilation systems equipped with heat recovery technology can lead to substantial reductions in final energy consumption. Applying ventilation heat recovery for space heating and ventilation can result in a primary energy saving of up to 55%. The primary energy benefit is heavily influenced by both the heat supply system and the airtightness of buildings (Dodoo et al., 2011).

2.7.3. Renewable Energy- Installing PV Panels

Incorporating renewable energy sources into the renovation strategy can further enhance energy efficiency. The use of radiant systems has been demonstrated to allow optimal integration with high-efficiency generation systems and renewable energy sources (Georgescu et al., 2018).

It's important to note that the cost of such renovations can be high, and homeowners may be reluctant to invest due to the initial cost. A step-by-step renovation project, dividing necessary actions into certain sub-actions, can be a more feasible approach. This approach not only makes the renovation more affordable but also allows for adjustments based on the results of each step (Ashrafian et al., 2019). Demand for renewable energy solutions is being driven by growing concerns about climate change. Employing solar energy for generating electricity using photovoltaic panels has the potential to be a viable alternative to the current electricity mix, which includes non-renewable energy sources.

The average available roof area per person in Sweden for solar PV installations is 49 m^2. Sweden has significant potential for further expansion in its solar photovoltaic (PV) sector (Yang et al., 2020). The utilisation of solar energy, an inexhaustible energy source, has the potential to alleviate the ongoing climate crisis.

2.7.4. Building Physics Considerations

2.7.4.1. Airtightness Improvement

In Sweden, a building's airtightness is quantified through a specific measure known as specific air flow (expressed in $l/s.m^2$). This metric indicates the rate of air flow per square meter of the building envelope per second, measured at a pressure difference of 50 Pa. A building's airtightness is closely linked to the extent of unwanted ventilation, often termed as infiltration or air leakage. Infiltration accounts for a considerable proportion of heating losses within a building and minimising the entrance of uncontrolled air is crucial to maintaining an effective ventilation system equipped with heat recovery capabilities (Bankvall, 2013).

Previously, Boverket’s Building Regulations (BBR) determined that air leakage through building envelopes should not exceed 0.8 litters per square meter per second (l/s.m²) to optimise energy efficiency. However, this regulation has since been replaced. The updated requirement indicates that the building's envelope must achieve a level of tightness such that it meets the criteria for the building's primary energy demand for heating (Boverket, 2019).

In a Swedish study, researchers conducted a simulation on a six-story building with a mechanical ventilation system to assess its airtightness. The simulation resulted in varying levels of airtightness, ranging from 0.8 to 2.0 litters per square meter per second (l/s.m²). The building model subjected to testing represents a multi-family residential unit constructed between 1971 and 1985. It was noted that the lowest recorded level of airtightness was 2 litters per square meter per second, a common measurement for buildings constructed during that era (Bankvall, 2013).

Simulation data indicates a clear correlation between a building's airtightness and its energy consumption, primarily due to infiltration. Studies demonstrate that doubling the air leakage rate leads to a proportional increase in energy losses resulting from infiltration. For example, in a simulation scenario where a building had a high leakage rate of 2.0 l/s.m² in an urban setting, infiltration contributed to 23% of total energy losses. On the other hand, when the building achieved the airtightness standard of 0.8 l/s.m², infiltration accounted for only 10% of total energy losses. These findings underscore the substantial influence of building airtightness on energy efficiency, emphasizing the necessity of minimising air leakage to minimise energy consumption (Bankvall, 2013)

2.7.4.2. U-Value Improvement

The U-value, or thermal transmittance, is a measure of how well a building element conducts heat. The unit of measurement is watts per square meter per degree Kelvin (W/m²K). A lower U-value signifies superior insulation characteristics, resulting in reduced heat loss through the building component. During energy-efficient renovation of residential buildings, it's crucial to consider the U-values of different building elements to minimise heat loss and improve energy efficiency (Nardi and Lucchi, 2023).

It should be noted that in order to comply with the current Boverket building regulations, the building envelope must have a mean U-value of less than 0.6 (W/m²K). The U-values for the roof are below 0.13 (W/m²K), for the walls below 0.18 (W/m²K), for the ground floor below 0.15 (W/m²K), and for the windows and doors below 1.2 (W/m²K) (Boverket, 2019).

Other measures have been reviewed including heat pump, and etc; however, the mentioned five measurements were more fit to our studies and more efficient based on our goals and scope.

3. Methodology

This chapter outlines the methods used to explore the potential of increased floor area for financial and environmental benefits in existing residential buildings. The aim is to investigate the most viable measures to renovate Swedish multi-family houses, focusing on adding a floor area and analysing the financial cost, carbon emission, and energy consumption of implementing such changes during the renovation from the perspective of LCA and LCC. The study employed mixed method (qualitative and quantitative) to carry out the research. The process consists of four main steps: literature review, data collection, simulation, and analysis. The workflow of this research is presented in Figure 6.

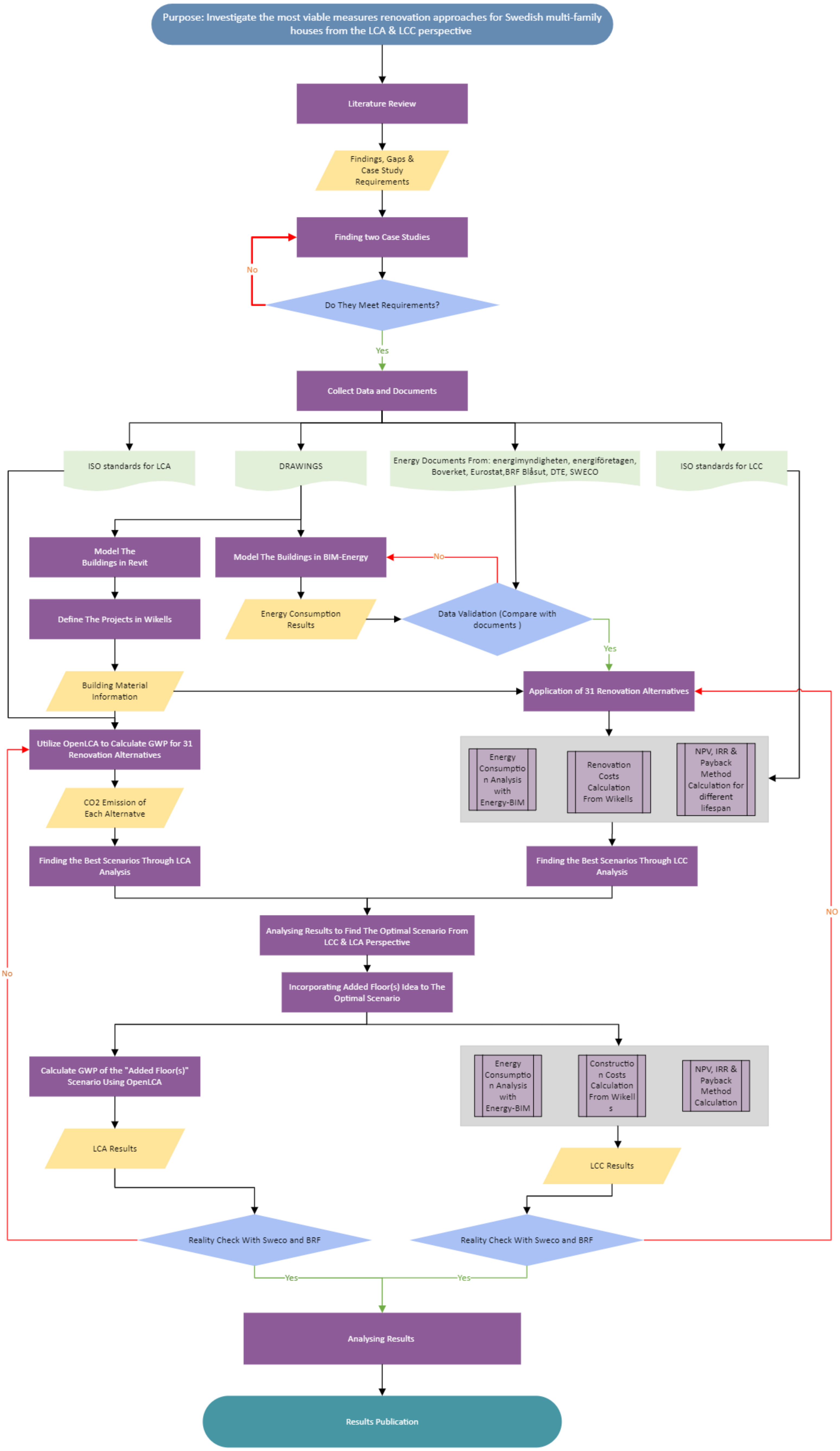

Figure 6-Workflow of the research.

1

3.1. Literature review

First, a comprehensive literature review is conducted to gather existing knowledge related to the topic, and data need for the analysing data and simulation based on related keywords, such as energy efficiency measures, renovation, environmental impacts, and cost analysis in Sweden. This review led to identifying the gaps in the existing literature and requirements needed for selecting case studies. Key findings from the literature review will present in the Results section. In addition, through reviewing the literature we have found that the most common residential buildings in Sweden among four different types is multi-family buildings, which approved that decision regarding choosing the building type was correct. Furthermore, we have concluded that to gain the most beneficial results and cover thesis goals, a vertical and a horizontal building should be investigated in current study.

3.2. Case studies

As part of an ongoing study of strategies for urban growth and the use of existing buildings, this master's thesis aims to investigate LCA and LCC of adding floor during renovation in multi-family buildings in Sweden. To support this research, two case studies were selected: BRF Blåsutgatan 8 in Majorna and Byalagsgatan 8 in Hisingen, both located in Gothenburg.

3.3. Documents and Data Collection

The data for this study was collected from several primary sources. Key among them is the Wikells Sektiondata 2023.10 database, which provided detailed information on renovation and construction, material costs, labour and transportation expenses. Additionally, energy related data were obtained from Swedish Energy Agency, Swedenergy, Eurostat, and DTE.pmtric.com. “DTE” is a digital twin database that contains information about the energy demand and CO_2 emissions of buildings in Gothenburg City. This platform provides stakeholders with comprehensive data on energy use, helping to identify patterns and develop strategies to improve energy efficiency and reduce overall energy demand. Some additional energy related database including energy declaration and drawings of the buildings were also provided by the BRF representative for Blåsutgatan 8 and by Sweco for Byalagsgatan 8. Additionally, relevant ISO standards such as EN 15978, SS-ISO 15686-5:2022, and ASTM-E917 were accessed through the Swedish Institute for Standards (SIS).

3.4. Data analysis

3.4.1. Simulation and calculation tools

First, due to limited construction data from the BRF representative, Blåsutgatan 8 was modelled in Revit based on the original hand drawn construction drawings. This initial step was essential to create a comprehensive 3D model that could be further imported to OpenStudio 3.7 for design and energy simulations. The results from OpenStudio were then compared with energy related data provided by the BRF representative to verify accuracy. Despite the adaptations in the modelling process, the initial results significantly differed from the actual data provided by the BRF representative for this specific building. Therefore, a shift to the BIM-Energy software was made, which offered more precise energy simulations, closely aligning with the data provided by the BRF representative, energy declaration for the building and the data from DTE.pmtric.com. Below is the software employed for this study.

Revit

To enhance the depth of information and use BIM to examine the renovation comprehensively, Blåsutgatan 8 was modelled in Revit software. This method allowed for precise detailing of building elements like the number and characteristics of windows, doors, and exterior wall areas. This detailed modelling was specifically performed for Blåsutgatan 8, as the construction details for the other building were more complete.

Open Studio

Open Studio software is an interface for the Energy Plus engine. It was initially employed in the study of Blåsutgatan 8 for comparative analysis with the existing data. A model of the building was created, incorporating details necessary for energy analysis, such as material specifications and HVAC systems. The Open Studio application was selected for its ability to integrate with EnergyPlus. This integration utilized Gothenburg weather data to enhance the simulation's accuracy.

BIM-Energy

BIM Energy is a web-based online tool that is used for energy performance simulations. It has two main parts including Evaluation and Renovation. It effectively calculates and evaluates the energy performance of buildings based on their design data. In renovation part it has simplified the energy analysis process, helps the user to analyse and understand the potential energy savings of a building. Users can also construct different types of construction elements, adjust the infiltration rate, and change the model to enhance accuracy. These capabilities enable users to explore how different environmental conditions and design choices affect a building's energy efficiency. It is also possible to adjust the U-values of various construction elements, select materials with varying thermal conductivity, and choose among different ventilation systems.

Wikells Sektionsdata

Wikells Sektionsdata is a software program used primarily in the construction industry for estimating and cost calculation. It includes Swedish databases with price information, material costs, and labor costs for various construction projects. Contractors, architects, and other professionals in the building sector use it to create accurate budgets and cost analyses. The tool helps streamline workflows and ensure projects stay within budget and on schedule. The program is constantly updated, providing the user with the most recent data.

OpenLCA

For the LCA part of the study, the program OpenLCA made it possible to estimate and analyse environmental impacts in detail. The inventory data for this study were modelled using OpenLCA version 2.1.1, with the Ecoinvent version 3.10 database. The impact assessment method used is the IPCC 2013 GWP 100a. For a more detailed understanding of the data gathering process and the assumptions made for each aspect, refer to section 3.7. To enhance accuracy in the exiting data gaps, assumptions were made when it comes to selecting inputs from the inventory data. Every calculation and choice that affected the results of the study are fully described in 3.7. Through the utilization of OpenLCA, we created flows, processes, and product systems for each scenario. Consequently, we were able to calculate the CO_2-equivalent emissions for each scenario, as depicted in the subsequent discussions in 5.4.

3.5. Applied Equations

The simulation results of the existing state were compared and validated with the report provided by BRF database, Energydekleration, SWECO, and DTE.pmtric.

The annual heating demand is determined by estimating heat transmission through the building envelope and accounting for heat loss through ventilation.

The inputs for building envelopes comprise the dimensions of the buildings and the U-values of the windows, walls, roofs, and floors. (Equation 1, (Equation 2, and $U = 1/Rt$ (Equation 3 show formulas in this regard.

$R = \lambda/d$ *(Equation 1)*

$Rt = R1 + R2 + \cdots + Rn$ *(Equation 2)*

$U = 1/Rt$ *(Equation 3)*

Where:

U is U-value, the thermal transmittance (W/m²K),

R is the thermal resistance of the material (m²·K/W),

λ is the conductivity (W/m/K),

d is the thickness (m),

3.6. LCC Analysis

For the calculation and analysis in the Life Cycle Cost (LCC) section of this study, ASTM-E917-17 standard was employed. The method, formulas, and instructions provided in this standard were utilized for conducting the LCC analysis, ensuring consistency and adherence to established practices in life cycle cost assessment. Initially, the LCC of each renovation strategy was calculated individually. In the process of combining techniques, shared costs such as scaffolding for wall improvement and window replacement were not counted twice. The LCC calculation encompassed material costs, labour costs, tool rental expenses, and post-maintenance expenditures. Additionally, expenses for district heating and electricity were factored in. To address the uncertainty associated with longer timeframes, this study considered different lifespans: 10, 15, 20, 35, and 50 years. These durations were computed using an expected interest rate of 4% and an escalation rate of 5%. All anticipated future costs were converted to net present value (NPV) and added to the initial investment to determine the total cost of each renovation strategy. Afterwards PVLCC (Present Value of Leveraged Cash Flows) of each scenario will be calculated. Furthermore, for each scenario, the payback method, and Internal Rate of Return (IRR) were calculated. Formulas are provided below in (Equation 4, (Equation 5, (Equation 6, and (Equation 7. All costs are considered Swedish Krona.

$NPV = \Sigma (CF_t / (1 + r)^t)$ *(Equation 4)*

Where:
NPV = Net Present Value
CF_t = Cash flow at time t
r = Discount rate (the rate at which future cash flows are discounted to their present value)
n = Number of periods (usually years) in the investment's lifespan

$PVLCC = \Sigma [CF\_i / (1 + r)\text{^}i]$ *(Equation 5)*

CFi = Cash flow in period i
r = Discount rate

$IRR = r_0 + [(NPV_0) / (NPV_0 - NPV_1)] * (r_1 - r_0)$ *(Equation 6)*

Where:

IRR = Internal Rate of Return

r_0, r_1 = Discount rates for the periods where NPV changes sign (usually the two closest rates that bracket the IRR)

NPV_0, NPV_1 = Net Present Values corresponding to r_0 and r_1, respectively

Payback Period = Y - (C - B) / A (Equation 7)

Where:

Y = Number of full years before the investment is fully recovered

A = Annual cash inflow (or savings) generated by the investment

B = Initial investment cost or cash outlay

C = Remaining investment cost or cumulative cash outlay at the end of year Y

3.7. Life Cycle Assessment

International standards determine the guidelines for life cycle assessments. The lifetime of a building, according to the EN 15978 (SIS, 2011) and EN 15804 (SIS, 2019) standards, is segmented into four phases: Product and Construction (A1-A5), use phase (B1-B7), end-of-life phase (C1-C4), and a fourth phase (D) encompassing loads and benefits beyond the building life cycle. The phases are subsequently subdivided as illustrated in Figure 7(Van Gulck et al., 2022).

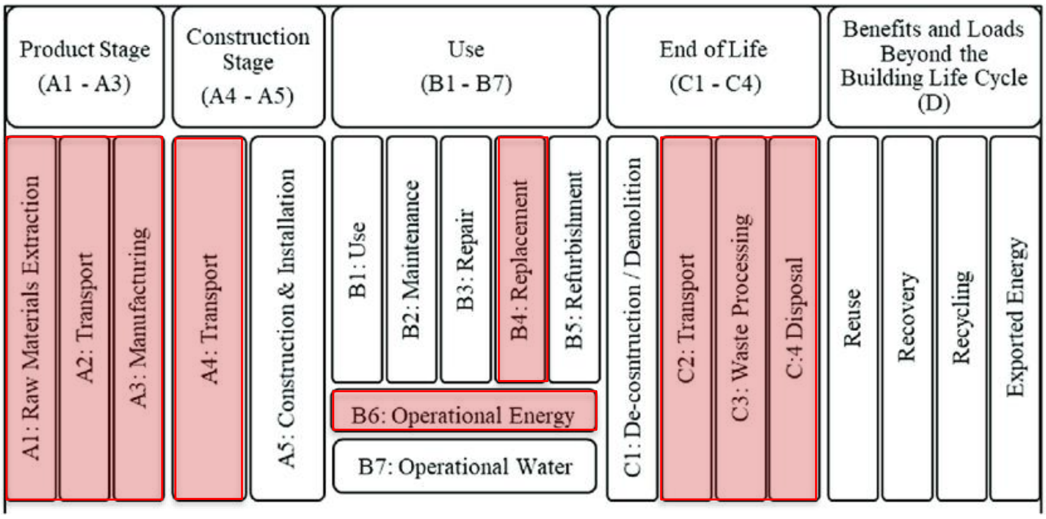

Figure 7-The different LCA modules (Van Gulck et al., 2022), and the modules used in CAALA marked in red.

A circular approach was employed within the OpenLCA software program, ensuring that all assumptions and information were supported by reputable articles and academic papers. Inputs were selected based on the given inventory data, and where discrepancies were identified, assumptions were made in order to achieve the greatest possible accuracy. Prior to modelling the LCA analysis, a flowchart was created to provide a structural framework for the model. A spreadsheet was then utilized to track inputs and changes in OpenLCA, and all processes and flows were thoroughly examined to minimise the risk of errors in the calculation of the assessment. All calculations, assumptions, and decisions that impacted the study's results will be presented in detail. Based on the study's goal and scope, an appropriate impact assessment method was selected, and spreadsheets and visualization graphs were employed to effectively compare and present the results.

3.7.1. Goal and scope

In this part of the study, the goal and scope for the LCA part will be explained. Furthermore, the system boundaries, functional unit, impact categories and allocation method will also be presented and explained.

The goal of this report is to investigate how the renovation of the multi-family residential building BRF Blåsutgatan 8 and Byalagsgatan 8 affects the environment and especially climate change. The focus of this report is to calculate the biggest contributors that will contribute to climate change in order to provide an insight into where the hotspots of the emissions are located for a possible improvement of the building's environmental performance.

The investigation focuses on EPS and mortar for constructing insulated external walls, new windows installation (PVC and glass), EPS for constructing insulated roof, PV panels, district heating demand, and electricity demand. The plastic components of the Smart1 unit were calculated based on the limited data available for the ventilation unit, excluding ceramics and fans. The Global Warming Potential (GWP) for all scenarios was computed using OpenLCA and Excel. System boundary for products in life cycle assessments is displayed in Figure 13. The intended audience of this study are employees of the company that renovate these buildings, in order to use the results from these buildings for future projects in Sweden.

The scope of this part will be explained through the choice of system boundaries, impact categories and limitations on our database OpenLCA.

3.7.2. Functional unit

When comparing two services or products that have an LCA impact assessment it's important to have a functional unit that makes it possible to compare them (Table database, n.d.). In this study the functional unit is 1 sqm of heated floor area.

3.7.3. System boundaries

The residential buildings Blåsutgatan 8 and Byalagsgatan 8 are located in Gothenburg, Sweden therefore it is accurate to look into the Swedish and European standards and inputs regarding the LCA analysis in open LCA. The electricity is based on the information from the municipality of Gothenburg to get a more accurate representation.

The life cycle modules considered in this LCA analysis are based on a cradle to grave perspective according to the European Standard (EN 15978:2011). By following the standard, it will provide a more accurate and more controlled assessment of the life cycle and it works like a checklist according to (Boverket, 2019). Therefore, this study will also focus on cradle to grave by choosing the following stages A1: Raw material supply, A2 transport, A3 manufacturing, A4 transport, B4 replacement, B6 operational energy use, C2 transport, C3 waste processing and C4 disposal. By choosing these stages in this report the impact can be estimated of the intended apartment buildings and investigate and compare the functional unit to other buildings. By excluding following stages will enable the study to look more into how the different stages in the user stage affect our functional unit or if it has any impact on it.

The reasoning why this study will not include A5, B1-3, B5 and C1, C2 is that previous studies show that the impact on the climate from harvesting materials for construction was the biggest contributor therefore A1-A3 was selected (Skullestad et al., 2016). Other studies show that the stage B6 are also big contributors and were selected as well (Huang et al., 2017). According to (Naturvårdsverket, 2023) the largest contributor for disposal in Sweden are the construction sector, therefore the stages C3-C4 will also be taken into consideration of the study (Naturvårdsverket, n.d.). In addition to this the transportation industry has very ambitious goals for 2030, and has a long way to go before reaching those goals therefore the transport stages of A4 and C2 were also selected in this study (Gota et al., 2015).

3.7.4. Impact categories

Climate change:

Climate change was decided as the impact category because it has a high importance for the ecosystem. It can dramatically change the Earth system. That is why it is a core boundary (Steffen et al., 2015). The boundary is a rise of the global mean temperature of maximum 2 degrees Celsius

(Rockström et al., 2009). The effects are a loss of polar ice sheets, regional climate disruptions and a loss of the supply of glacial freshwater. Climate change has two indicators. The atmospheric CO_2-concentration and the top-of-atmosphere radiative forcing. These indicators stand for the global warming potential (GWP). The parameter for GWP is CO_2-eq. CO_2 stands for the chemical compound carbon dioxide. In the building sector the following activities are important: Transportation of the materials, electricity and waste. The most important activity is the materials, for e.g. the processing of cement is responsible for half of all CO_2-emissions (Labaran et al., 2022). Above all, the building sector has a total impact of 39% from process-related emissions on this planet, which is why it is so important to investigate (UNEP, 2020).

For this study the cut-off method stated in EN 15978/19804 was chosen. The reason this was chosen is because this allocation method was seen as the most suitable since this follows the "polluter pays"-principle where the waste produced from used materials are burdened upon the producer of the virgin material (Ecoinvent, 2024). By using this method, it also incentivises recycling to a higher degree since recycled material is already "paid" for by the original producer.

3.7.5. Life-cycle inventory analysis

As a foundation for the upcoming analysis in OpenLCA, the following chapter specifies the assumptions for different types of information including material, their density, weight etc. Here all the different material processes and their contributions are investigated. This initial flowchart made as a basis for modelling in OpenLCA is presented in Figure 8.

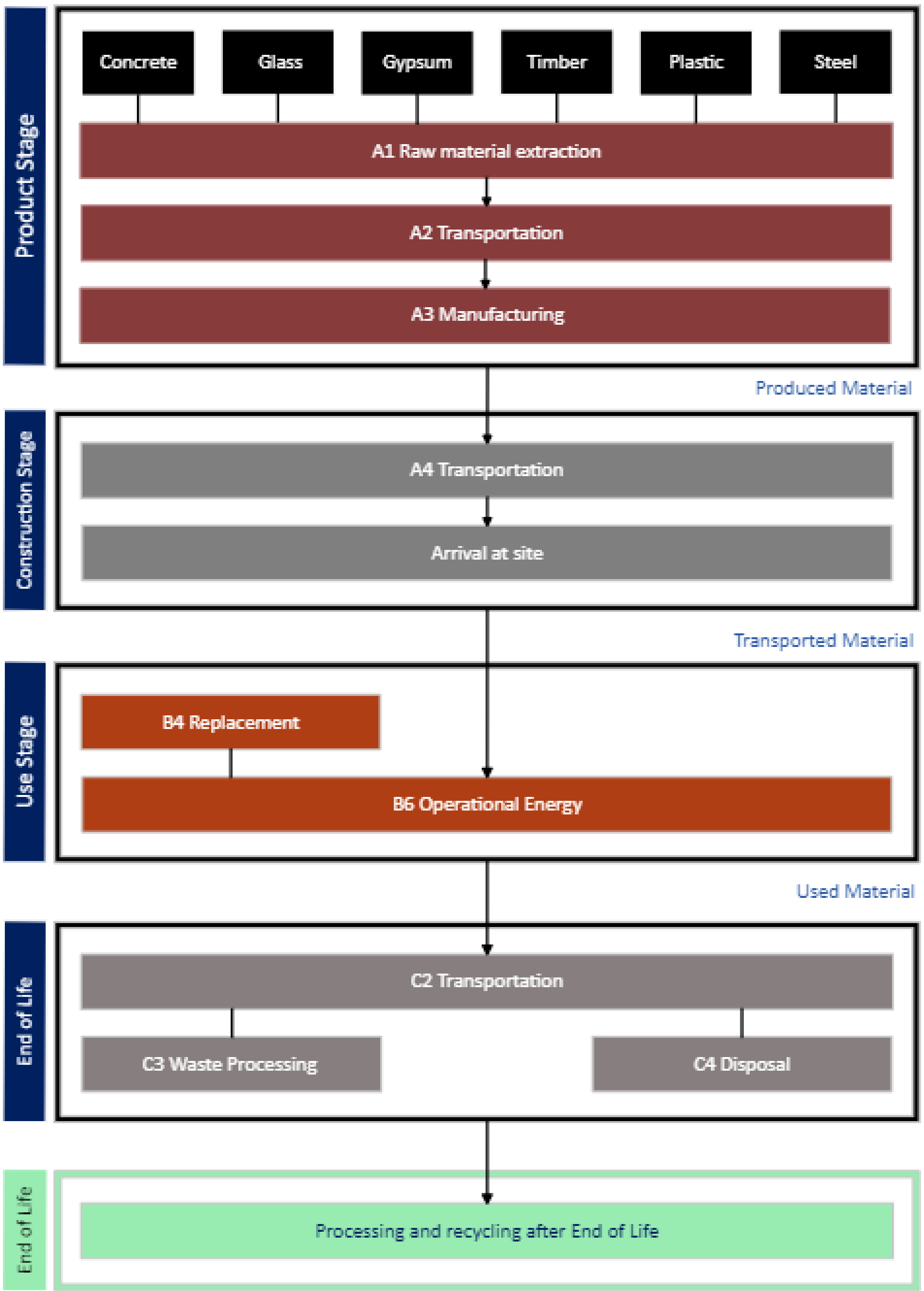

Figure 8- Life-cycle inventory analysis Flow chart

Assumptions module A1-A3 (Production):

These assumptions will be explained in detail further below when each of the different building elements are presented.

Assumptions for module A4 (Transport):

Many of the building elements contain the same materials. One suggestion here would be to calculate the transport of each of the different materials. However, this doesn't make logistical sense since the windows for the renovation and all its other components will be needed first, while the windows will be used for the added floors won't be needed in the beginning of the renovation. Therefore, the choice of transporting each of the materials included in each element was decided upon. The standard of EURO6 transports was assumed to be used in this study.

Another assumption that had to be made regarding the transportation of all materials was how far from each of the materials would have to be transported. Here the assumption is based on the Boverket Climate Database (2023) which in turn is based primarily upon valid EPDs of construction materials. Following this assumption, the study was able to assume the average distance from where these materials could be sourced and transported.

Assumptions for module B4 (Replacement):

The lifespan of the building is assumed to be 50 years (Scherz et al., 2023). However, something that needs to be considered is that some parts of the buildings won't have as long of a lifespan; for example, the fans of the Smart1 ventilation devices will need to be replaced. The study assumes the fans of Smart1 needs replacement every 8 years based on the manufacturer recommendation during the interview. Nevertheless, due to the information limitation in OpenLCA regarding the materials used in Smart1, the replacement of Smar1 was ignored. The roofing membrane (bitumen) will be replaced also one time in the lifespan.

Assumptions for module B6 (Operational energy use):

The energy consumption utilised in the Life Cycle Assessment (LCA) was obtained from simulations of building energy. The district heating in Göteborg splits up in three parts. About 70 % is from industrial waste heat and the incineration of waste. Almost 20 % occurs through renewable fuel, e.g. biofuel and the last 10 % is provided through natural gas (PartilleEnergi, 2023).

Assumptions for module C2 (Transport):

The transport to the location of the waste management plant was assumed to be 40 km in accordance with what is being stated in the Construction and demolition waste transport in Stockholm (2017).

Assumptions for module C3-4 (Waste management and disposal):

The following Table 1 shows the distribution of how the building materials are being disposed of. The assumptions have been made using external references as a tool to provide for an understanding as to what degree each of the different materials are recyclable. The data derives from EPDs, waste management reports and other reports.

Table 1-Distribution of means of disposal among different building materials.

Materials	Landfill percentage	Energy resource percentage	Recycling percentage	Source
Concrete	20%		80%	(Conelement AB, 2022)
Plastic film		50%	50%	(Material Economics Sverige AB, n.d.)
EPS		50%	50%	(BEWI, 2021; Finja, 2022)
Mortar	100%			(IBU, 2022)
Gypsum board			100%	(Kozicki & Carlson, n.d.)
Glass wool	100%			(EPD international, 2013)
Steel	8%		92%	(Sveriges geologiska undersökning, 2020)
Wood		100%		(Ragnsells AB, n.d.)
Roofing felt	40%	45%	15%	(EWA, 2016)
Cellulose fibre paper		100%		(ISOCELL, 2014) expired
Window			100%	(Ragnsells AB, n.d.)

In OpenLCA software there is no virgin paper board item; however, cellulose fibre was available, which is preferable concerning sustainability. The use of cellulose fibre instead of virgin paper and boards can help reduce the environmental impact of paper production while maintaining similar quality and cost-effectiveness. This is why it is becoming an increasingly popular choice for paper and cardboard packaging, insulation, and other applications.

3.7.6. Life-cycle impact assessment method

To evaluate the building's life cycle impact in respect of the impact category of climate change the assessment method of IPCC 2013 GWP 100a was chosen. IPCC, formally known as Intergovernmental Panel on Climate Change is the UN's panel to scientifically evaluate climate change, what might be the consequences, what to be expected in the future and how to mitigate risks regarding this topic (IPCC, n.d.). The impact assessment method describes the emissions of CO_2-eq over a time span of 100 years (Neves et al., 2018). This impact assessment method suits the impact category of climate change since it is providing the result as a GWP measured in kg CO_2-eq.

3.8. Exploring the Best Scenario

To determine the best scenario that balances minimal CO_2 emissions with the maximum NPV, a systematic approach is required. Here is explanation of exploring method:

Normalization of Units:

It is necessary to normalise all LCC and LCA values to the same units. This step is crucial because LCC and LCA use different units, such as currency value and environmental impact respectively.

Calculation of Contribution Percentages:

For each scenario, the contribution percentage of both CO_2 emissions and NPV relative to their total amounts across all lifespans will be calculated. This can be done by dividing the final NPV and total CO_2 equivalent of each scenario by the sum of NPV and CO_2 emissions for all scenarios in different lifespans, respectively.

Ratio of NPV to CO_2 Emissions:

To find the best scenario, the ratio of NPV to CO_2 emissions for each scenario will be computed. This ratio will provide a direct comparison of economic benefit to environmental impact.

Selection of the Best Scenario:

The scenario with the highest NPV to CO_2 emissions ratio is considered best, as it indicates the highest economic return per unit of CO_2 emitted.

4. Case Studies

4.1. Primary situation of the vertical building

General information

HSB Brf Blåsut comprises 11 separate buildings that house 578 condominium apartments in Gothenburg, Sweden. These apartments are positioned ideally at Gröna Gatan 32, 41-57, 59-71, Blåsutgatan 1-7 and 2-12, and Kabelgatan 15 A-C. The association's location in the popular Majorna area, near Chapmans Torg, offers unique accessibility. To gain insight from HSB Brf Blåsut and explore environmentally friendly renovation methods, Blåsutgatan 8 was selected as the first case study for this research as a vertical building. It has 8 floors among which 7 of them are residential, each floor has 4 apartments. The first floor is common area including storage and laundry. Brf is intended to renovate this building and add floors during the renovation. The site plan is shown in Figure 9.

Figure 9- Location of Blåsutgatan 8 on Google Map

The height of each floor is 2.7 meters. The general information of this complex is shown in Table 2.

Table 2- General information of Blåsutgatan 8

Name	Blåsutgatan 8	Reference	Unit
Total Building Area	2904	Energideklaration	m2
Net Conditioned Building Area	2807	Energideklaration	m2
Unconditioned Building Area	97	Energideklaration	m2
Gross Exterior Wall Area	1191	BRF documents & BIM-Energy	m2
Window Opening Area	436	BRF documents & BIM-Energy	m2
Gross Roof Area	363	BRF documents & BIM-Energy	m2
HVAC system	Central Exhaust	BRF documents/ DTE	
Heat recovery	0	BRF documents	%
Heating source	District Heating	Energideklaration & BRF documents	

Each floor has 4 apartments with the same area. The apartments in this complex have two bedrooms and one balcony. People per space floor area was assumed 0.028. There are a total of 28 apartments and 84 occupants in the complex. More information about different parts of the buildings is listed in Table 3.

Table 3- Details of different areas

	Area (m2)	Conditioned (Y/N)	Above Ground Gross Wall Area [m2]	Window Glass Area = Opening Area [m2]
Apartments	2357.6 (84.2 each)	Yes	1191	436
Balcony	70 (2.5 each)	No	168	220
Corridor	89.75	Yes	15	0.72
Laundry	174.25	Yes	50.4	19.8
Staircase	32	No	0	0
Elevator	32	No	0	0
Storage	185.4	Yes	98.6	9.6
Total	2941		1359	450
Conditioned total	2807		1191	405

Construction details

Exterior Walls:

Figure 10 illustrates how the exterior concrete wall is built. It is made of plaster board, concrete, mineral wool, and bricks that are layered from the outside inward. The external concrete wall has a U-value of 0.34 W/m²K.

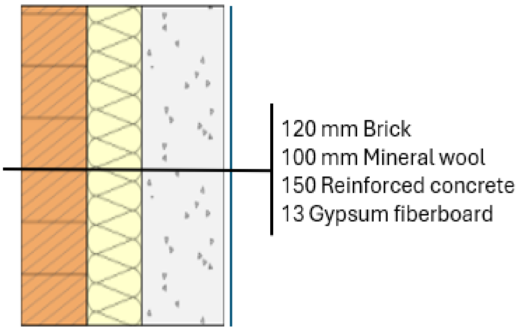

Figure 10- Details of existing exterior concrete wall (Laven and Strandberg, 2019, Cecilia Björk, 2021)

Roof:

Due to the limitations of the software, the roof of the highest floor was considered to represent the roof of the building, which was assumed to be flat instead of sloping. Figure 11 shows how the building's roof was constructed using assemblies of sheets metal, waterproofing membrane, PE foil, two layers of mineral wool, reinforced concrete, and gypsum fibreboard from outside in. This construction has a U-value of 0.23 W/m²K.

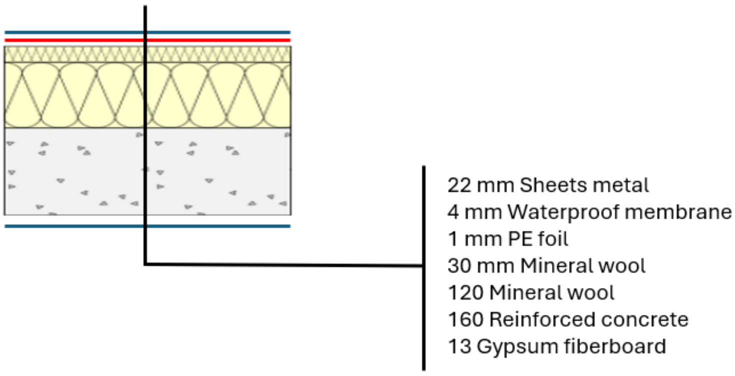

Figure 11- Details of existing roof (Laven and Strandberg, 2019, Cecilia Björk, 2021)

Windows:

The Existing building have double-glazed windows with wooden frames; the U-value is estimated to be 2.9 W/m²K. Some windows are not tightly sealed and have large air gaps between the panes as a result of their poor condition, which could allow air convection to draw heat directly from the inner panes. Quantifying the U-value of windows in this scenario is challenging, though. Since the number of windows under comparable circumstances is unknown, the building energy simulation uses the U-value of a typical double-glazed window used for the million programs based on the BIM-energy database and (Cecilia Björk, 2021). As a result, the simulation's results for heating energy demand may be lower than reality.

Ventilation:

The ventilation system is an exhaust ventilation system, but because of inadequate cleaning and maintenance, the fresh airflow is currently less than what is needed. The ventilation rate in the building energy simulations was set to the BBR standard minimum of 0.35 l/s/m².

Energy Consumption:

District heating is the primary source of heating energy in this building for both space heating and domestic hot water. The monthly district heating energy consumption of the building during a year is shown in Table 4 extracted from BRF database.

Table 4- District heating Blåsutgatan 8, during a year

Datum	Consumption (kWh)	Highest hour
November 2022	33 891.90	85.00
December 2022	55 542.00	108.00
January 2023	49 962.00	94.00
February 2023	45 058.80	196.00
March 2023	48 128.00	94.00
April 2023	28 589.00	96.00
May 2023	15 322.00	70.00
June 2023	5 657.00	53.00
July 2023	5 727.00	50.00
August 2023	7 623.80	51.00
September 2023	6 299.00	57.00
October 2023	32 487.00	77.00
Total	334 287.50	

There is some additional data for Blåsutgatan 8 in Gothenburg is provided by DTE. The figures below illustrate various annual values for 2018: Figure 10 shows delivered energy, Figure 11 shows final energy, Figure 12 shows heat demand, and Figure 13 shows primary energy. These figures also include projections for temperature increases of +1, +1.5, and +2°C. Specifically, in 2018, the delivered energy for the building was 102.3 kWh/m², the final energy was 102.3 kWh/m², the heat demand was 86.7 kWh/m², and the primary energy was 103.3 kWh/m². Figure 14 provides monthly values for final energy and heat demand for Blåsutgatan 8, with all units measured in kWh/m². Additionally, Figure 15 depicts the building's greenhouse gas emissions.

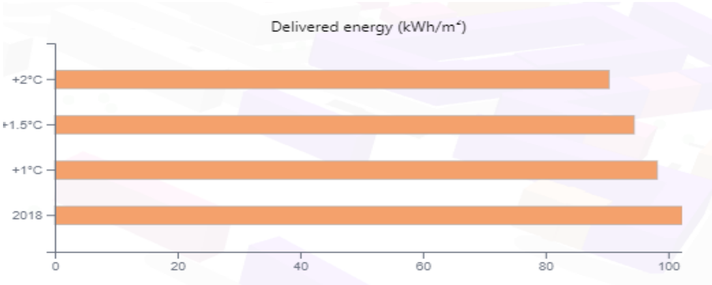

Figure 12 - Delivered Energy, Båsutgatan 8, 2018 (kWh/m2)

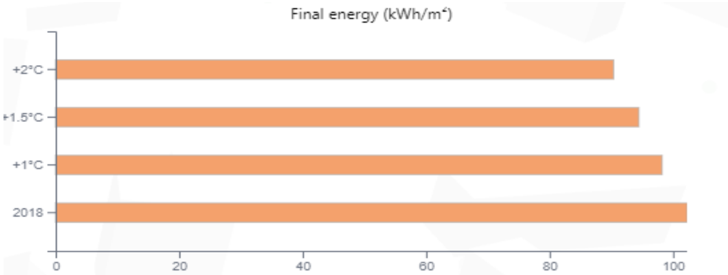

Figure 13 - Final Energy, Båsutgatan 8, 2018 (kWh/m2)

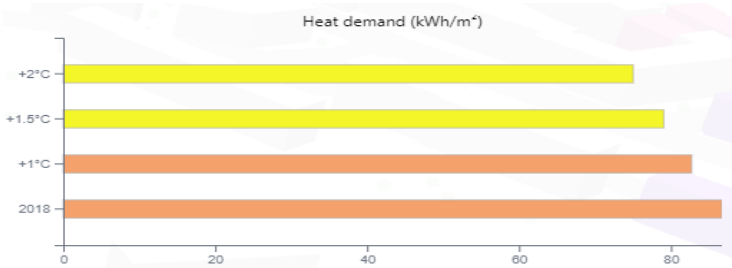

Figure 14 - Heat Demand, Båsutgatan 8, 2018 (kWh/m2)

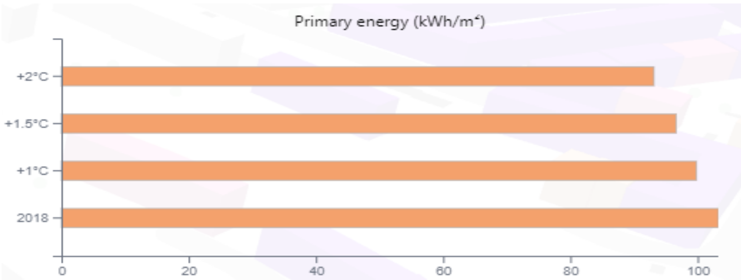

Figure 15 - Primary Energy, Båsutgatan 8, 2018 (kWh/m2)

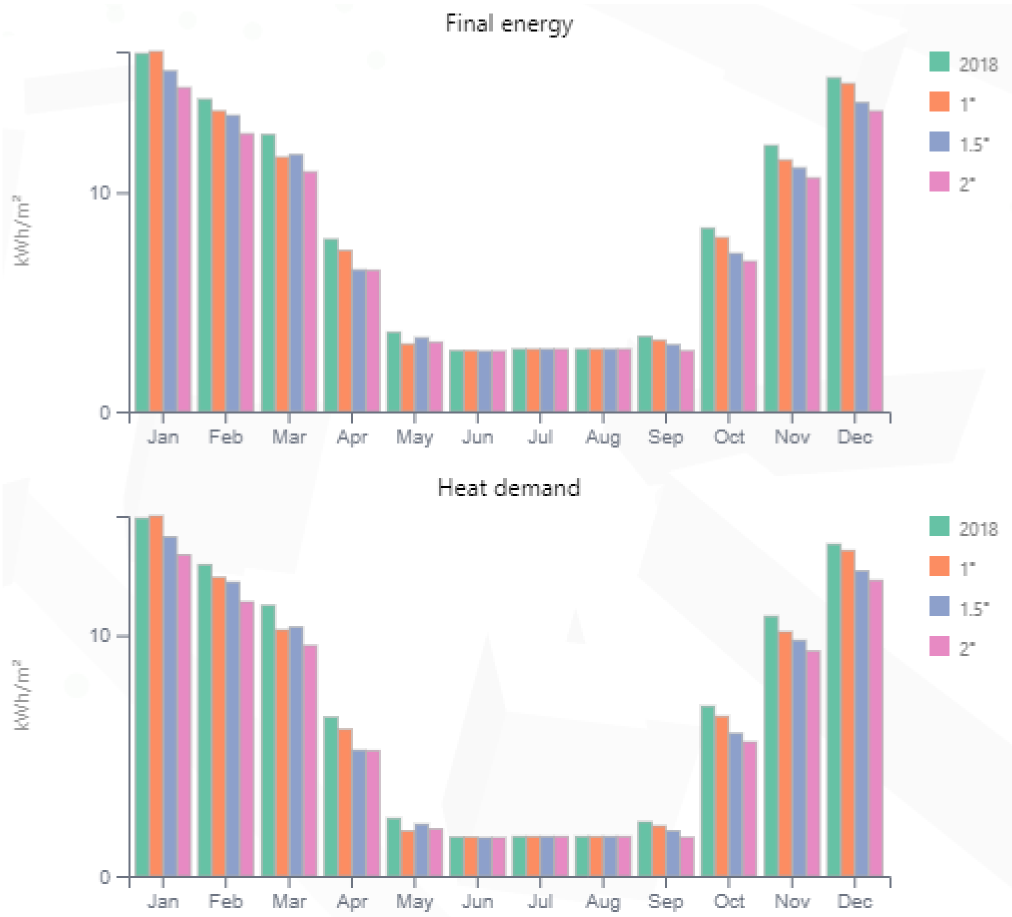

Figure 16 - Monthly Energy Consumption, Blåsutgatan 8 (kWh/m2)

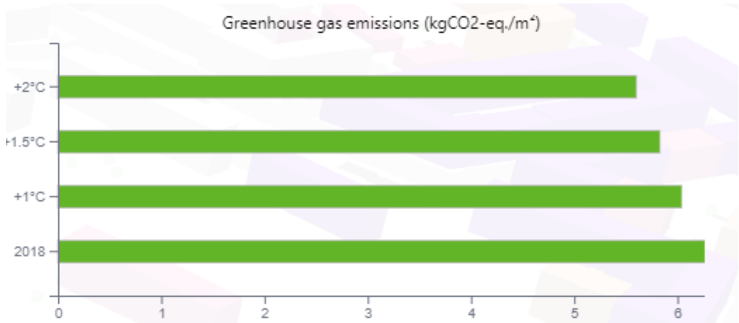

Figure 17- Greenhouse gas emission, Blåsutgatan 8 (kgCO$_2$-eq/m2)

Energy declaration of Sweden published the report in 2019, which is based on 2018 energy consumption of Blåsutgatan 8. The most important information that has not been mentioned before is explained in Table 5.

Table 5- Energy declaration report, Blåsutgatan 8

Information category	**Details**
Energy Consumption	133 kWh/m2
Building's Energy Class	E
Energy Declaration Date	2019-05-30
Energy Declaration Valid Until	2029-05-30
Energy for Heating	222,481 kWh
Tap Water	70,176 kWh
Fuels	- Heating oil: 10,000 kWh/m³ - Natural gas: 11,000 kWh/1,000 m³ (effective calorific value)

	- City gas: 5,880 kWh/1,000 m³ - Pellets: 4,500-5,000 kWh/ton, depending on wood type and moisture content
Total Energy for Heating, Domestic Hot Water, Comfort Cooling, and Property Electricity	309,873 kWh
Electricity	17,216 kWh
Suggestions	- Investigate creating heat recovery with air source heat pumps - Insulate the facade during future renovations - Replacing lighting to LED, especially outdoors - Investigate converting to IMD electricity to improve profitability of solar cells -PV panels

4.2. Primary situation of the horizontal building

General information

The other selected case study is one of several identical buildings located at Byalagsgatan 8 in Hisingen, Gothenburg. These buildings, positioned side by side, share the same architectural design and structure. Each building is a horizontal type with three stories, which has 13 apartments per floor, amounting to a total of 39 apartments in each building. The apartments in each building are of three different types: 1-room on 22 m^2, 2-room on 55 m^2, and a bigger 2-room on 70 m^2, providing a variety of living spaces for residents. This study will specifically examine one building (Byalagsgatan 8) to gain insights into its design, functionality, and energy reduction potential, which can later be applied to other buildings.

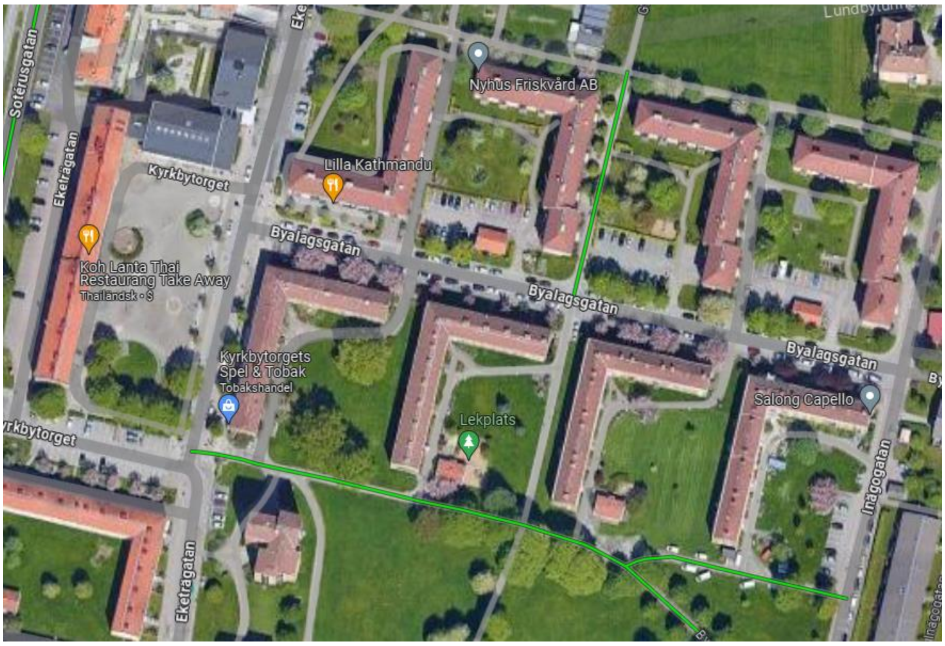

Figure 18 - Location of Byalagsgatan 8 on Google Map

Table 6 - General information of Byalagsgatan 8

Name	Blåsutgatan 8	Reference	Unit
Total Building Area	3780	Energideklaration	m2
Net Conditioned Building Area	3209	Energideklaration	m2
Unconditioned Building Area	571	Energideklaration	m2
Gross Exterior Wall Area	1461	BRF documents & BIM-Energy	m2
Window Opening Area	382	BRF documents & BIM-Energy	m2

Gross Roof Area	945	BRF documents & BIM-Energy	m2
HVAC system	Natural Exhaust	BRF documents/ DTE	-
Heat recovery	0	BRF documents	%
Heating source	District Heating	Energy declaration & BRF documents	-

Table 7 - Details of different areas

	Area (m2)	**Conditioned (Y/N)**	**Above Ground Gross Wall Area [m2]**	**Window Glass Area = Opening Area [m2]**
Apartments	2091	Yes	1027	382
Balcony	0	-	-	-
Corridor	0	-	-	-
Laundry	450	Yes	-	-
Staircase	20	No	0	0
Elevator	0	-	-	-
Storage	450	Yes	98.6	9.6
Total	3780		1359	
Conditioned total	3209		1191	

Construction details

Exterior Walls:

Figure 11 illustrates how the exterior concrete wall is built. The exterior wall is constructed with an interior layer of mortar, followed by a layer of 250mm light concrete and an additional layer of mortar on the outside. The external concrete wall has a U-value of 0.39 W/m²K.

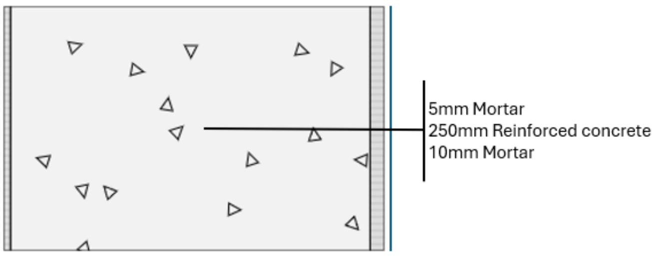

Figure 19 - Existing exterior concrete wall at Byalagsgatan 8 (Laven and Strandberg, 2019, Cecilia Björk, 2021)

Roof:

The existing roof of the building is constructed with multiple layers that work together to provide structural integrity and thermal insulation. The first layer is 100mm of coke ash, which serves as a lightweight filler and provides basic insulation. Above this is a 150mm layer of particle board. The top layer consists of 140mm of reinforced concrete, which ensures the roof's strength and durability, capable of withstanding various loads and stresses. Together, these materials achieve a U-value of 0.46 W/m²K.

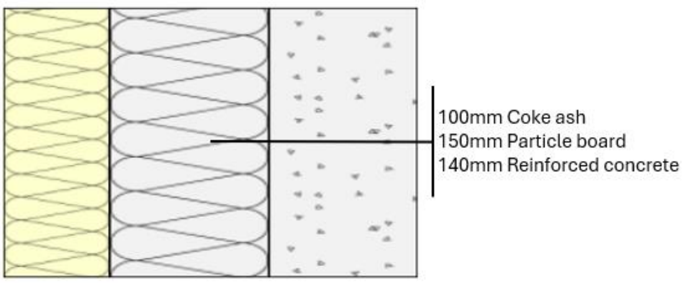

Figure 20 - Existing roof at Byalagsgatan 8 (Laven and Strandberg, 2019, Cecilia Björk, 2021)

Windows:

Byalagsgatan 8 is assumed to have windows identical to those used in the first building. These windows are double-glazed with PVC frames, and the U-value of these windows is estimated to be 2.9 W/m²K. This indicates their inefficiency in reducing heat transfer and contributing negatively to the overall energy efficiency of the building.

Ventilation:

In Byalagsgatan 8, the ventilations system is Natural draught ventilation. This system relies on natural airflow, where fresh air enters through vents and gaps, and warm air rises and exits through the roof. Natural ventilation systems are simple, but they can be less effective in regulating airflow and temperature compared to modern mechanical ventilation systems (Bankvall, 2013)

Energy Consumption:

District heating serves as the main energy source for both space heating and domestic hot water in this building. In Table 8, the energy consumption associated with district heating is shown, with data provided by Sweco.

Table 8- District heating Byalagsgatan 8, during a year

Datum	**Consumption (kWh)**
November 2017	56 360
December 2017	51 190
January 2018	50 720
February 2018	27 770
March 2018	9 790
April 2018	4 430
May 2018	3 990
June 2018	4 190
July 2018	15 060
August 2018	30 240
September 2018	38 790
October 2018	46 160
Total	338 690

The figures below provide an illustration of the energy consumption of Byalagsgatan 8, the data is collected from DTE.

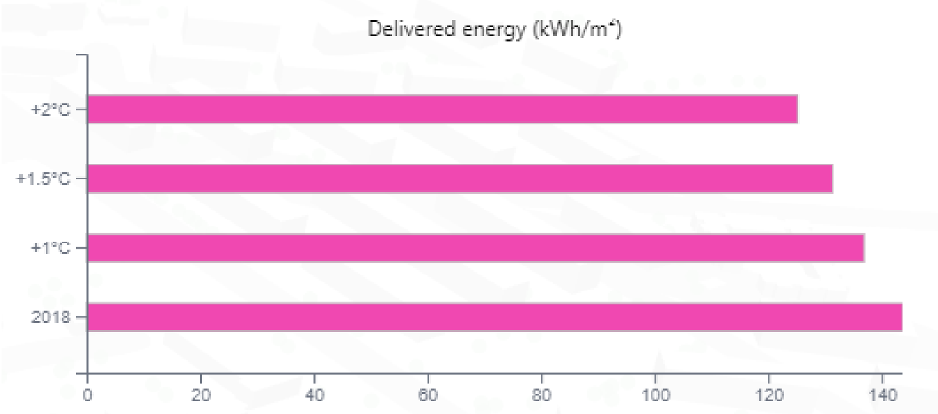

Figure 21 - Delivered Energy, Byalagsgatan 8, 2018 (kWh/m2)

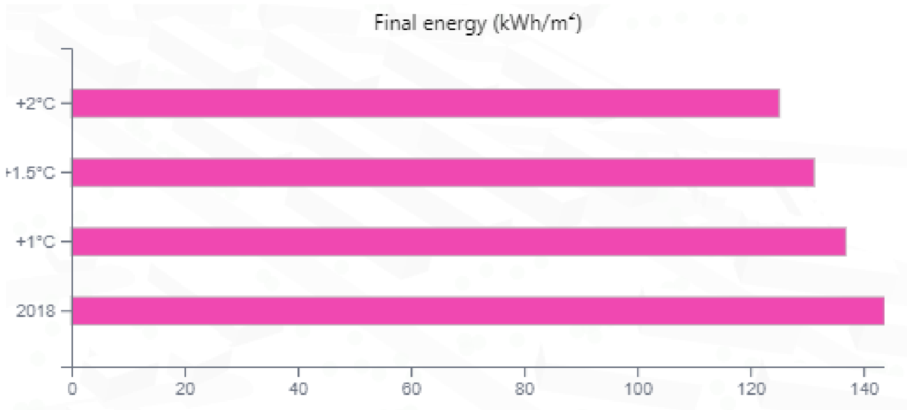

Figure 22 - Final Energy, Byalagsgatan 8, 2018 (kWh/m2)

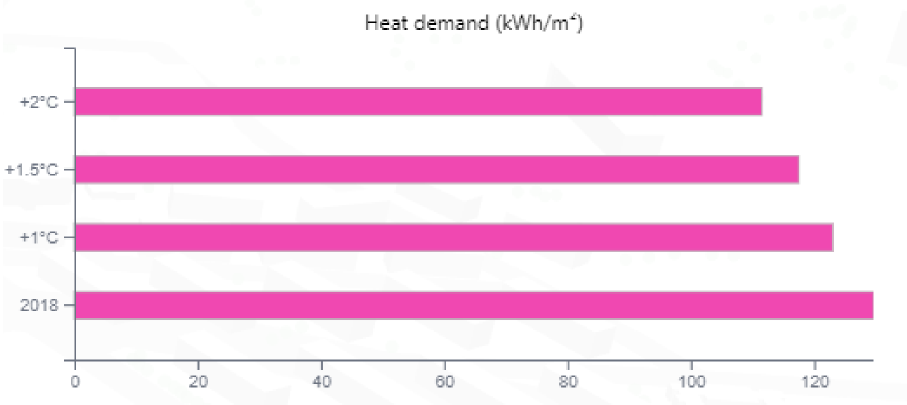

Figure 23 - Heat Demand, Byalagsgatan 8, 2018 (kWh/m2)

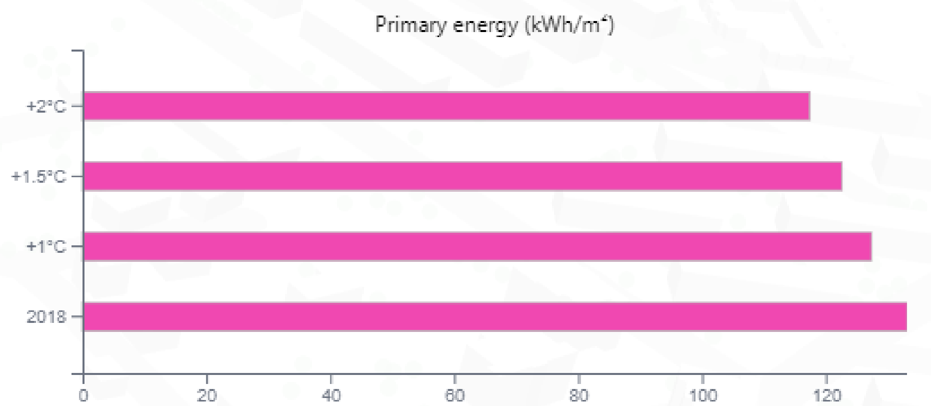

Figure 24 - Primary Energy, Byalagsgatan 8, 2018 (kWh/m2)

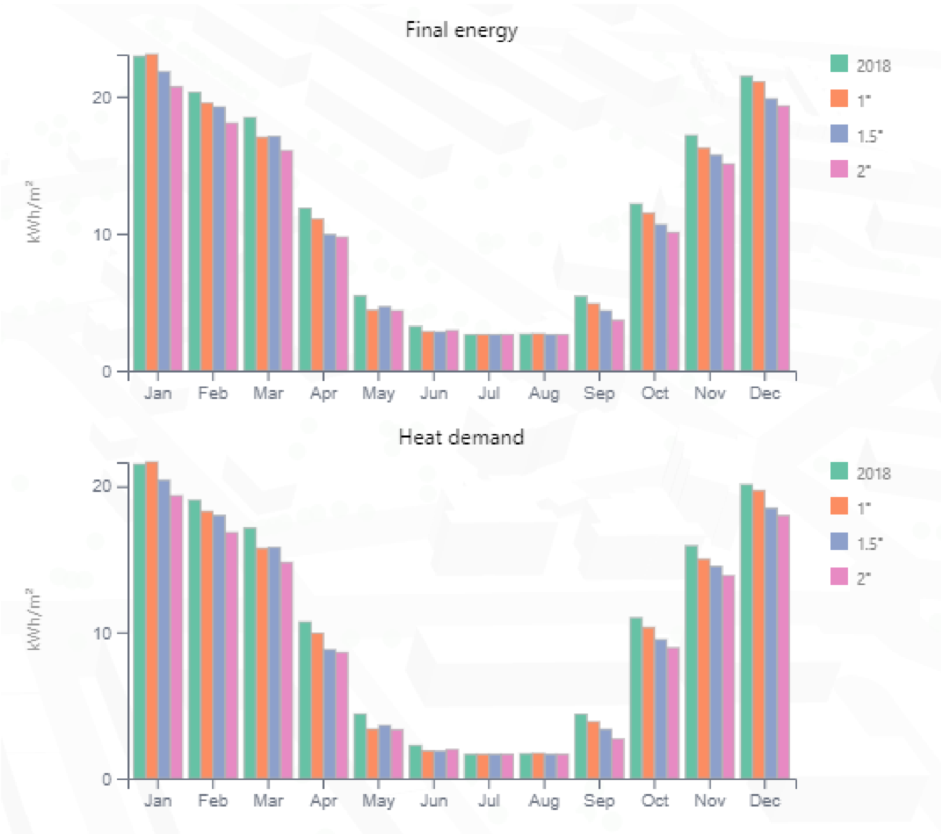

Figure 25 - Monthly Energy Consumption, Byalagsgatan 8 (kWh/m2)

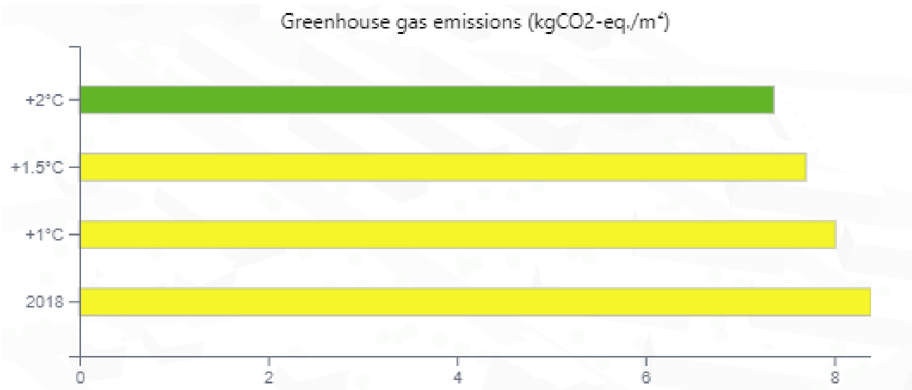

Figure 26- Greenhouse gas emission, Byalagsgatan 8 (kgCO$_2$-eq/m2)

Table 9 - Energy declaration report, Byalagsgatan 8

Information category	**Details**
Energy Consumption	136 kWh/m2
Building's Energy Class	E
Energy Declaration Date	2019-12-02
Energy Declaration Valid Until	2029-12-02
Energy for Heating	259,729 kWh
Tap Water	76,100 kWh
Fuels	- Heating oil: 10,000 kWh/m³ - Natural gas: 11,000 kWh/1,000 m³ (effective calorific value) - City gas: 5,880 kWh/1,000 m³ - Pellets: 4,500-5,000 kWh/ton, depending on wood type and moisture content

Total Energy for Heating, Domestic Hot Water, Comfort Cooling, and Property Electricity	358,296 kWh
Electricity	22,485 kWh
Suggestions	- Continue replacing lighting to LED. - Renovation of windows

4.3. Energy Simulation

In the following simulations, the Gothenburg weather data is used as outdoor climate conditions. The outdoor mean temperature is 7 °C, and the average wind speed is 14 km/h. Global horizontal irradiation is 1.45 kWh/m²/d.

Building energy simulation is conducted using OpenStudio at first, and BIM-Energy eventually was chosen which further elaborated upon in section 3.4.1.

Openstudio

In the modelling process of the building in Openstudio, the thickness of building components was ignored. Only their U-values were involved in the energy simulation. Also, windows which were so close to each other were merged. To simplify the process and shorten the time needed for modelling and simulation, the apartments inside floors are not modelled. In terms of thermal zone, first floor included storage, laundry, corridor, and staircase/elevator. The ninth floor is just storage. Each of the second to eighth floors includes apartments, corridors, staircase, and elevators. As a result, the building has 6 types of zones and a total of 33 zones. Consequently, there may be some differences between the model and the as-built construction. This was deemed acceptable for the purposes of this study, which compared the effects of hypothetical renovations. A building model was also created in Openstudio and applied for building energy simulations. An example of the created building model is presented in Figure 27.

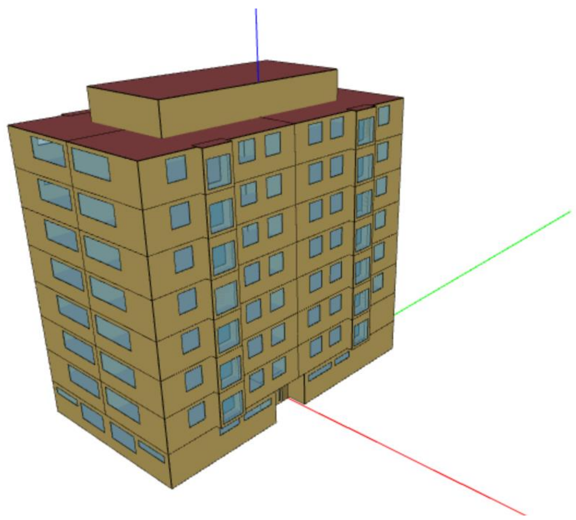

Figure 27- Blåsutgatan 8 in Openstudio

BIM-Energy

In this software, firstly, a model of the buildings based on its database were created. Then, any construction details data that was not aligned with our main sources was adjusted based on the BRF database and (Cecilia Björk, 2021). Next, each scenario was created, and their energy consumption was calculated. Materials, construction details, and U-values were utilized when the scenarios were applied. For those scenarios that included heat recovery, a ventilation system was separately designed. The results were subsequently compared with the energy consumption declared by

Energidekleration, the BRF database, and DTE, to which they were found to be reasonably close. An example of the modelled building in BIM Energy is presented in

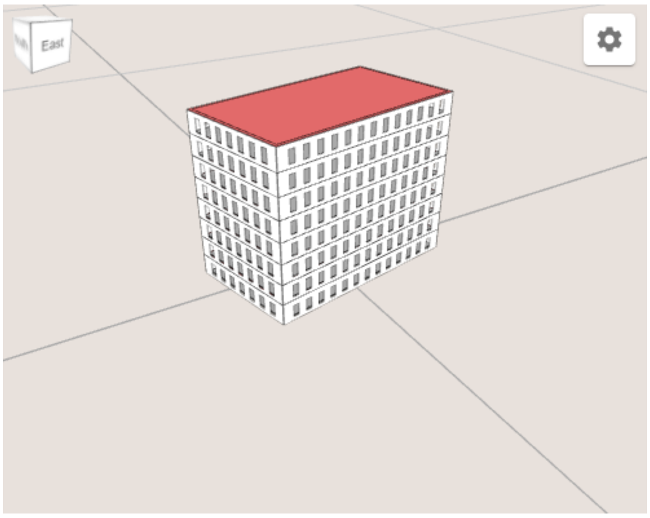

Figure 28- Blåsutgatan 8 in BIM-Energy

Preliminary simulation of the existing buildings has been undertaken. The input parameters utilised in the base case are detailed in Table 10.

Table 10- Parameters used for the energy simulation of the existing state of Blåsutgatan 8.

Inputs	**Unit**		**Reference**
U-value of window	2.9	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
U-value of wall	0.34	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
U-value of roof	0.23	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
Infiltration rate	1	L/s·m²	(Bankvall, 2013)
Window to wall ratio	0.38	-	(Cecilia Björk, 2021), BIM-Energy software
Occupant density	28	m²/person	(BEN 2 BFS, 2017:6)
Equipment power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Lighting power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Heating setpoint temperature	21.5	°C	-
Heating setback temperature	18	°C	-
Ventilation flow	0.35	l/s.m²	(BBR, 2018:4)
Heat recovery	0	-	
Solar absorption	50	%	BIM-Energy software

Table 11- Parameters used for the energy simulation of the existing state of Byalagsgatan 8

Inputs	**Unit**		**Reference**
U-value of window	2.9	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
U-value of wall	0.34	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
U-value of roof	0.23	W/m²K	(Cecilia Björk, 2021), BIM-Energy software
Infiltration rate	1	L/s·m²	(Bankvall, 2013)
Window to wall ratio	0.26	-	(Cecilia Björk, 2021), BIM-Energy software
Occupant density	28	m²/person	(BEN 2 BFS, 2017:6)
Equipment power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Lighting power density	5	Wh/m²	(BEN 2 BFS, 2017:6)
Heating setpoint temperature	21.5	°C	-
Heating setback temperature	18	°C	-
Ventilation flow	0.35	L/ m²·s	(BBR, 2018:4)
Heat recovery	0	-	
Solar absorption	50	%	BIM-Energy software

Several input parameters were modified after adding walls' insulation, replacement of windows, improving roof's insulation, and adding heat recovery to ventilation system. The U-value of the external walls and roof decreased due to the increased thickness of the insulation material, while the U-value of the windows decreased following their replacement. Additionally, those three renovation measures are expected to lower the infiltration rate of the buildings. Detailed information regarding the altered input parameters can be referenced in Table 12.

Table 12-The altered input parameters at Blåsutgatan 8

Input						Unit
Added EPS	0	100	120	150	200	mm
U-Value of wall	0.34	0.14	0.12	0.1	0.08	W/m²K
Infiltration rate	1	0.5	0.5	0.5	0.5	l/s.m²
Windows	Old		New			
U-Value	2.9		0.8			W/m²K
Infiltration rate	1		0.5			l/s.m²
Roof	Old		New			
U-Value	0.23		0.07			W/m²K
Infiltration rate	1		0.5			l/s.m²

Table 13- The altered input parameters at Byalagsgatan 8

Input						Unit
Added EPS	0	100	120	150	200	mm
U-Value of wall	0.39	0.177	0.16	0.14	0.11	W/m²K
Infiltration rate	1	0.5	0.5	0.5	0.5	l/s.m²
Windows	Old		New			
U-Value	2.9		0.8			W/m²K
Infiltration rate	1		0.5			l/s.m²
Roof	Old		New			
U-Value	0.46		0.09			W/m²K
Infiltration rate	1		0.5			l/s.m²

Table 14-The altered input parameters of mounting Smart1

Input		Unit
Specific fan power	0.45	W/l/s
Heat recovery	85	%

The recorded outputs used to quantify each simulation included: annual heating demand (kWh/m²/y), heating peak load (W/m²), and annual electricity demand (kWh/m²/y).

4.4. Renovation Strategies

Through literature review different energy efficient renovation strategies were reviewed. Among which five distinct renovation measures which were more effective and are applicable were selected to be applied for our case studies. The specifics of each are elucidated below.

4.4.1. Improving Exterior walls

It was assumed that extra insulation materials will be installed on the external surfaces of the buildings' exterior concrete walls. Due to the inadequate airtightness of the buildings, it is necessary to construct a vapour barrier at the same time as the installation of insulation materials. Ultimately, facade of the building will be redecorated with mortar and a finishing layer.

The proposed insulation material is EPS, which has a thermal conductivity of 0.037 W/m/K (Laven and Strandberg, 2019). Due to its rigidity and lightweight nature, Expanded Polystyrene (EPS) can be easily and quickly installed. EPS has low embodied energy and can be recycled when the building is supposed to be demolished. Four distinct thicknesses of insulation materials were evaluated for potential installation on the exterior walls. Mortar's thermal conductivity is 1.65 W/m/K. Thinness of the mortar is assumed to be 8 mm. Their information came from Wikells sektionsdata.

Table 15 displays the U-values and total thicknesses. The depicted new constructions are illustrated in Figure 29 below.

Table 15- Details of the external concrete walls after various EPS thicknesses were added (Laven and Strandberg, 2019).

Building Name	**Added EPS thickness**	**0**	**100**	**120**	**150**	**200**	**mm**
Blåsutgatan 8	U-value	0.34	0.14	0.12	0.1	0.08	W/m²K
	Wall thickness	350	458	478	508	558	mm
Byalagsgatan 8	U-value	0.39	0.177	0.16	0.14	0.11	W/m²K
	Wall thickness	265	373	393	423	473	Mm

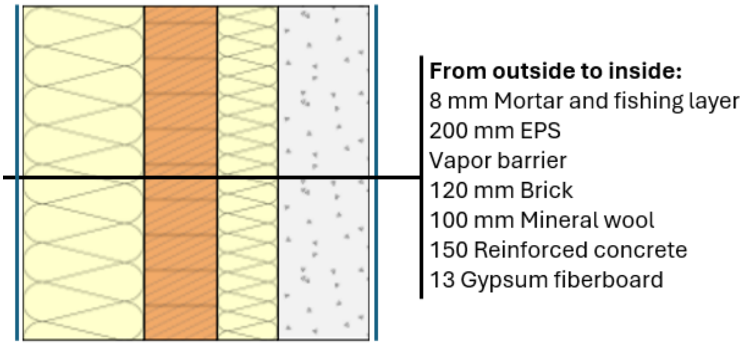

Figure 29- Details of proposed exterior concrete wall at Blåsutgatan 8.

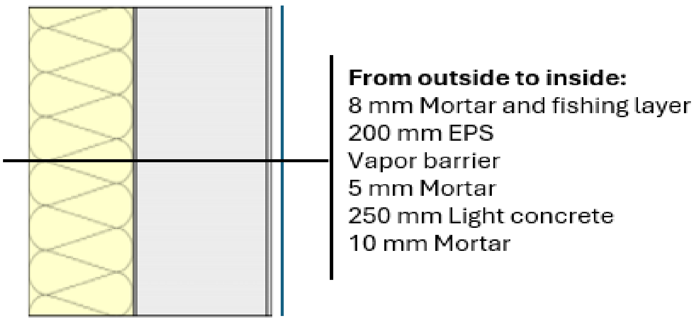

Figure 30- Details of proposed exterior concrete wall at Byalagsgatan 8.

4.4.2. Improving Windows

Windows, like other solid parts of a building's structure, transmit heat through conduction and convection, as well as radiation.

Advanced windows have triple glazing with Low-E coating and are filled with argon gas in the gap between the panes. The window frame is made of PVC (polyvinyl chloride), featuring a thermally efficient design that minimises heat transfer and provides excellent insulation. The overall U-value of the window is 0.8 W/m²K based on Wikells Sektionsdata 2023.10 and BIM-Energy software. Furthermore, it is important to ensure the airtightness of the window by employing seals during the installation of new windows. Details of these windows is shown in Figure 31.

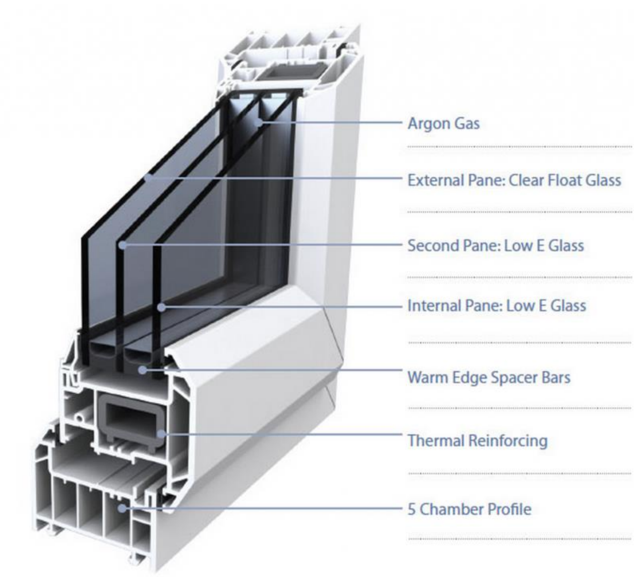

Figure 31- Details of PVC windows.

4.4.3. Improving the roof

In this measurement, there are two different strategies. The initial approach is tailored specifically for renovation projects, involving the addition of insulation to existing roofs. Similar to exterior walls, the recommended type of insulation for this purpose is EPS. The process of determining the best thickness and other relevant considerations mirrors that of exterior walls. Figure 32 displays the construction details of proposed renovated roof.

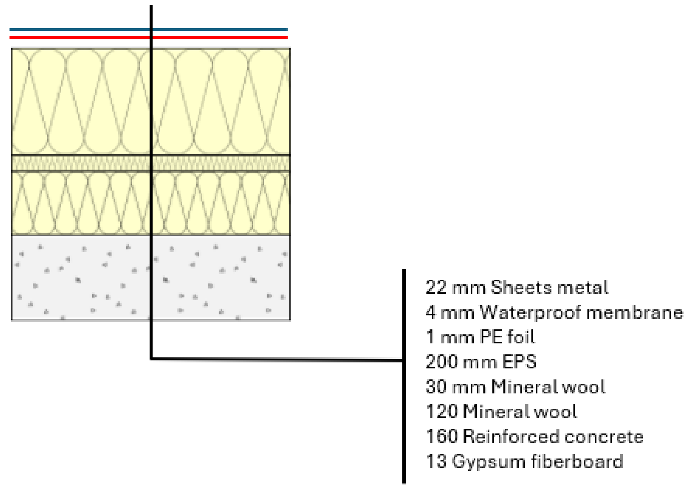

Figure 32- Proposed renovated roof details.

Concerning added floor scenario to the existing building, the new ceiling and roof of the building should be designed and constructed. Therefore, for a more realistic investigation, it was considered that the storage located on top of the building would be removed, then two floors will be added with new construction details extracted from Wikells.

The construction details for the ceiling of the top floor are displayed in Figure 33 and the new roof are illustrated in Figure 34. The U-value of the roof is 0.07 W/m²K. The ceiling components, from the exterior to the interior, consist of layers of stone wool, wooden panel, a vapor barrier, and gypsum.

As for the roof components, they include concrete tiles, counter battens, battens, asphalted cardboard, panels, and trusses set at a 27-degree angle.

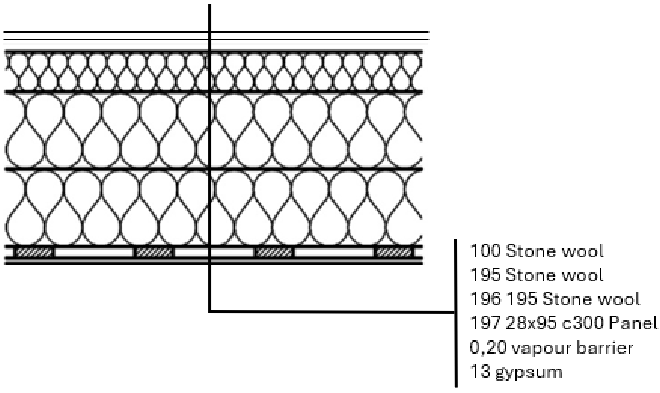

Figure 33- Construction details the top floor's ceiling.

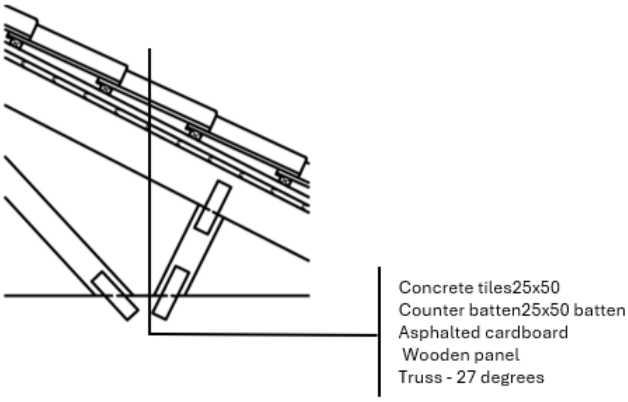

Figure 34- Construction details the new roof.

They provide thermal insulation and minimise heat transfer between a building's interior and exterior, which leads to energy conservation by ensuring stable indoor temperatures and reducing the workload on heating and cooling systems. The U value varies for stone wool insulated roof panels, depending on the stone wool thickness. As a finishing layer installing PV panels to absorb sunlight and meet the building's energy demands is recommended which will be discussed further. Also, the finishing layer of the roof can be slightly inclined towards the south to absorb the maximum amount of sunlight for PV panels.

4.4.4. Improving ventilation system

According to the BRF database, the current ventilation system operates solely on exhaust, resulting in significant energy wastage. To rectify this deficiency and introduce heat recovery into the ventilation system of these buildings, we are considering the installation of Smart1 (Smartvent, 2023) units on external walls to supplement the existing airflow. In this regard, an interview was conducted with the inventor, who is also its manufacturer, to obtain more information about this device. During the interview, several key aspects of Smart1 functionality, integration, regulatory adaptability, cost analysis, component lifespan, and visual representation were discussed.

Smartvent AB is a company that specializes in ventilation systems, specifically the Smart One ventilation system. The Smart One system is designed for decentralized ventilation, which is becoming increasingly popular due to its simplicity and cost-effectiveness compared to traditional centralized systems. Figure 35 illustrates air flow and their features.

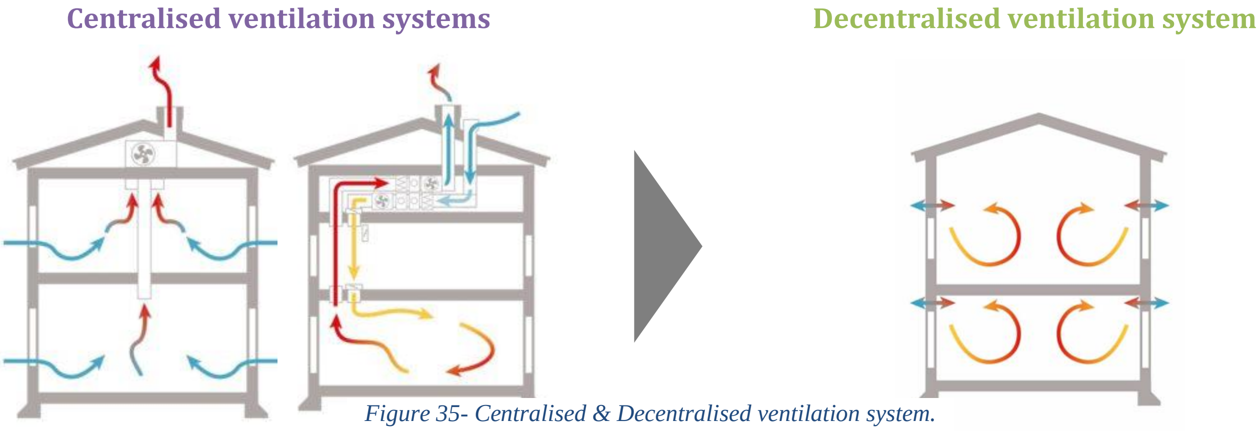

Figure 35- Centralised & Decentralised ventilation system.

The system is designed to be installed on the exterior walls of buildings and can be adjusted to meet specific ventilation requirements, such as the Swedish Ventilation Association's recommendation of 0.35 litters per second per square meter. The system is also designed to be user-friendly, with adjustable settings for airflow and temperature control.

The Smart One system is well-suited for various types of buildings, including villas, apartment buildings, and even garages, storage rooms, and small offices. It is estimated that there is potential for over 10 million Smart1 units in the Swedish market alone, as many buildings lack adequate ventilation systems or have outdated ones. Specifically, including 1.5 million multi-family houses in Sweden, which means there is a demand for 4.5 million Smart1 units.

The Smart One system is designed to be energy-efficient and can help reduce energy consumption and operating costs. Its system is also designed to be easy to install, with the potential to reduce installation costs compared to traditional systems. It can be installed in both new and existing buildings, and it is compatible with existing ventilation systems in buildings with "mörka badrum," which are bathrooms located centrally in the building and not connected to the exterior wall.

In terms of maintenance, the Smart One system is designed to be low maintenance, with static components expected to last for at least 30 years without needing replacement. It is also designed to be durable, with components expected to have a long lifespan. For example, the fans in the Smart One system have a minimum L10 life of 70,000 hours at 40 degrees Celsius, and the transformer is expected to have a lifespan of 100 years. (L10 means the time it took 10% of a random number of fans to fail).

Each unit offers a customizable airflow ranging from 6 l/s to 15 l/s, allowing for precise adjustment based on the occupancy of each apartment. Simultaneously, the Smart1 system boasts an impressive heat recovery efficiency of approximately 85%, effectively conserving energy while enhancing outdoor air supply. With a power consumption typically around 2 W and a maximum of 4 W at full capacity, the Smart1 device ensures efficient operation without excessive energy usage. Figure 36shows 3D view of its functionality and air flow in an apartment.

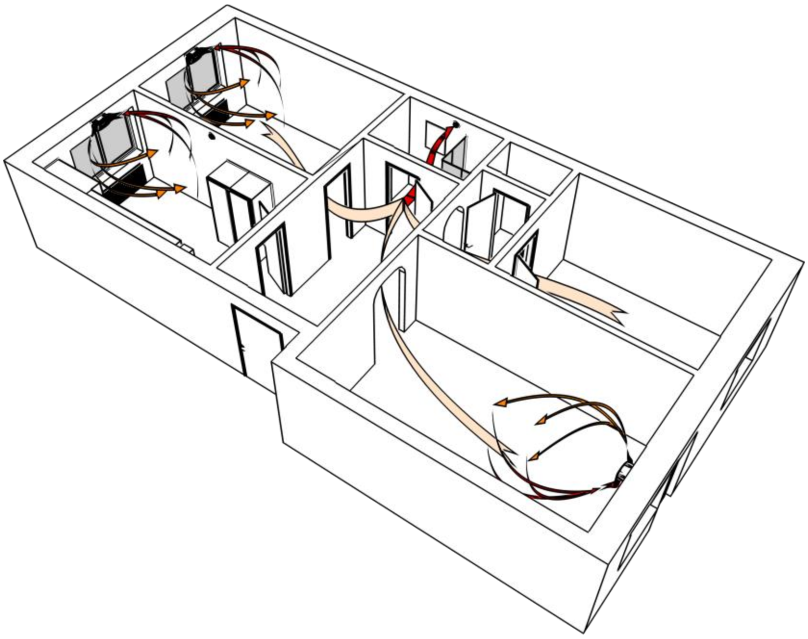

Figure 36- 3D view of functionality and airflow generated by Smart1.

For visual reference, Figure 37 displays the appearance and dimensions of a Smart1 unit. From an aesthetic standpoint, its appearance on building facades could be considered a drawback.

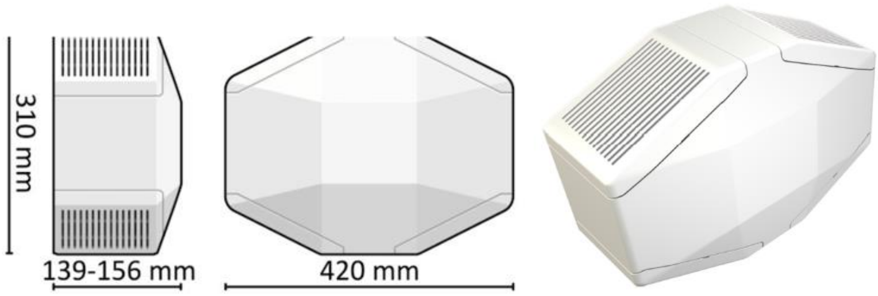

Figure 37-Smart one appearance.

In Blåsutgatan 8 where the apartments are bigger, Smart1 units will be installed in bedrooms, the kitchen, and the living room, each providing ventilation at approximately 8 l/s. These Smart1 units offer flexibility, allowing for adjustments to accommodate varying apartment sizes and occupancies. It's worth noting that the noise level emitted by the Smart1 system correlates directly with the airflow volume and is not anticipated to surpass 30 dB, rendering it relatively quiet. To provide a tangible example, the layout of the new ventilation system in a Blåsutgatan 8 and Byalagsgatan 8 apartments are visually represented in Figure 38 and Figure 39. These depictions offer insight into optimising airflow distribution throughout the living space.

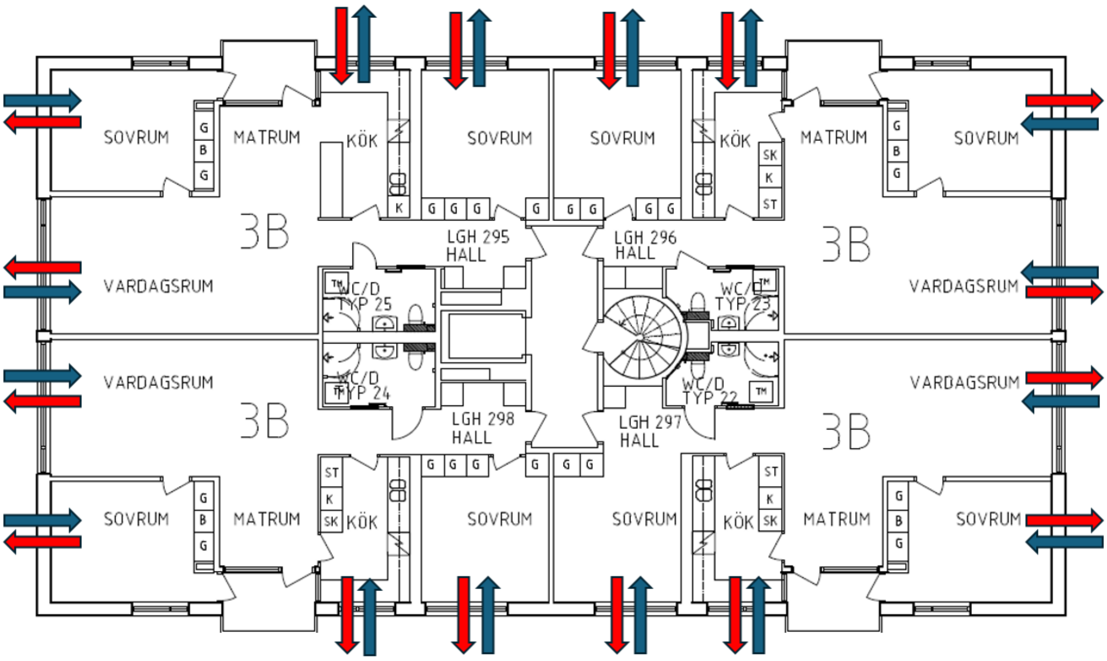

Figure 38- Smart 1 Placement at Blåsutgatan 8

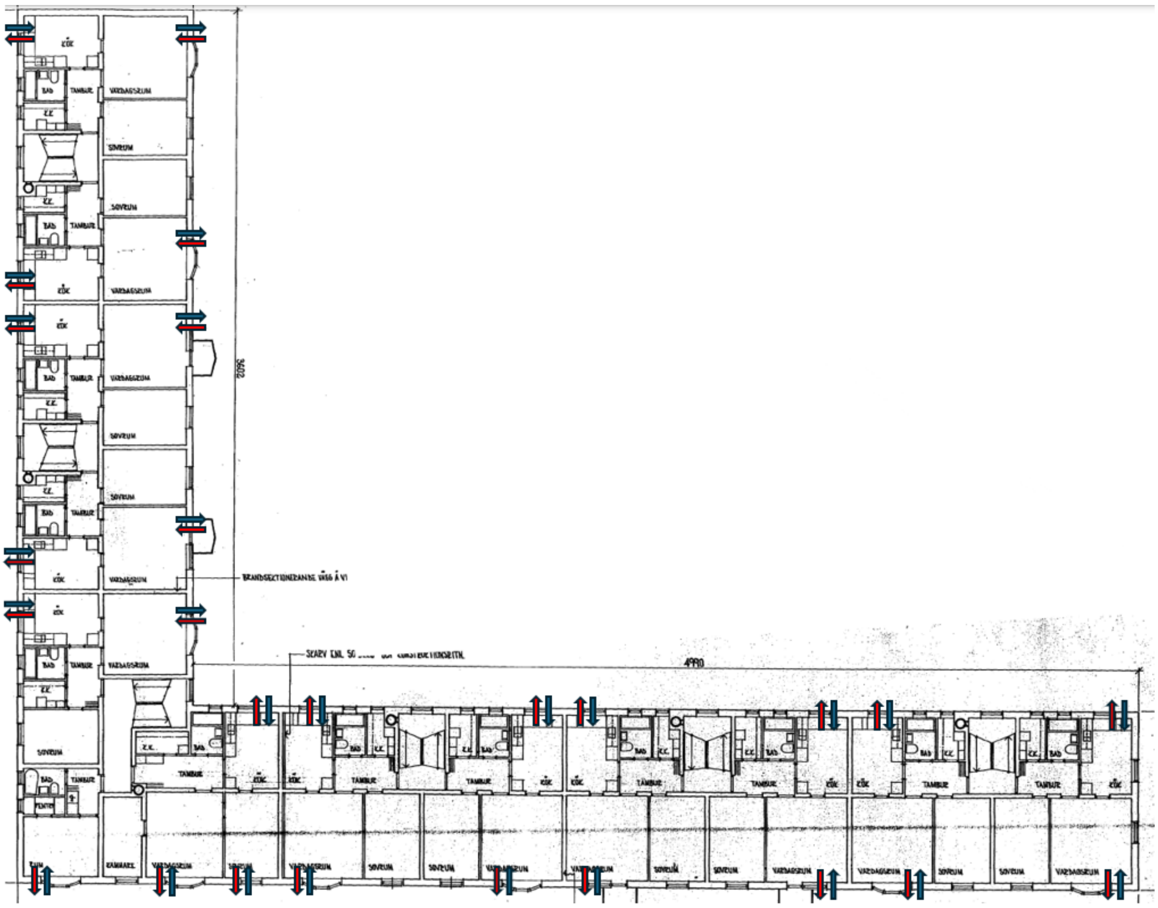

Figure 39 - Smart1 placement in Byalagsgatan 8

The apartments in this building have different types of rooms. The number of Smart1 adopted in apartments and the airflow provided is shown in Table 16 and Table 17 below.

Table 16- Smart1 number and airflow at Blåsutgatan 8

	Blåsutgatan 8 existing	**Blåsutgatan 8 added floor**	**Total**	**Unit**
Smart 1 number	112	32	144	Qt
Smart1 Airflow	112*8=896	32*8=256	1152	L/s

Table 17- Smart1 number and airflow at Byalagsgatan 8

	Byalagsgatan 8 existing	Byalagsgatan 8 added floor	Total	Unit
Smart 1 number	78	26	104	Qt
Smart1 Airflow	78*8=624	26*8=208	832	L/s

Following the renovation, Smart1 contributes a total airflow of 896 l/s. With its enhanced heat recovery capability of 85%, Smart1 significantly improves the efficiency of airflow supplied post-renovation. Notably, the overall specific fan power of the new ventilation system has been reduced from 0.6 W/l/s to 0.45 W/l/s. This reduction is attributed to the utilization of higher efficiency fans integrated into the Smart1 units. As a result, the renovated ventilation system not only delivers increased airflow but also operates with improved energy efficiency, demonstrating the positive impact of incorporating Smart1 technology.

4.4.5. Installing PV panels on the roof

Solar panels can be integrated into the roof design to generate renewable energy. In this case the area of roof is 363 m^2. Since there is no taller building beside the building, it is assumed there is no serious issue related to neighbours to cover the roof with PV panels. Afterwards, we decided to be in contact with the Enwell AB, a company in Gothenburg. The company also provided us a report containing every detail needed for ordering and installing PV panel in this project. Below is the summary of their report.

PV system is connected to the grid rather than a battery-powered system. The existing building is 15° oriented from south to east which is ideal for photovoltaic panels to absorb the maximum sunlight. Therefore, it is recommended that the PV panels are installed exactly in line with the roof. The tilt of the PV panels is 27 °, where the production is maximised in the parametric simulation. Solar panel model is DMEGC Mono All Black 535W. The most cost-effective area is determined 177 m^2. Other key details of the PV systems are listed in Table 18.

Table 18- Key Details of PV Panels

Information	**Value**
Installed peak power	36.915 kWp
Estimated annual production	27,920 kWh
System size	36.915 kWp
Installation area	177.77 sqm
Number of panels	69 pcs
Number of inverters	1 pcs
Price of complete installation	389,060 kr

They also specified guarantee period based on the different components illustrated in Table 19.

Table 19- Guarantee of different components of PV Panels.

Component	**Guarantee Period**
Mounting system	10 years
Solar cell product	12 years
Solar cell performance	25 years
Inverter	10 years

In the following they modelled the placement of solar panels on the roof of the project can be seen in Figure 40.

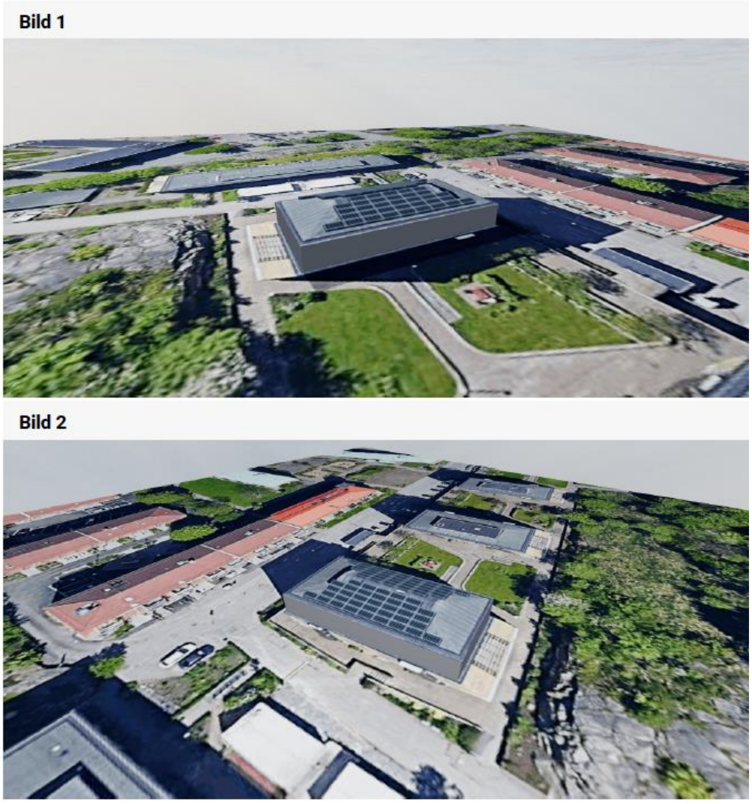

Figure 40- Replacement of solar panels on roof.

4.5. Airtightness

To ensure that the selected buildings in the case studies are not labelled as having the poorest airtightness, an infiltration rate of 1 litter per square meter per second was opted for them. This rate represents a more sensible scenario rather than an extreme one. Additionally, incorporating a vapor barrier layer into the external walls during insulation setup is projected to reduce the infiltration rate by approximately 50%, leading to an infiltration rate of 0.5 l/s.m². Employing a vapor barrier composed of PE (polyethylene) film is advised to enhance building airtightness. This type of barrier effectively addresses both airtightness and moisture movement concerns. Consequently, the airtightness for wall, windows, and roof in energy simulation assumed to be changed from 1 to 0.5 after applying mentioned considerations.

4.6. Cost Analysis of renovation components

All calculations will perform using Excel. The main database utilized for finding labour and materials prices is Wikells sektiondata 2023.

The prices for these calculations are detailed in tables in Appendix 9.1 and 9.4. Table 20 illustrates the total costs of each renovation measures for Blåsutgatan 8 and Byalagsgatan 8 respectively. Costs are in Swedish Krona.

Table 20- Cost of Renovation Measurements at Blåsutgatan 8 and Byalagsgatan 8

Renovation Measures	**Description**		**Total Cost (Blåsutgatan 8) (SEK)**	**Total Cost (Byalagsgatan 8) (SEK)**
Wall Renovation	Various items including scaffolding, surface	100mm	1,556,251	1,909,093
		120mm	1,577,392	1,935,537

	cleaning, vapor barrier, insulation, and mortar	150mm	1,740,643	2,139,741
		200mm	1,801,496	2,215,859
Changing Window	Mean cost for PVC window components		7,053	2,698,976
Roof Improvement	Adding EPS 200		120,552	314,167
Ventilation	Installation of Smart 1 ventilation system		716,800	499,200
PV Panel Investment	Installation of PV panels and related equipment		389,060	389,060

The influence on energy prices can be attributed to three main sources: the power distribution grid, the energy price negotiated with the energy company, and the energy tax determined by the government. Sweden is divided into various energy zones with varying energy costs. Gothenburg is located within zone 3 and follow regulations and energy cost in zone 3. Escalation rate for energy demand for heating is assumed 5% in calculations. Then all anticipated future costs were converted to net present value (NPV) considering 4% discount rate. Energy cost for heating and Electricity are assumed 2 Kr per kWh including production and transportation.

4.6.1. Cost Analysis of Additional Floor Components

Table 21 is depicting the total expenditures of each segment calculated for adding floors. Costs are in Swedish Krona.

The prices utilized for the calculations of the additional floor are outlined in the tables in Appendix 9.2, and 9.5 in detail. Those tables provide a breakdown of the costs associated with constructing various components.

Table 21- Total expenditures of each segment calculated for adding floors at Blåsutgatan 8 and Byalagsgatan 8.

Category	Description	Total Cost (Blåsutgatan 8) (SEK)	Total Cost (Byalagsgatan 8) (SEK)
Exterior Walls Construction	Various components including climate boards, panels, and studs	858,133	1,403,257
Interior Walls Construction	Components like OSB chipboards, gypsum boards, and studs	541,101	928,423
Intermediate Floors Construction	Components like acoustic profiles, chipboards, and beams	596,489	1,146,085
Attic Floors Construction	Components like stone wool boards, gypsum boards, and safety films	440,233	
Roof Construction	Components like timber trusses, panels, and tiles	343,344	893,853
Roof Demolition	Removal of plastic films, roofing felt, panels, and trusses	148,162	282,857
Ventilation Installation	Smart1 unit, hole drilling, and installation	204,800	166,400
Windows Installation	Various sizes of PVC windows	829,978	899,942
Doors Installation	Entrance and interior doors	328,758	482,615
Staircase Construction	Pine staircase with railing	141,282	
Toilet Construction	Components like shower walls, mirrors, and washbasins	514,525	836,095
Kitchen Construction	Components like cabinets, appliances, and countertops	1,101,724	1,790,295
All		6,048,530	8,829,822

4.7. Building elements for LCA Analysis

Here, a description is given of what is included in each of the building elements, and the reasons for the choices regarding the materials and other parts are explained. The distance was assumed to be according to what is listed in the Boverket Climate Database (2023). Also, for providers the closest provider to Sweden construction industry selected to the extent it was possible. In some cases, the weight was provided in either kilograms or tons, in other cases either the density, thickness, area and volume were provided and thus the weight could be calculated. Weight is listed in all tables as [kg], density (kg/m3), volume (m3) and distance is listed as (km). The providers have been abbreviated to RER-Rest of Europe, RoW-Rest of World, RERwA-Rest of Europe without Austria, RERwS-Rest of Europe without Switzerland and CH-Switzerland. Building elements are divided into two distinct parts including A) renovation part and B) added floor part according to these two scenarios. Blow are tables explaining details materials utilised in renovation and added floor strategies. Weight, volume, and density are in Kg, m^3, and Kg/m^3 respectively.

4.7.1. Renovation Part

Here is data regarding elements related to renovation measures.

Improving Exterior Walls

Table 22- Materials in Improved Exterior Walls at Blåsutgatan 8.

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
0,20 säkerhetsfolie	Extrusion, Plastic film	RoW	207.36	262.98	600	124.42	157.79
Insulation EPS 200mm	Polystyrene, Expandable	RoW	3916	4966.39	400	1566.4	1986.56
Grundputs (Mortar)	Light mortar	CH	5760	7305	35	201.6	255.68
Galvat nät + hakspik	Reinforcing steel	RER	460	583.39	1000	460	583.39
Finishing mortar	Cover plaster, Mineral	CH	5760	7305	35	201.6	255.68

Windows

Table 23- Materials of the Changed Windows

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
Fönster PVC 12x12 inåtg sidoh	Window frame, poly vinyl chloride	RoW	24416	7168	300	7324.8	2150.7
Glas	Glazing, double, U<1.1 W/m2K, laminated safety glass	RER					

Improving Roof

Table 24- Materials in Improved Roof.

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8

Insulation EPS 200mm	Polystyrene, Expandable	RoW	1233	3209	400	493.2	1283.6

Ventilation

Table 25- Materials in Smart1.

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
Plastic	Styrene	RER	84	58.5	350	176.4	122.85
	Acrylonitrile	RER	84	58.5			
	Butadiene	RER	84	58.5			
Ceramics	Ceramics	CH	252	175.5			

PV Panels

The data on PV Panels is consistent across both buildings.

Table 26- Material in PV Panels.

Material (Wikells)	OpenLCA Name	Provider	Weight	Distance	ton*km
DMEGC Mono All Black 535W	photovoltaic panel, single-Si wafer	GLO/ RoW/ etcetera.	1980.3	350	226.8

Materials for PV panels are a one-time consideration, unaffected by the choice between renovation or adding a new floor, as they remain constant in either scenario.

4.7.2. Added Floor Part

Here is data regarding additional floors elements.

Ceilings

Table 27- Materials in the added floors' ceilings at Blåsutgatan 8.

Ceiling	Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
Intermediate floor (8th ceiling)	22 spånskiva	Particle board, uncoated	RoW	5662.80	7.99	709.09	600	3397.68
	45x220 bjälkar C24 c 600	sawn wood, beam, softwood, raw, dried (u=20%)	CH	3882.29	8.27	469.70	500	1941.145
	45 stenullsskiva-36	Stone Wool	CH	475.53	16.34	29.11	400	190.212
	13 gipsskiva (B=900)	Gypsum plasterboard	CH	2432.00	4.72	515.36	250	608
	0,20 säkerhetsfolie	Extrusion, Plastic film	RoW	54.45	0.07	750.0	600	32.67
	Krysskolvning	sawn wood, board, softwood, raw, dried (u=20%)	CH	166.98	-	-	500	83.49
	Riktning golvbjälkar	sawn wood, board, softwood, raw, dried (u=20%)	CH	-	141.5	-	500	-
Attic floor (9th floor)	195 stenullsskiva-36	Stone Wool	CH	4109.16	7	29.03	400	1643.664
	100 stenullsmatta-37	Stone Wool	CH	1016.40	36.30	28.00	400	406.56
	13 gipsskiva lättvikt (B=900)	Gypsum plasterboard	CH	2432.10	4.72	515.38	250	608.025
	28x95 glespanel c 300	sawn wood, board, softwood, raw, dried (u=20%)	CH	1633.50	3.48	469.92	500	816.75

	0,20 säkerhetsfolie	Extrusion, Plastic film	RoW	54.45	0.07	750	600	32.67

Gypsum plasterboard, known as gypsum board or drywall, is a common material used in the construction of buildings for ceilings and walls.

From an LCA perspective, fibreboard and particle board share several similarities, including:

Raw material source: Both fibreboard and particle board are made from wood particles or fibres that are typically sourced from the waste products of sawmills and other wood-processing operations. This means that they are considered to be environmentally friendly materials.

Manufacturing process: The manufacturing processes for both fibreboard and particle board are similar, with both materials being produced through a process of compressing and bonding wood particles or fibres together using adhesives.

Transportation: Both fibreboard and particle board are typically produced in large quantities in centralized manufacturing facilities and transported to their end-use locations, which means that transportation impacts can be similar for both materials.

End-of-life disposal: Both fibreboard and particle board are biodegradable and can be recycled or composted at the end of their useful life. This means that they have similar end-of-life impacts in terms of waste management.

Table 28- Materials in the added floors' ceilings at Byalagsgatan 8.

Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
195 stenullsskiva-36	Stone Wool	CH	10697.4	959.4483471	11.15	400	10.6974
100 stenullsmatta-37	Stone Wool	CH	2646	246.0123967	10.76	400	2.646
13 gipsskiva lättvikt (B=900)	Gypsum plasterboard	CH	6331.5	31.98161157	197.97	250	6.3315
28x95 glespanel c 300	sawn wood, board, softwood, raw, dried (u=20%)	CH	4252.5	9.04932	469.92	500	4.2525
0,20 säkerhetsfolie	Extrusion, Plastic film	RoW	141.75	0.492024793	288.10	600	0.14175

Staircase

Table 29-Materials in the staircases.

Buildings	Staircase	Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
Blåsutgatan 8	Stairs	Trappa av furu med integrerat vilplan	Sawn wood, Parana pine, dried (u=10%)	RoW	400	0.8514	469.81	500	200
Byalagsgatan 8					200	0.4257	469.81		100
Blåsutgatan 8	Banister	Inv träräcke med fyllning av furu			500	1.065	469.48		250
Byalagsgatan 8					250	0.5325	469.48		125

Roof

Table 30- Materials in roof

Buildings	Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
Blåsutgatan 8	Prefab träfackverk - 27 grader	Sawn wood, board, softwood, raw, dried (u=20%)	RER	3230.70	-	-	600	1615.35
Byalagsgatan 8				8410.5	-	-		4205.25
Blåsutgatan 8	23 råspontad panel	Planks	RoW	3753.42	8.35	449.57	600	2252.05
Byalagsgatan 8				9771.3	56.59	172.69		5862.78
Blåsutgatan 8	Betongtakpannor, ytbeh, svarta	Concrete Roof Tile	RoW	12276.66	-	-	35	429.68
Byalagsgatan 8				31959.9	-	-		1118.6
Blåsutgatan 8	Underlagspapp YAP 2200	Roofing felt, single layer, (Bitumen seal) 1410 kg/m3	RERwS	798.60	-	-	500	319.44
Byalagsgatan 8				2079	-	-		831.6
Blåsutgatan 8	25x50 bärläkt	Sawn wood, beam, softwood, raw, dried (u=20%)	RER	631.62	1.36	464	400	315.81
Byalagsgatan 8				1644.3	3.54	464		822.15
Blåsutgatan 8	25x50 ströläkt	Sawn wood, beam, softwood, raw, dried (u=20%)	CH	421.08	0.91	464	400	210.54
Byalagsgatan 8				1096.2	2.36	464		548.1

Plastic film, vapor barriers, and extruded plastic films have similar impacts throughout their life cycle, including impacts related to raw materials, manufacturing, installation, and end-of-life disposal. Bitumen seal or roofing felt is a type of waterproofing membrane that is commonly used in the construction of buildings as a protective layer between the roof deck and the roofing material. It is typically made from asphalt-saturated felt, which is coated with a layer of bitumen or tar for added durability and waterproofing.

Added Floors' Exterior Walls

Table 31- Materials of added Floors' Exterior Walls

Buildings	Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
Blåsutgatan 8	70 våningshög klimatskiva-33	Stone Wool	CH	1460.20	20.86	70	400	584.08
Byalagsgatan 8				2387.77	55.78	42.81		955.11
Blåsutgatan 8	22 profilspontad	Planks	CH	2950.20	6.56	450	600	1770.12

Byalagsgatan 8	panel grundmålad			4824.27	17.53	275.19		2894.56
Blåsutgatan 8	195 stenullsskiva-36	Stone Wool	CH	1686.68	58.11	29	400	674.672
Byalagsgatan 8				2758.12	155.39	17.75		1103.25
Blåsutgatan 8	45x195 reglar C24 c 600	Sawn wood, beam, softwood, raw, dried (u=20%)	RoW	4297.16	9.15	469.52	500	2148.58
Byalagsgatan 8				7024.60	14.96	469.52		3512.3
Blåsutgatan 8	145 stenullsskiva-36	Stone Wool	CH	1254.58	43.21	29.03	400	501.832
Byalagsgatan 8				2051.53	115.54	17.76		820.61
Blåsutgatan 8	70 stenullsskiva-36 (B=410)	Stone Wool	CH	604.94	20.86	29	400	241.976
Byalagsgatan 8		Sawn wood, beam, softwood, raw, dried (u=20%)		989.22	55.78	17.73		395.69
Blåsutgatan 8	45x70 reglar c 450		CH	1543.64	3.29	469.84	500	771.82
Byalagsgatan 8				2523.40	5.37	469.84		1261.7
Blåsutgatan 8	13 gipsskiva (B=900)	Gypsum plasterboard	CH	1996.00	3.87	515.23	250	499
Byalagsgatan 8				3263.93	10.36	315.08		815.99
Blåsutgatan 8	34x70 läkt c 600	Sawn wood, beam, softwood, raw, dried (u=20%)	CH	1197.96	2.13	563.3	500	598.98
Byalagsgatan 8				1957.74	3.48	563.03		978.87
Blåsutgatan 8	0,20 plastfolie inkl tejp	Extrusion, Plastic film	RoW	53.64	0.06	900	600	32.184
Byalagsgatan 8				87.71	0.16	550.38		52.63

Added Floors’ Interior Walls

Table 32- Materials of added Floors’ Interior Walls

Buildings	Material (Wikells)	OpenLCA Name	Provider	Weight	Volume	Density	Distance	ton*km
Blåsutgatan 8	11 OSB-spånskiva (B=900)	Particle board, uncoated	CH	1460.20	8.21	636.36	600	3133.2
Byalagsgatan 8				8960	14.08	636.36		5376
Blåsutgatan 8	13 gipsskiva (B=900)	Gypsum plasterboard	CH	2950.20	9.70	515.36	250	1249.5
Byalagsgatan 8				8575.66	28.55	300.36		2143.91
Blåsutgatan 8	45x70 reglar c 450	Sawn wood, beam, softwood, raw, dried (u=20%)	CH	1686.68	4.70	469.84	500	1104.08
Byalagsgatan 8				3788.8	8.064	469.84		1894.4

Blåsutgatan 8	45 stenullsskiva-36 (B=410)	Stone Wool	CH	4297.16	16.79	29.11	400	195.452
Byalagsgatan 8				838.4	49.42	16.97		335.36
Blåsutgatan 8	GPD 70/100 polyetenduk	Fleece, Polyethylene	-					
Byalagsgatan 8								

In this part due to lack of data regarding Fleece, Polyethylene we could not find the distance, consequently it was removed from our calculations.

Windows

Table 33- Materials of the Windows

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
Fönster PVC 12x12 inåtg sidoh	Window frame, poly vinyl chloride	RoW	6272	7168	300	1881.6	2150.7
Glas	Glazing, double, U<1.1 W/m2K, laminated safety glass	RER					

At first, the windows were separated into two parts which are glass and frame. Glazing triple, laminated safety glass was selected since it is the most popular glass used by contractors currently. Also, the selected item in OpenLCA contains PVC as well. The windows are assumed to have a frame-factor of 80/20, meaning 80% of the window's total area is transparent glass, the remaining 20% is window frame material.

Doors

Table 34- Materials of the Doors

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
Innerdörr 9x21 allmoge, lackad	Door, inner, Wood	RoW	1302	1634.57	500	651	817.29
Entredörr Klimatdörr 9x21 målad	Door, inner, Wood	RoW	463.23	752.75		231.61	376.37

Ventilation

Table 35- Materials in Smart1 for added floor.

Material (Wikells)	OpenLCA Name	Provider	Weight		Distance	ton*km	
			Blåsutgatan 8	Byalagsgatan 8		Blåsutgatan 8	Byalagsgatan 8
Plastic	Styrene	RER	24	19.5	350	50.4	225
	Acrylonitrile	RER	24	19.5			
	Butadiene	RER	24	19.5			
Ceramics	Ceramics	CH	72	58.5			

5. Results

The results include key findings from the literature review, energy demand simulations, LCC, and LCA calculation outcomes for all 31 different renovation scenarios across various lifespans. The goal was to identify the best scenario, which will be integrated with the concept of adding floor(s). The LCC and LCA results will be described in detail.

5.1. Literature review key findings

The literature review highlights that Sweden's residential sector is a significant contributor to the country's total energy consumption, with a notable portion attributed to heating and domestic hot water requirements. This sector faces substantial renovation needs, as an estimated 75% of homes require updates before 2050 to align with EU regulations and climate objectives. Barriers such as high initial costs, reduced tax incentives, and lack of information hinder the implementation of energy-efficient improvements. The review also emphasises the importance of LCA in renovations, especially as buildings approach nearly-zero energy or carbon emissions. Multi-family houses, which make up a substantial portion of the residential stock, present considerable opportunities for energy savings through renovation, particularly those built during the "Million Program" era. Adding floors during renovations emerges as a strategic approach to increase property value, rental income, and building efficiency while potentially reducing the carbon footprint. The literature underscores the need for objective assessment methods in planning renovations and the potential of insulation and PV panels to improve energy performance. Financially, renovations can enhance property value, increase rental income, and improve marketability, although the landlord-tenant dilemma may affect incentive mechanisms for energy-saving measures. The results section should synthesise these findings to inform the selection of case studies and the development of renovation strategies that align with Sweden's sustainability goals and the financial interests of stakeholders. The subsequent phases of the thesis will involve results regarding detailed simulation and data analysis of the selected case studies to further elucidate the impacts and benefits of renovation strategies.

5.2. Energy demand simulation

5.2.1. Primary condition

The energy demand simulations for Blåsutgatan 8 and Byalagsgatan 8, obtained from BIM-Energy, are presented in Table 36. The results are compared with reports provided by the property owner (BRF Blåsutgatan) and the consulting company (Sweco), as well as with energy declarations from Boverket and Digital Twins Gothenburg.

Table 36- Simulation result comparison, 2018

Building	Parameters	BIM Energy/ OpenLCA	Energy declaration	BRF/SWECO	DTE	Unit
Blåsutgatan 8	Primary Energy	386 804	372 132	-	289963	kWh
Byalagsgatan 8		425 513	432 411	-	427 117	
Blåsutgatan 8	Heat Demand	302 033	284 740	287 888.6	243366.9	
Byalagsgatan 8		328 602	333 844	338 400	416 207	
Blåsutgatan 8	Domestic hot water	70 175	70 176	-	-	
Byalagsgatan 8		80 225	76 082			
Blåsutgatan 8	Facility Electricity	14 596	17 216	-	-	
Byalagsgatan 8		16 686	22 485			
Blåsutgatan 8	CO_2-eq	7.3	-	-	6.3	kg/m2
Byalagsgatan 8		7.1			8.4	

The difference between BIM-Energy in the simulation and databases results is within the acceptable range. The subsequent analyses were based on BIM-Energy simulation results.

5.2.2. Applied Renovation Scenarios

5.2.2.1. Improving Wall

Enhancing the building's insulation by retrofitting additional EPS to the walls, along with improving envelope airtightness from 1 to 0.5 l/s.m², can notably decrease the demand for space heating. Table 37 shows a comparison of EPS performance based on thickness at Blåsutgatan 8 and Byalagsgatan 8.

Table 37- EPS performance based on thickness at Blåsutgatan 8 and Byalagsgatan 8.

Building Name	Added EPS thickness	0	100	120	150	200	mm
Blåsutgatan 8	U-value	0.34	0.14	0.12	0.1	0.08	W/m²K
	Wall thickness	350	458	478	508	558	mm
	Energy Demand	137.8	117.3	116.3	115.2	114.3	kWh/m²
	Saved Energy annually	0	57543.5	60350.5	63438.2	65964.5	kWh
Byalagsgatan 8	U-value	0.39	0.177	0.16	0.14	0.11	W/m²K
	Wall thickness	265	373	393	423	473	mm
	Energy Demand	132.6	118.2	117.4	116.6	115.6	kWh/m²
	Saved Energy annually	0	46209.6	48776.8	51344	54553	kWh

The data presented in the table above suggests that enhancing the airtightness of the walls and incorporating EPS with thicknesses of 100, 120, 150, and 200 can lead to significant reductions in the building's energy demand. Specifically, the energy demand can be decreased by 14.88%, 15.60%, 16.40%, and 17.05% respectively for each corresponding thickness of EPS in Blåsutgatan 8 and 10.86%, 11.46%, 12.07%, 12.82% in Byalagsgatan 8.

5.2.2.2. Changing Windows

The replacement of older, less efficient windows with new, advanced triple-glazed windows has demonstrated a notable decrease in the building's heating demand. This improvement is evidenced by the enhancement of window airtightness, which has reduced from 1 to 0.5 l/s.m². Further details are provided in Table 38.

Table 38- Windows performance at Blåsutgatan 8 and Byalagsgatan 8

Building Name	Items	Old Windows	New Windows	Unit
Blåsutgatan 8	U-value	2.9	0.8	W/m²K
	Heating demand	137.8	96.7	kWh/m²
	Saved Energy annually	0	115367.7	kWh
Byalagsgatan 8	U-value	2.9	0.8	W/m²K
	Heating demand	132.6	107.4	kWh/m²
	Saved Energy annually	0	80866.8	kWh

By changing windows, the energy demand of the building will be declined 29.8% and 19% in Blåsutgatan 8 and Byalagsgatan 8, respectively.

5.2.2.3. Improving Roof

By adding 200mm EPS to the existing roof and enhance its airtightness from 1 to 0.5 l/s.m² the reduction of energy demand can be witnessed. Table 39 shows further details.

Table 39- Roof performance at Blåsutgatan 8 and Byalagsgatan 8.

Building Name	Roof Area	Items	Existing Roof	Renovated Roof	Unit
Blåsutgatan 8	362 m²	U-value	0.23	0.07	W/m²K
		Heating demand	137.8	134.9	kWh/m²

		Saved Energy annually	0	8140.3	kWh
Byalagsgatan 8	945 m^2	U-value	0.23	0.07	W/m²K
		Heating demand	132.6	120.5	kWh/m^2
		Saved Energy annually	0	38828.9	kWh

The notable fact can be realised through the table above is the impact of roof area on the amount of decrease in energy demand. Blåsutgatan 8 is a vertical building, hence the effect of the ratio of the roof to the height of the building is less than Byalagsgatan 8. As a result, the effect of the improving roof is less noticeable in Blåsutgatan 8. Improving roof reduced energy demand in Blåsutgatan 8 and Byalagsgatan 8, 2.1% and 9.13% respectively.

5.2.2.1. Ventilation

New ventilation system can recover 85% of heating by installing Smart1. Enhance the envelope of buildings make the Smart1 more effective. Table 40 explains more details in this regard.

Table 40- Ventilation performance at Blåsutgatan 8 and Byalagsgatan 8.

Building Name	Items	Existing Ventilation	Smart1	Unit
Blåsutgatan 8 (Exhaust)	Heat recovery	0	85	%
	Heating demand	137.8	107.1	kWh/m2
	Saved Energy annually	0	86174.9	kWh
Byalagsgatan 8 (Natural)	Heat recovery	0	85	%
	Heating demand	132.6	120.1	kWh/m2
	Saved Energy annually	0	40112.5	kWh

Consequently, by recover the 85% of heated air, heating demand will be deducted by approximately 22.3% in Blåsutgatan 8 and 9.43% in Byalagsgatan 8.

5.2.2.2. Installing PV Panels

By mounting PV Panel not only the whole electricity of the buildings will be covered, but also the rest of electricity can be used to meet electricity needed for Smart1 fan and even part of heating demand of the residential buildings. Table 41 depicts PV Panels performance.

Table 41- PV Panel performance at Blåsutgatan 8 and Byalagsgatan 8.

Building Name	PV Panel Area	Primary electricity demand	Produce Energy annually	Unit
Blåsutgatan 8	178 m^2	17216	28000	kWh
Byalagsgatan 8	178 m^2	22 485	28000	kWh

A noteworthy observation is that 38.5% of the electricity generated in Blåsutgatan 8 and a 19.7% of the electricity generated in Byalagsgatan 8, exceeds consumption needs. This surplus energy presents an opportunity to fulfil additional energy demands within the respective buildings, contributing to greater efficiency.

5.2.2.3. Combinational Scenarios

As previously noted, a total of 31 distinct renovation scenarios have been examined. Table 42 outlines the specific details of each scenario for Blåsutgatan 8 and Byalagsgatan 8, including the components involved, the resulting changes in energy demand, and the potential energy savings achievable through their implementation. It's important to note that scenarios involving PV panels should take into account the additional electricity production of 28000 kWh. Units are in kWh/m^2.

Table 42- Renovation Scenarios Performance at Blåsutgatan 8 and Byalagsgatan 8.

Scenarios	Renovation Measures	Energy Demand		Energy Saved	
		Blåsutgatan 8	Byalagsgatan 8	Blåsutgatan 8	Byalagsgatan 8
0	Nothing	137.8	132.6	0	0

1a	100mm EPS	117.3	118.2	20.5	14.4
1b	120mm EPS	116.3	117.4	21.5	15.2
1c	150mm EPS	115.2	116.6	22.6	16
1d	200mm EPS	114.3	115.6	23.5	17
2	Change windows PVC	96.7	107.4	41.1	25.2
3	Improving roof	134.9	120.5	2.9	12.1
4	Ventilation	107.1	120.1	30.7	12.5
5	PV panels	137.8	132.6	0	0
6	Improving wall + Change windows	76.6	90.4	61.2	42.2
7	Improving wall + Improving roof	111.8	103.2	26	29.4
8	Improving wall + Ventilation	87.4	102.6	50.4	30
9	Improving wall + PV panels	114.3	115.6	23.5	17
10	Change windows + Improving roof	95	94.5	42.8	38.1
11	Change windows + Ventilation	67.4	94.8	70.4	37.8
12	Change windows + PV panels	96.7	107.4	41.1	25.2
13	Improving roof + Ventilation	104.2	107.2	33.6	25.4
14	Improving roof + PV panels	134.9	120.5	2.9	12.1
15	Ventilation + PV panels	107.1	120.1	30.7	12.5
16	Improving wall + Change windows + Improving roof	74.4	77.2	63.4	55.4
17	Improving wall + Change windows + Ventilation	48.2	77.4	89.6	55.2
18	Improving wall + Change windows + PV panels	76.6	90.4	61.2	42.2
19	Improving wall + Improving roof + Ventilation	85.2	89.3	52.6	43.3
20	Improving wall + Improving roof + PV panels	111.8	103.2	26	29.4
21	Improving wall + Ventilation + PV panels	87.4	102.6	50.4	30
22	Change windows + Improving roof + Ventilation	67.4	82	70.4	50.6
23	Change windows + Improving roof + PV panels	95	94.5	42.8	38.1
24	Change windows + Ventilation + PV panels	69.3	94.8	68.5	37.8
25	Improving roof + Ventilation + PV panels	104.2	107.2	33.6	25.4
26	Improving wall + Change windows + Improving roof + Ventilation	45.6	64.3	92.2	68.3
27	Improving wall + Change windows + Improving roof + PV panels	74.4	77.2	63.4	55.4
28	Change windows + Improving roof + Ventilation + PV panels	67.4	82	70.4	50.6
29	Improving wall + PV panels + Improving roof + Ventilation	85.2	89.3	52.6	43.3
30	Improving wall + Change windows + Ventilation + PV panels	48.2	77.4	89.6	55.2
31	All	45.6	64.3	92.2	68.3

Upon analysing Table 42, Scenario 31 emerges as the most energy-efficient option, incorporating a comprehensive suite of measures. Notably, while Scenario 26 and Scenario 31 exhibit similar levels of energy demand, Scenario 31 offers additional benefits, including the generation of 28,000 kWh from photovoltaic (PV) panels. Specifically, Scenario 31 achieves an energy demand of merely 45.6 kWh/m² or almost 128000 kWh in Blåsutgatan 8, and 64.3 kWh/m² or 206339 kWh for Byalagsgatan 8, with 25 kWh/m² attributed to hot water usage. This implies that for space heating, only 20.6 kWh/m² is required, resulting in a substantial saving of 92.2 kWh/m² for Blåsutgatan 8. Similarly, space heating for Byalagsgatan 8 will be 39.3 kWh/m² and energy saved will be 68.3 kWh/m². In practical terms, this equates to a nearly 67%, and 51.5% reduction in total energy demand for Blåsutgatan 8 and Byalagsgatan 8, marking a significant achievement in energy savings.

Following closely, in Blåsutgatan 8 Scenario 30 is identified as the second most efficient scenario, offering an annual energy saving of 89.6 kWh/m². This translates to an approximate 65% reduction in the demand for energy. The only difference between Scenario 30 and the top-performing Scenario 31 is the exclusion of roof improvements in Scenario 30. The data reveals that the impact of enhancing the roof is less significant compared to other measures, a point further elaborated in Section 5.2.2.3. Nevertheless, at Byalagsgatan 8, the impact of improving the roof is notable, making Scenario 27 the second-ranked scenario by reducing energy demand by 55.4 kWh/m² or 41.8%.

Ranking third, Scenario 28 and Scenario 30 are located at Blåsutgatan 8 and Byalagsgatan 8. These scenarios achieve reductions in energy demand of 70.4 kWh/m² (almost 56%) and 55.2 kWh/m² (42%), respectively.

5.3. LCC Results

In evaluating renovation scenarios to determine the financially superior option, it's essential to analyse both the NPV and the IRR metrics. NPV, a critical financial measure, quantifies the profitability of an investment by calculating the difference between the present value of cash inflows and outflows over time. A higher NPV signifies a more lucrative investment. In this section, various financial indicators are provided for different lifespan, encompassing initial investment, energy demand costs, potential savings resulting from the implementation of renovation scenarios, final costs associated with each scenario, Net Present Value (NPV) reflecting savings (while considering initial costs), Internal Rate of Return (IRR), and the payback period.

The point at which the NPV turns positive signifies the year from which the investment becomes financially advantageous. In some of the renovations' scenarios, instances can be observed in which although the NPV is positive, IRR falls below 4%. This might initially seem counterintuitive, given our assumption of a 4% for interest rate. However, it's crucial to account for the escalation rate for energy demand, which it is assumed to be set at 5%. Upon closer examination through sensitivity analysis, it can be concluded that higher assumptions regarding the escalation rate of energy costs during the usage phase can lead to a larger deviation between the IRR and the interest rate. In such cases, the IRR may indeed be lower than 4%, while the NPV remains positive. Therefore, it is reasonable and justifiable for the NPV to be positive even when the IRR is less than 4%. This highlights the importance of considering dynamic factors like escalating energy costs in our financial assessments to ensure a comprehensive economically evaluation.

Assuming that bill prices remain unchanged from pre-renovation levels, the savings generated from energy-efficient renovations will be redirected back to the investing companies, serving as revenue to offset the costs of the renovations.

Further details regarding the costs of renovation measurements and energy prices are provided in Appendix 9.19.4.

5.3.1. LCC of Wall Improvement

Table 43, and Table 44 offer a detailed breakdown of LCC for EPS thicknesses of 100mm, 120mm, 150mm, and 200mm across various lifespans at Blåsutgatan 8 and Byalagsgatan 8.

Table 43- LCC of Wall Renovation at Blåsutgatan 8.

Wall Renovation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing Wall	50	-	49,368,036		
Renovated Wall (200EPS)		1,801,496	40,948,958	6,617,581	12.04%
Renovated Wall (150EPS)		1,740,643	41,271,391	6,519,252.60	12.00%
Renovated Wall (120EPS)		1,577,392	42,023,734	6,146,309	12.40%
Renovated Wall (100EPS)		1,556,251	42,023,734	5,788,050	12.12%
Existing Wall	10	-	8,079,556		
Renovated Wall (200EPS)		1,801,496	6,701,693	-423,633	-1.37%
Renovated Wall (150EPS)		1,740,643	6,754,462	-415,549	-1.45%
Renovated Wall (120EPS)		1,577,392	6,818,957	-316,794	-0.64%
Renovated Wall (100EPS)		1,556,251	6,877,590	-354,285	-1.21%

Existing Wall	15	-	12,418,688		
Renovated Wall (200EPS)		1,801,496	10,300,842	316,350	5.60%
Renovated Wall (150EPS)		1,740,643	10,381,951	296,094	5.54%
Renovated Wall (120EPS)		1,577,392	10,481,085	360,212	6.19%
Renovated Wall (100EPS)		1,556,251	10,571,206	291,232	5.73%
Existing Wall	20	-	16,970,484		
Renovated Wall (200EPS)		1,801,496	14,076,388	1,092,600	8.57%
Renovated Wall (150EPS)		1,740,643	14,187,226	1,042,615	8.52%
Renovated Wall (120EPS)		1,577,392	14,322,694	1,070,398	9.09%
Renovated Wall (100EPS)		1,556,251	14,445,847	968,385	8.69%
Existing Wall	35	-	32,008,651		
Renovated Wall (200EPS)		1,801,496	26,549,992	3,657,164	11.40%
Renovated Wall (150EPS)		1,740,643	26,759,047	3,508,961	11.36%
Renovated Wall (120EPS)		1,577,392	27,014,558	3,416,701	11.80%
Renovated Wall (100EPS)		1,556,251	27,246,842	3,205,558	11.49%
Existing Wall	14	-	11,534,174		
Renovated Wall (200EPS)		1,801,496	9,567,170	165,507	4.67%
Renovated Wall (150EPS)		1,740,643	9,642,502	151,028	4.60%
Renovated Wall (120EPS)		1,577,392	9,734,575	222,207	5.28%
Renovated Wall (100EPS)		1,556,251	9,818,277	159,646	4.80%
Existing Wall	13	-	10,658,083		
Renovated Wall (200EPS)		1,801,496	8,840,485	16102	3.56%
Renovated Wall (120EPS)		1,740,643	9,175,122	82,479	4.20%

Analysis of Table 43 reveals that the payback period for wall renovation is 13 years when including EPS thicknesses of 200mm and 120mm, with corresponding IRR of 3.56% and 4.20% respectively. Conversely, the payback period extends to 14 years for 100mm and 150mm thicknesses, with IRRs of 4.80% and 4.60% respectively.

Table 44- LCC of Wall Renovation at Byalagsgatan 8.

Wall Renovation	**Lifespan (Years)**	**Initial Investment (SEK)**	**NPV of Energy Cost (SEK)**	**NPV of saving (SEK)**	**IRR**
Existing Wall	50	-	54,308,456	-	-
Renovated Wall (200EPS)		2215859	47345834	4,746,764	9.25%
Renovated Wall (150EPS)		2,139,741	47755400	4,617,520	9.09%
Renovated Wall (120EPS)		1,935,537	48083053	4,316,311	9.39%
Renovated Wall (100EPS)		1,909,093	48410705	3,988,658	9.14%
Existing Wall	10	-	8,888,103	-	-
Renovated Wall (200EPS)		2215859	7,748,603	-1,076,358	-7.43%
Renovated Wall (150EPS)		2,139,741	7,815,632	-1,072,471	-7.79%
Renovated Wall (120EPS)		1,935,537	7,869,256	-916,689	-7.09%
Renovated Wall (100EPS)		1,909,093	7,922,879	-943,869	-7.67%
Existing Wall	15	-			
Renovated Wall (200EPS)		2215859	11,909,997	-464,389	0.69%
Renovated Wall (150EPS)		2,139,741	12,013,025	-491,298	0.40%
Renovated Wall (120EPS)		1,935,537	12,095,447	-369516	0.96%
Renovated Wall (100EPS)		1,909,093	12,177,869	-425,494	0.49%
Existing Wall	20	-	18,668,775		
Renovated Wall (200EPS)		2215859	16,275,343	177,574	4.37%
Renovated Wall (150EPS)		2,139,741	16,416,133	112,902	4.12%
Renovated Wall (120EPS)		1,935,537	16,528,765	204,474	4.60%
Renovated Wall (100EPS)		1,909,093	16,641,397	118286	4.20%
Existing Wall	35	-	35,211,862	-	-
Renovated Wall (200EPS)		2215859	30,697,520	2,298,482	8.20%
Renovated Wall (150EPS)		2,139,741	30,963,070	2109051	8.02%
Renovated Wall (120EPS)		1,935,537	31,175,509	2100815	8.37%
Renovated Wall (100EPS)		1,909,093	31,387,949	1,914,820	8.08%
Existing Wall	19	-	17,648,056	-	-

Renovated Wall (200EPS)		2215859	15,385,484	46,712	3.82%
Renovated Wall (120EPS)		1,935,537	1,935,537	87468	4.05%
Renovated Wall (100EPS)		1,909,093	15,731,525	7438	3.65%

Analysis of Table 44 claim that the payback period for wall renovation with 200mm, 120mm, and 100mm EPS thicknesses is 19 years, with corresponding IRRs of 3.82%, 4.05%, and 3.65%, respectively. However, the payback period extends to 20 years for a 150mm thickness, with an IRR of 4.12%.

Both analyses reveal that incorporating 120mm of EPS emerges as the most financially efficient option for wall renovation, consistently yielding the highest IRR across all lifespans. However, due to considerations regarding CO_2 emissions associated with energy demand (detailed in section 5.4.1), 200mm of EPS was ultimately chosen for subsequent calculations in both cases.

5.3.2. LCC of Changing Windows

Initially, two options were considered: windows with wooden frames and windows with PVC frames. The initial cost for wooden frames was lower than that of PVC frames. Upon factoring in energy-related costs, wooden frames proved more advantageous for shorter lifespans. However, PVC frames exhibited superior performance over longer lifespans. Additionally, it's crucial to consider maintenance costs, especially over extended periods. Since the assumption was made that the building would remain intact for at least the next 50 years, calculations were based on this lifespan. Over this timeframe, total costs, including maintenance, energy-related expenses, and initial investments, were higher for wooden frames. Furthermore, assuming a 50-year lifespan, the CO_2 emissions associated with PVC frames were found to be lower than those of wooden frames. Consequently, PVC frames were selected, and the subsequent analysis will be based on this choice.

It could also be assumed that the old windows would be sold to Eastern Europe countries, as they are still functional and could be useful for countries that still use single-glazed windows. In this manner, income could be generated by selling the windows, potentially offsetting some of the costs associated with acquiring new windows. However, the potential earnings from selling the old windows will not be considered in this study. Consequently, income from this source will not be included in our calculations.

Table 45, and Table 46provide a comprehensive breakdown of LCC associated with changing windows across various lifespans at Blåsutgatan 8 and Byalagsgatan 8.

Table 45- LCC of Changing Windows at Blåsutgatan 8.

Windows renovation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing Windows	50	-	49368036		
New windows		3240747	34643607	11483682	11.8%
Existing Windows	10	-	8079556		
New windows		3240747	5669761	-830952	-1.8%
Existing Windows	15	-	12418688		
New windows		3240747	8714711	463230	5.2%
Existing Windows	20	-	16970484		
New windows		3240747	11908895	1820841	8.2%
Existing Windows	14	-	11534174		
New windows		3240747	8094010	199416	4.3%
Existing Windows	35	-	32008651		
New windows		3240747	22461804	6306100	11.1%

The table above highlights that the payback period for window replacement spans 14 years, accompanied by an IRR of 4.3%. This lengthy payback period may deter investor interest despite the substantial impact on reducing heating energy demand. The primary deterrent is the considerable initial investment required, encompassing the uninstall process of old windows, the procurement cost of triple-glazed PVC windows, and their installation.

Table 46- LCC of Changing Windows at Byalagsgatan 8.

Windows renovation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing Windows	50	-	54308456	-	
New windows		2698975	43987392	7,622,089	10.5%
Existing Windows	10	-	8888103	-	
New windows		2698975	7198962	-1,009,833	-4.5%
Existing Windows	15	-	13661467	-	
New windows		2698975	11065170	-102,678	3.0%
Existing Windows	20	-	18668775	-	
New windows		2698975	15120863	848,937	6.4%
Existing Windows	16	-	14643854		
New windows		2698975	11860859	84020	3.9%
Existing Windows	35	-	35211862	-	
New windows		2698975	28520015	3992872	9.7%

Table 46 indicates that the payback period for window replacement is 16 years, with IRR of 3.9% for Byalagsgatan 8, which is longer than Blåsutgatan 8. The reason is that the ratio of transparent area to facade area is higher in Blåsutgatan 8. Consequently, the impact of changing windows is less significant in Byalagsgatan 8 compared to Blåsutgatan 8.

5.3.3. Improving Roof

Investing in enhancing the roof of both buildings by adding 200mm EPS insulation and reducing air leakage by half incurred minimal costs. Table 47, and Table 48**Error! Reference source not found.** provide detailed LCC of this roof improvement.

Table 47- LCC of Improving Roof Blåsutgatan 8.

Roof Renovation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing Roof	50	-	49368036	-	
Renovated Roof		120552	48329086	918398	18.5%
Existing Roof	5	-	3943150	-	
Renovated Roof		120552	3860167	-37569	-8.8%
Existing Roof	10	-	8079556	-	
Renovated Roof		120552	7909522	49482	10.1%
Existing Roof	15	-	12418688	-	
Renovated Roof		120552	12157337	140799	15.1%
Existing Roof	20	-	16970484	-	
Renovated Roof		120552	16613340	236591	16.9%
Existing Roof	8	-	16970484	-	
Renovated Roof			16613340	14161	5.7%
Existing Roof	35	-	32008651	-	
Renovated Roof			31335029	553070	18.3%

According to the data provided in the table above, the payback period is less than 8 years, with an Internal Rate of Return of 5.7%. While the energy savings may not be substantial due to the buildings dimensional and roof area, the initial investment required was minimal, which makes this measurement cost effective.

Table 48- LCC of Improving Roof Byalagsgatan 8.

Roof Renovation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing Roof	50	-	178160755		

Renovated Roof		314166	161903250	4,641,583	29.7%
Existing Roof	5	-	4702460		
Renovated Roof		314166	4273352	81,662	11.0%
Existing Roof	10	-	10704124		
Renovated Roof		314166	9727352	496,890	25.6%
Existing Roof	15	-	18363936		
Renovated Roof		314166	16688192	932,469	28.5%
Existing Roof	20	-	28140013		
Renovated Roof		314166	25572184	1,389,395	29.3%
Existing Roof	35	-	76865002		
Renovated Roof		314166	69850926	2,898,983	29.7%
Existing Roof	4	-	3453520		
Renovated Roof		314166	3138380	974	2.5%

For the Byalagsgatan 8 payback period is less than 4 years, with IRR of 2.5%. The numbers indicates that the most cost-effective renovation measure in short-term for Byalagsgatan 8 is improving the roof. These tables also indicate that while both buildings benefit from roof renovations, Byalagsgatan 8 demonstrates greater financial benefits and energy savings in all lifespans, highlighting the impact of larger roof area.

5.3.4. Improving Ventilation System

By considering installing the Smart 1, substantial energy reduction has been observed in building energy modelling. As mentioned in section 4.4.4, 85% heat recovery was applied for simulation. offer a detailed breakdown of the LCC implications related to installing Smart1 over different lifespans at Blåsutgatan 8 and Byalagsgatan 8.

Table 49- LCC of Ventilation Blåsutgatan 8

Ventilation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing ventilation	50	-	49,368036	-	
Smart1		716800	38369497	10,281,739	29.0%
Existing ventilation	5	-	3943150	-	
Smart1		716800	3064669	161,681	9.9%
Existing ventilation	10	-	8079556	-	
Smart1		716800	6279539	1,083,217.15	24.8%
Existing ventilation	15	-	12418688	-	
Smart1		716800	9651970	2,049,918	27.8%
Existing ventilation	20	-	16970484	-	
Smart1		716800	13189686	3,063,997.14	28.6%
Existing ventilation	35	-	32008651	-	
Smart1		716800	24877551	6,414,300	29.0%

In the table above, it's evident that incorporating smart1 yields a payback period of just under 5 years, the shortest among all five main measurements, with an IRR of 9.9% over 5 years. Given these numbers, this feature presents the most compelling investment opportunity.

Table 50- LCC of Ventilation Byalagsgatan 8.

Ventilation	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
Existing ventilation	50	-	54,308,456	-	-
Smart1		499,200	49,188,881	4,620,375	21.1%
Existing ventilation	5	-	4,337,754	-	-
Smart1		499,200	3,928,841	-90287	-3.7%
Existing ventilation	7	-	6,131,810	-	-
Smart1		499,200	5,553,774	78836	6.8%
Existing ventilation	10	-	8,888,103	-	-
Smart1		499,200	8,050,235	338,668	14.0%

Existing ventilation	15	-	13661467	-	
Smart1		499,200	12373621	788,646	18.4%
Existing ventilation	20	-	18668775	-	
Smart1		499,200	16908898	1,260,677	19.9%
Existing ventilation	35	-	35211862	-	
Smart1		499,200	31892493	2,820,169	21.0%

In Byalagsgatan 8 the payback period is 7 years, with the IRR of 6.8%, which is longer than Blåsutgatan 8. This difference can be attributed to the types of ventilation systems in place: Blåsutgatan 8 uses an exhaust ventilation system, whereas Byalagsgatan 8 relies on natural ventilation.

5.3.5. Installing PV Panels

The detailed LCC of PV Panels also is presented in Table 51 for both buildings.

Table 51- LCC of PV Panels in Blåsutgatan 8 and Byalagsgatan 8.

Solar panels	Lifespan (Years)	Initial Investment (SEK)	NPV of Energy Cost (SEK)	NPV of saving (SEK)	IRR
DMEGC Mono All Black 535W	50	389,060	3,573,651.91	3,184,592	19.4%
	5	389,060	285437	-103,623	-7.0%
	7	389,060	403491	14,431	3.9%
	10	389,060	584863	195,803	11.5%
	15	389,060	898964	509,904	16.3%
	20	389,060	1228459	839,399	18.0%
	35	389,060	2317041	1,927,981	19.2%

Based on the data in the table, the payback period for PV Panels is less than 7 years, accompanied by an IRR of 3.9%. Despite a relatively modest initial investment, the substantial energy production and its cost render this measurement particularly compelling financially.

5.3.6. Combinatorial Scenarios

The rest of the scenarios are the combination of these five. Summary of LCC for these scenarios is presented in Table 52 for Blåsutgatan 8, and Table 53 for Byalagsgatan 8. For those scenarios containing PV Panels, 28000 kWh generating electricity should be considered. Energy units are in kWh/m2. The IRR presented in the table below reflects the scenarios' IRR during their payback period, offering insights into the financial viability of each scenario within that timeframe. Detailed LCC of each scenario; however, is provided in Appendix 9.39.6.

Table 52- LCC of all renovation scenarios in different lifespan for Blåsutgatan 8.

Scenario	Renovation Measures	NPV of Saving-50 Y (SEK)	NPV of Saving-10 Y (SEK)	NPV of Saving-15 Y (SEK)	NPV of Saving-20 Y (SEK)	NPV of Saving-35 Y (SEK)	Pay back (Years)	Initial Cost (SEK)	IRR
0	Nothing	-49368036	-8079556	-12418688	-16970483	-32008651	-	0	-
1a	100mm EPS	5788050	-354285	291232	968385	3205558	<14	1556251	4.8%
1b	120mm EPS	6125168	-316794	360212	1070398	3416701	<13	1577392	4.2%
1c	150mm EPS	6356001	-415549	296094	1042615	3508961	<14	1740643	4.6%
1d	200mm EPS	6617581	-423633	316350	1092600	3657164	<13	1801496	3.6%
2	Change windows PVC	11483682	-830952	463230	1820841	6306100	<14	3240747	4.3%
3	Improving roof	918398	49482	140799	236591	553070	<8	120552	5.7%

4	Ventilation	10281739	0	2049918	3063997	6414300	<5	716800	9.9%
5	PV panels	3184592	195803	509904	839399	1927981	<7	389060	3.9%
6	Improving wall + Change windows	16883183	-1453935	473169	2494721	9173500	<14	5042243	3.7%
7	Improving wall + Improving roof	7392675	-397604	421100	1279930	4117320	<13	1922048	4.1%
8	Improving wall + Ventilation	15537938	436781	2023808	3688615	9188787	<9	2518296	4.2%
9	Improving wall + PV panels	9802173	-120991	870116	1909797	5585145	<12	2190556	4.7%
10	Change windows + Improving roof	11972169	-851829	495884	1909649	6580430	<14	3361299	4.3%
11	Change windows + Ventilation	20583167	58778	2215749	4478433	11953865	<10	3957547	3.5%
12	Change windows + PV panels	14668273	-635150	973134	2660240	8234082	<13	3629807	4.7%
13	Improving roof + Ventilation	11200137	1132699	2190717	3300589	6967370	<5	837352	7.5%
14	Improving roof + PV panels	4102990	245285	650703	1075990	2481051	<7	509612	3.6%
15	Ventilation + PV panels	13466331	195803	2559822	3903396	8342281	<5	1105860	4.4%
16	Improving wall + Change windows + Improving roof	17550800	-1445496	550883	2645105	9563972	<14	5162795	3.8%
17	Improving wall + Change windows + Ventilation	26340928	-505573	2315808	5275466	15053549	<11	5759043	3.5%
18	Improving wall + Change windows + PV panels	20067775	-1258133	983072	3334119	11101482	<13	5431303	3.6%
19	Improving wall + Improving roof + Ventilation	16205554	445220	2101522	3839000	9579258	<9	2638848	4.1%
20	Improving wall + Improving roof + PV panels	10577267	-201801	931004	2119329	6045301	<11	2311108	3.5%
21	Improving wall + Ventilation + PV panels	18722530	632584	2533711	4528014	11116768	<9	2907356	5.0%
22	Change windows + Improving roof + Ventilation	21143306	49627	2266426	4591872	12274651	<10	4078099	3.5%
23	Change windows + Improving roof + PV panels	15156761	-656027	1005788	2749048	8508411	<13	3750359	4.7%
24	Change windows + Ventilation + PV panels	24448451	365982	2896882	5551823	14323185	<10	2907356	4.8%
25	Improving roof + Ventilation + PV panels	14384729	1,328,502	2,700,620	4139987	8895351	<5	1226412	3.2%
26	Improving wall + Change windows + Improving roof + Ventilation	27151848	-473681	2429570	5475111	15536933	<11	5879595	3.6%
27	Improving wall + Change windows + Improving roof + PV panels	20735392	-1249694	1060786	3484504	11491953	<13	5551855	3.7%
28	Change windows + Improving roof + Ventilation + PV panels	23647207	134028	2605100	5197280	13761294	<10	4467159	3.8%
29	Improving wall + PV panels + Improving roof + Ventilation	19390146	641023	2611425	4678398	1542404	<9	3027908	4.9%
30	Improving wall + Change windows + Ventilation + PV panels	29525520	-309770	2825712	6114865	16981530	<11	6148103	4.2%
31	All	30336440	-277878	2939474	6314510	16309166	<11	6268655	4.3%

Table 53- LCC of all renovation scenarios in different lifespan for Byalagsgatan 8.

Scenario	**Renovation Measures**	**NPV of Saving-50 Y (SEK)**	**NPV of Saving -10 Y (SEK)**	**NPV of Saving-15 Y (SEK)**	**NPV of Saving-20 Y (SEK)**	**NPV of Saving-35 Y (SEK)**	**Pay back (Years)**	**Initial Cost (SEK)**	**IRR**
0	Nothing	-54,308,456	-8,888,103	-13,661,467	-18,668,775	-35,211,861.58		0	-
1a	100mm EPS	3,988,658	-943869	-425,494	118,286	1,914,820	<19	1,909,092.64	3.6%

1b	120mm EPS	4,289,867	-916,689	-369,516	204,474	2,100,815	<19	1,935,536.74	4.1 %
1c	150mm EPS	4,413,316	-1067270	-491298	112,902	2,109,051	<20	2,139,740.71	4.1 %
1d	200mm EPS	4,746,764	-1076358	-464389	177,574	2,298,482	<19	2,215859	3.8 %
2	Change windows PVC	7,622,089	-1009833	-102678	848937	3,992,872	<16	2698975	3.9 %
3	Improving roof	4,641,583	496890	932469	1389395	2,898,983	<4	314166	2.5 %
4	Ventilation	4,620,375	338668	788646	1,260,677	2,820,169	<7	499200	6.8 %
5	PV panels	3,184,592	195803	509904	839,399	1,927,981	<7	389060	3.9 %
6	Improving wall + Change windows	12,368,853	-2086192	-567067	1,026,511	6,291,354	<17	4914834	3.7 %
7	Improving wall + Improving roof	8,835,796	-669898	329084	1377027	4,839,209	<14	2530024.81	4.1 %
8	Improving wall + Ventilation	9,571,922	-704176	375771	1,508,646	5,251,426	<14	2715059	4.2 %
9	Improving wall + PV panels	7,931,356	-720887	140387	1,043,873	4,226,464	<15	2604919	3.7 %
10	Change windows + Improving roof	12,591,325	-459319	912213	2350964	7,104,294	<12	3013141	3.8 %
11	Change windows + Ventilation	12,283,421	-664462	696270	2123693	6,839,595	<13	3198175	4.1 %
12	Change windows + PV panels	10,806,681	-814031	407226	1,688,336	5,920,853	<14	3088035	4.1 %
13	Improving roof + Ventilation	9,589,611	889182	1803536	2,762,704	5,931,591	<5	813366	3.4 %
14	Improving roof + PV panels	7,826,175	692693	1442372	2,228,794	4,826,964	<6	703226	11.6 %
15	Ventilation + PV panels	7,804,967	534471	1298549	2,100,076	4,748,150	<7	888260	5.6 %
16	Improving wall + Change windows + Improving roof	17,460,959	-1515569	478732	2,570,775	9,482,442	<14	5229000	3.7 %
17	Improving wall + Change windows + Ventilation	17,194,011	-1714009	273093	2,357,583	9,244,298	<15	5414034	4.1 %
18	Improving wall + Change windows + PV panels	15,553,445	-1890389	-57163	1,865,910	8,219,336	<16	5303894	4.2 %
19	Improving wall + Improving roof + Ventilation	14,704,985	-126850	1431873	3,066,989	8,469,068	<11	3029225	4.3 %
20	Improving wall + Improving roof + PV panels	12,020,388	-474096	838988	2,216,426	6,767,191	<12	2919085	3.6 %
21	Improving wall + Ventilation + PV panels	12,756,514	-508373	885674	2,348,045	7,179,407	<12	3104119	3.6 %
22	Change windows + Improving roof + Ventilation	17,211,700	-120651	1700858	3,611,641	9,924,463	<11	3512341	4.4 %
23	Change windows + Improving roof + PV panels	15,775,917	-263517	1422116	3,190,363	9,032,276	<11	3402201	3.7 %

24	Change windows + Ventilation + PV panels	15,468,013	-468660	1206174	2,963,092	8,767,577	<12	3104119	4.2%
25	Improving roof + Ventilation + PV panels	12,774,203	1,084,984	2313440	3,602,103	7,859,572	<6	1202426	6.2%
26	Improving wall + Change windows + Improving roof + Ventilation	22,245,160	-1,150,089	1308589	3,887,768	12,408,830	<13	5728200	4.2%
27	Improving wall + Change windows + Improving roof + PV panels	20,645,550	-1319766	988636	3,410,174	11,410,423	<13	5618060	3.6%
28	Change windows + Improving roof + Ventilation + PV panels	20,396,292	75151	2210762	4,451,040	11,852,444	<10	3901401	3.6%
29	Improving wall + PV panels + Improving roof + Ventilation	17,889,576	68952	1941776	3906388.012	951,189	<10	3418285	3.6%
30	Improving wall + Change windows + Ventilation + PV panels	20,378,603	-1518206	782996	3,196,982	11,172,279	<14	5803094	4.2%
31	All	25,429,752	-954287	1818493	4,727,167	13,181,063	<12	6,117,260	3.7%

5.3.7. The Best Scenario from LCC Perspective

In this section, the potential energy and cost savings achievable through various renovation scenarios are aimed to be compared to identify the best one. It is generally expected that a greater investment in energy-efficient renovations will result in higher energy savings. However, investing excessively is not considered financially prudent. Therefore, the most cost-effective scenario needs to be selected, which involves finding the scenario that maximises energy savings while minimising the required investment. Figure 41 Shows the relation between Initial cost and Saved energy among 31 scenarios including before renovation.

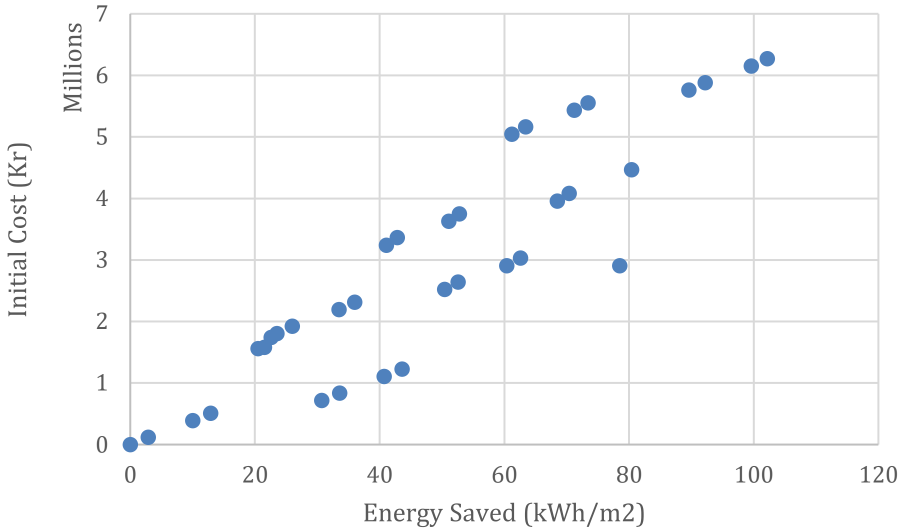

Figure 41- Comparison between Initial Cost & Energy Saved at Blåsutgatan 8.

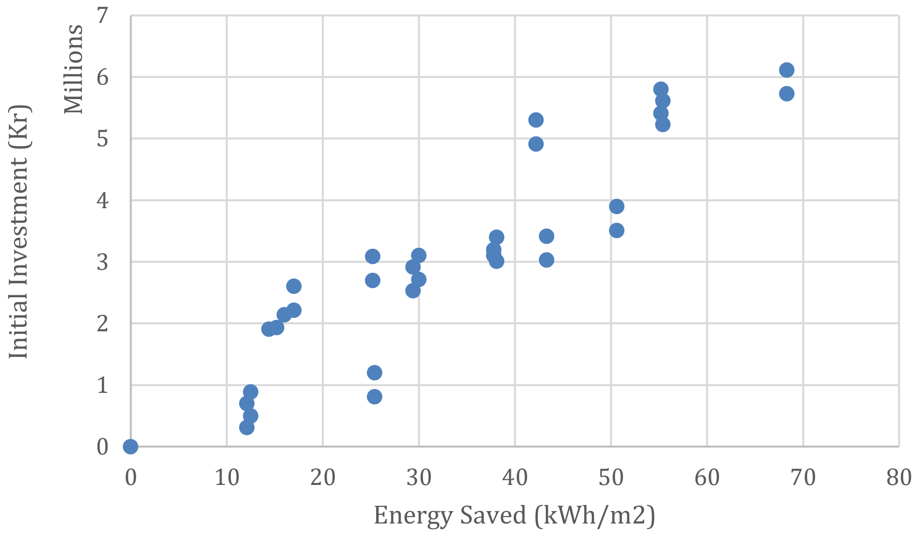

Figure 42- Comparison between Initial Cost & Energy Saved at Byalagsgatan 8.

The comparison of initial costs and energy savings is not straightforward because scenarios involving PV panels do not directly result in energy savings, although they require initial investments. Therefore, a more viable approach would be to compare the NPV of the savings and the energy saved. This method aligns the financial and energy metrics, facilitating a more accurate assessment of the benefits. Alternatively, it could be assumed that the electricity produced by the PV panels is equivalent to energy savings, given that their costs are comparable.

Method 1: Comparing NPV of Saving and Saved Energy

The lifespan of the renovation measures is a key factor in determining the best scenario.

<u>10 Years:</u>

According to Table 52, the most financially advantageous scenario over a 10-year period is Scenario 25 for both buildings which includes improvements to roofing and ventilation along with the installation of photovoltaic (PV) panels. This scenario boasts an impressive IRR of 19.5% at Blåsutgatan 8 and 17.1% for Byalagsgatan 8 for 10 years. There is also a relatively short payback period of 5 years for Blåsutgatan 8 and 6 years for Byalagsgatan 8, positioning it as the best choice for short-term financial returns. Figure 43 presents a graphical comparison of the LCC across different scenarios over a period of 10 years.

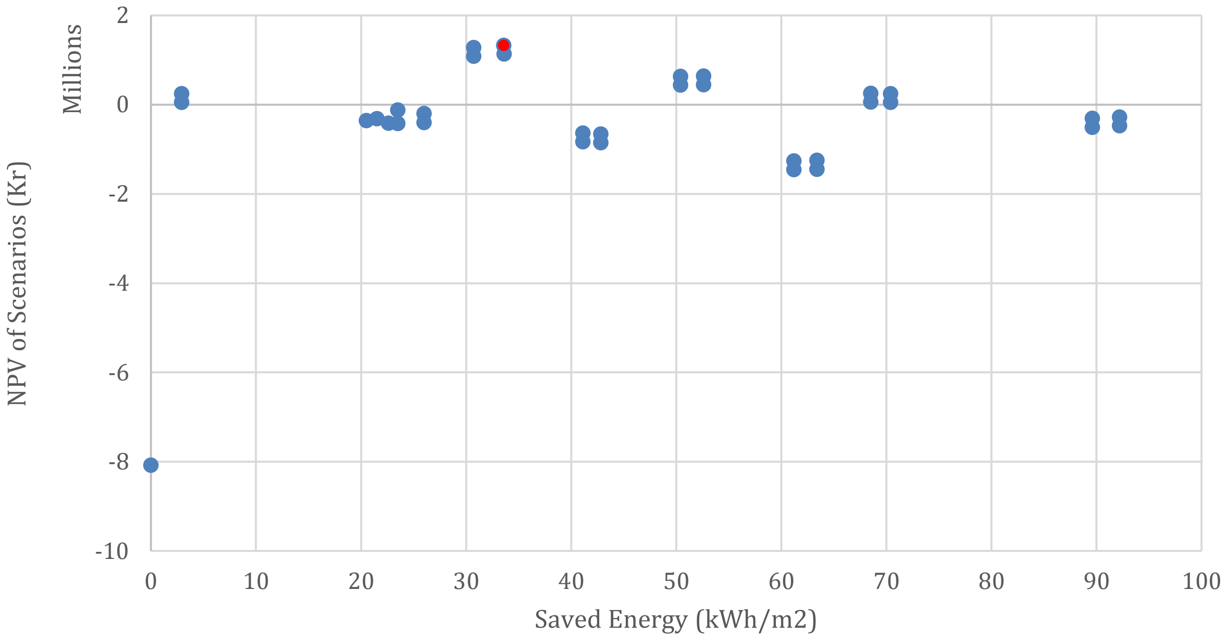

Figure 43- Comparison between NPV of Saved money and Saved Energy in 10 Years at Blåsutgatan 8

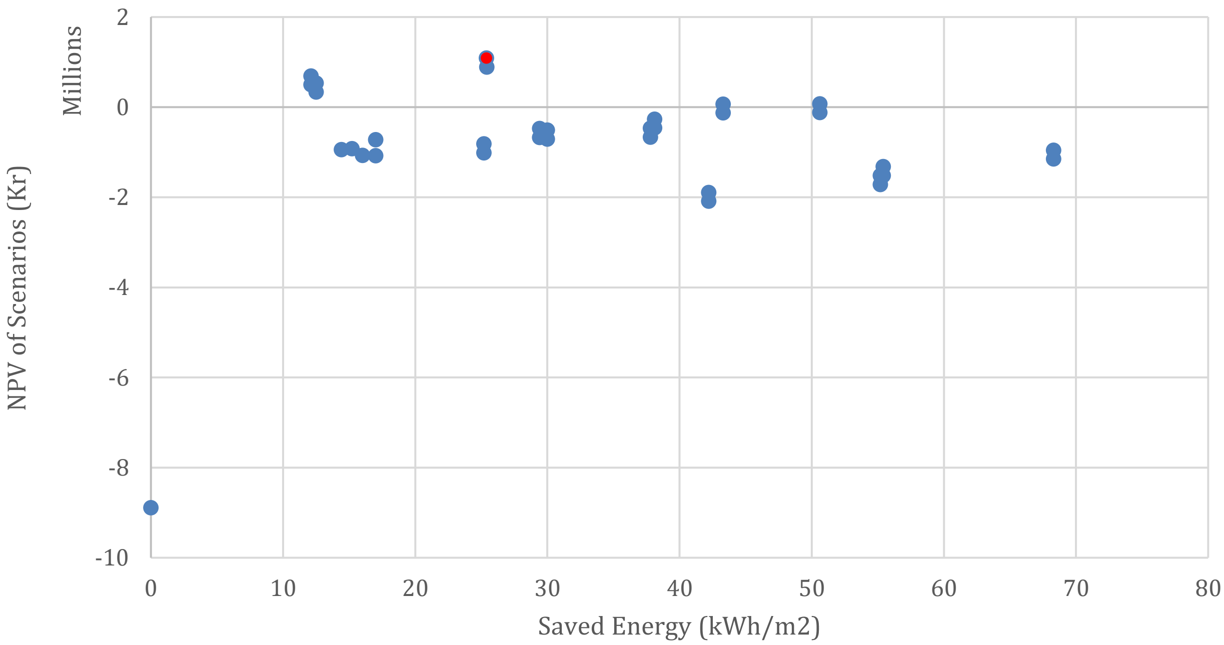

Figure 44-Comparison between NPV of Saved money and Saved Energy in 10 Years at Byalagsgatan 8

In a set of 32 scenarios, including an option without any renovations, the least beneficial outcome is do nothing scenario. Additionally, only 14 scenarios at Blåsutgatan 8, and 9 scenarios Byalagsgatan 8 at yielding a positive NPV.

15 Years:

When we extend the analysis to a 15-year lifespan, Scenario 31 emerges as the superior option at Blåsutgatan 8, offering an IRR of 8.7%. This comprehensive scenario, encompassing all proposed measures, has a payback period of 11 years at Blåsutgatan 8 and 12 years at Byalagsgatan 8, with corresponding IRRs of 4.3% and 3.7%, respectively, underscoring its viability for long-term financial planning. However, over 15 years, Scenario 25 at Byalagsgatan 8 has consistently remained the best option, boasting an IRR of 21.1%. Figure 45 and Figure 47 present the rankings of each scenario after 15 years for Blåsutgatan 8 and Byalagsgatan 8, respectively.

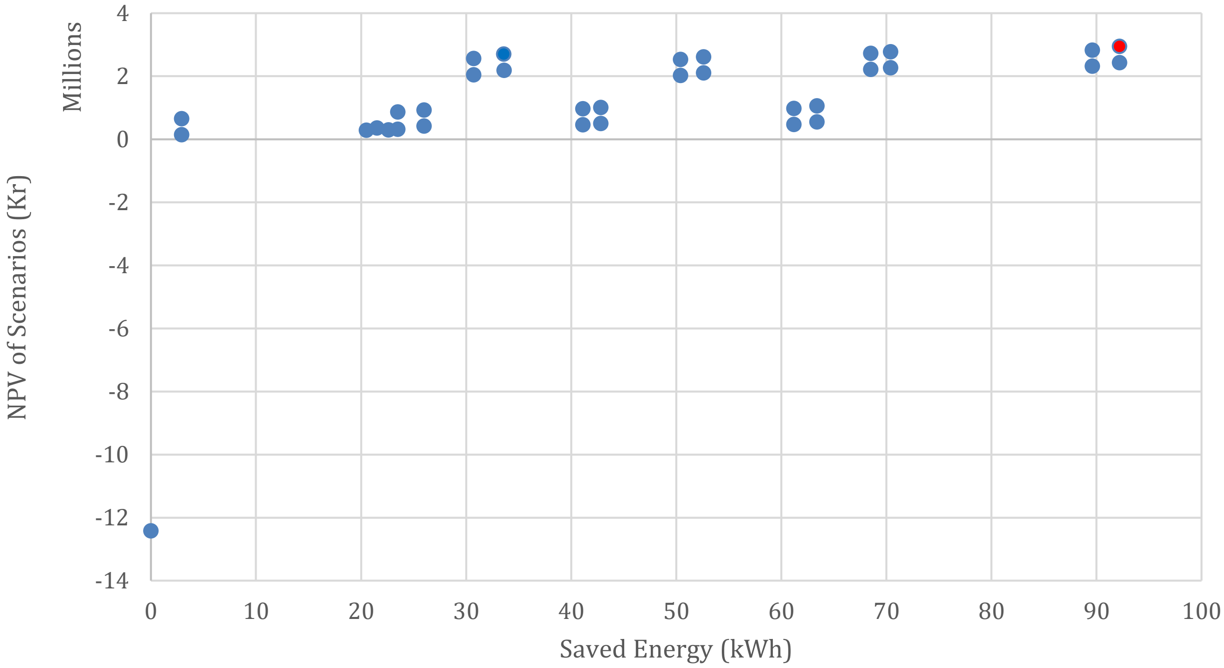

Figure 45- Comparison between NPV of Saved money and Saved Energy in 15 Years at Blåsutgatan 8.

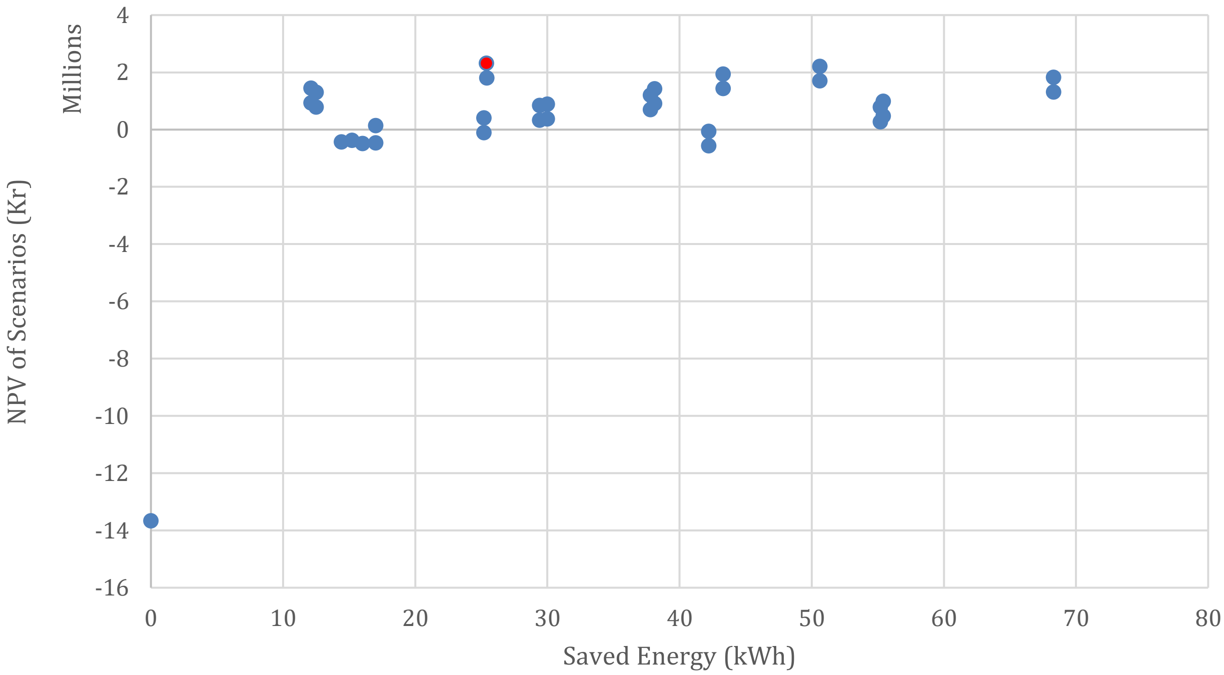

Figure 46- Comparison between NPV of Saved money and Saved Energy in 15 Years at Byalagsgatan 8.

20 Years:

Scenario 31 has been determined as the best for both buildings, with IRRs of 11.3% for Blåsutgatan 8 and 9.7% for Byalagsgatan 8. Figure 47, and Figure 48 show the ranking of each scenario for Blåsutgatan 8 and Byalagsgatan 8, respectively, over a 20-year period graphically.

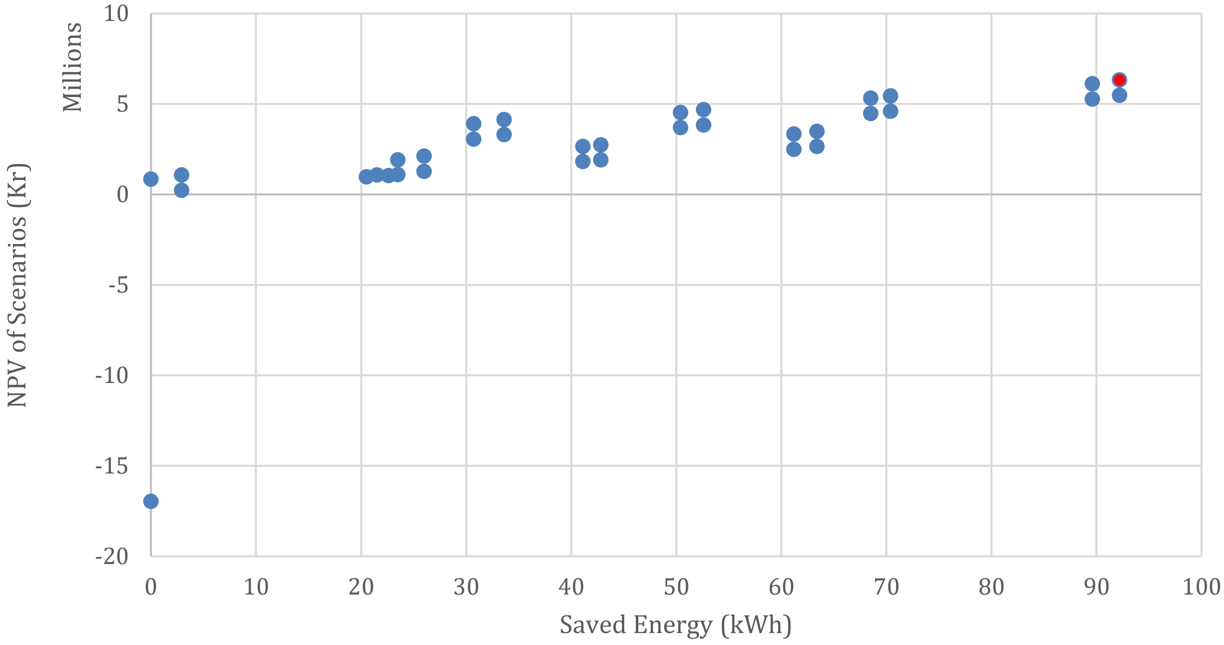

Figure 47- Comparison between NPV of Saved money and Saved Energy in 20 Years at Blåsutgatan 8

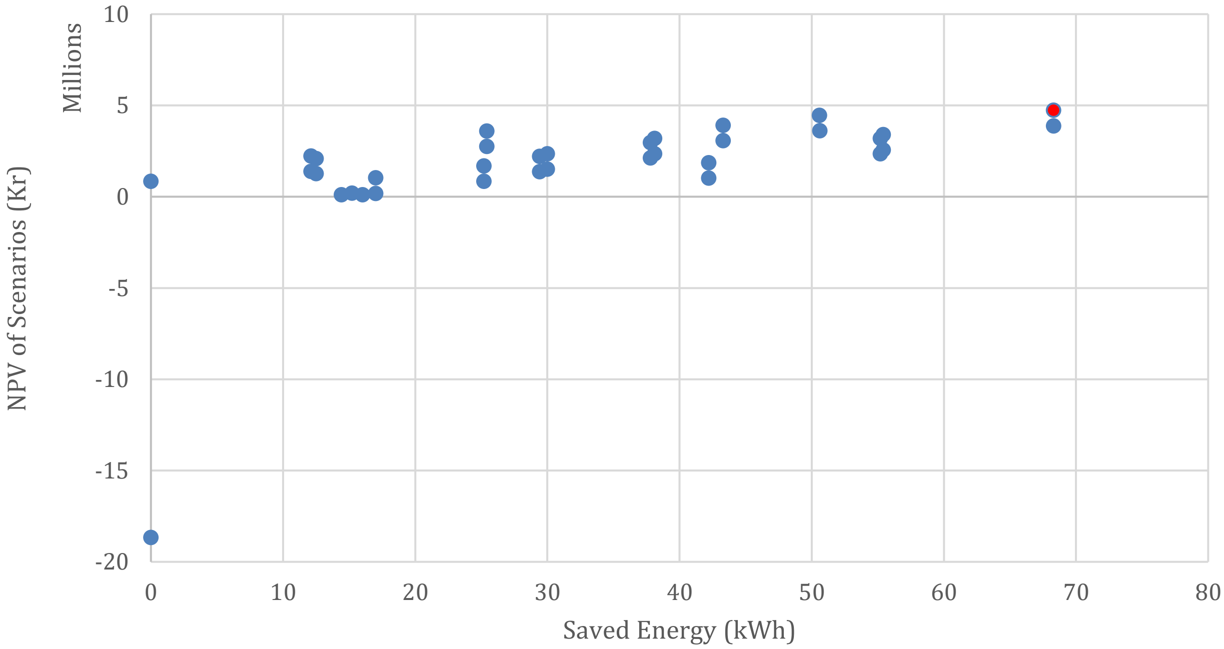

Figure 48- Comparison between NPV of Saved money and Saved Energy in 20 Years at Byalagsgatan 8.

35 Years:

When considering a lifespan of 35 years, the comparison becomes more complex and requires greater precision.

Blåsutgatan 8:

Scenario 30, with an NPV of 16,981,530 Kr, surpasses Scenario 31, which has an NPV of 16,309,166 Kr, indicating that Scenario 30 is more profitable in terms of present value net cash flows. On the other hand, IRR, which is the discount rate at which the NPV of all cash flows equals zero, serves as an indicator of an investment's potential profitability. Although Scenario 31 exhibits a marginally higher IRR of 13.6% compared to Scenario 30's 13.5%, suggesting a slightly better return on investment, the difference is minimal. The decision between these scenarios' hinges on the relative importance of NPV and IRR to the project's financial objectives. If maximising total return in today's money value is the goal, Scenario 30 is the preferred choice due to its higher NPV. Conversely, if the aim is to achieve a higher rate of return relative to the cost of capital, Scenario 31 could be considered slightly more appealing due to its higher IRR. However, given the substantial difference in NPV (672,364 Kr) between the scenarios and their identical 35-year lifespan, Scenario 30 is generally the better financial choice. It not only promises a greater overall value creation over the project's life but also demonstrates the significance of prioritising NPV over a marginally higher IRR in long-term investment decisions. Figure 49 illustrates this comparison in 35 years.

Byalagsgatan 8:

The situation for Byalagsgatan 8 is easier to analyse. Scenario 31 is the most beneficial, with the highest NPV of 13,181,063 and an IRR of 12.3%. Figure 49, and Figure 50 illustrate differences in each building.

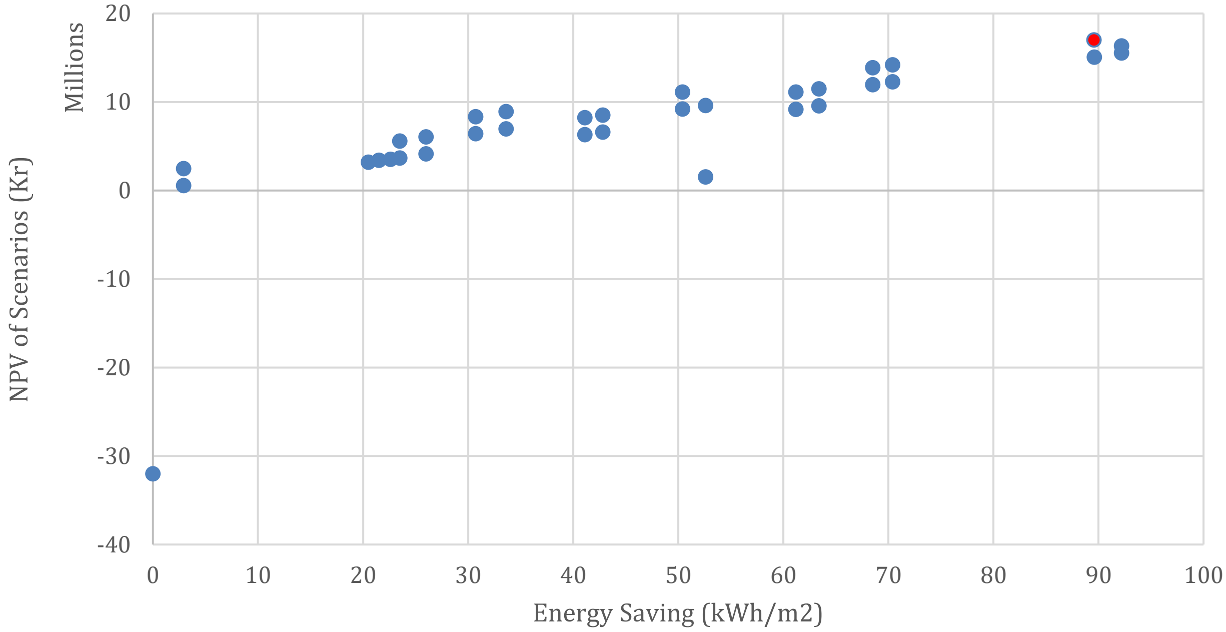

Figure 49-Comparison between NPV of Saved money and Saved Energy in 35 Years at Blåsutgatan 8

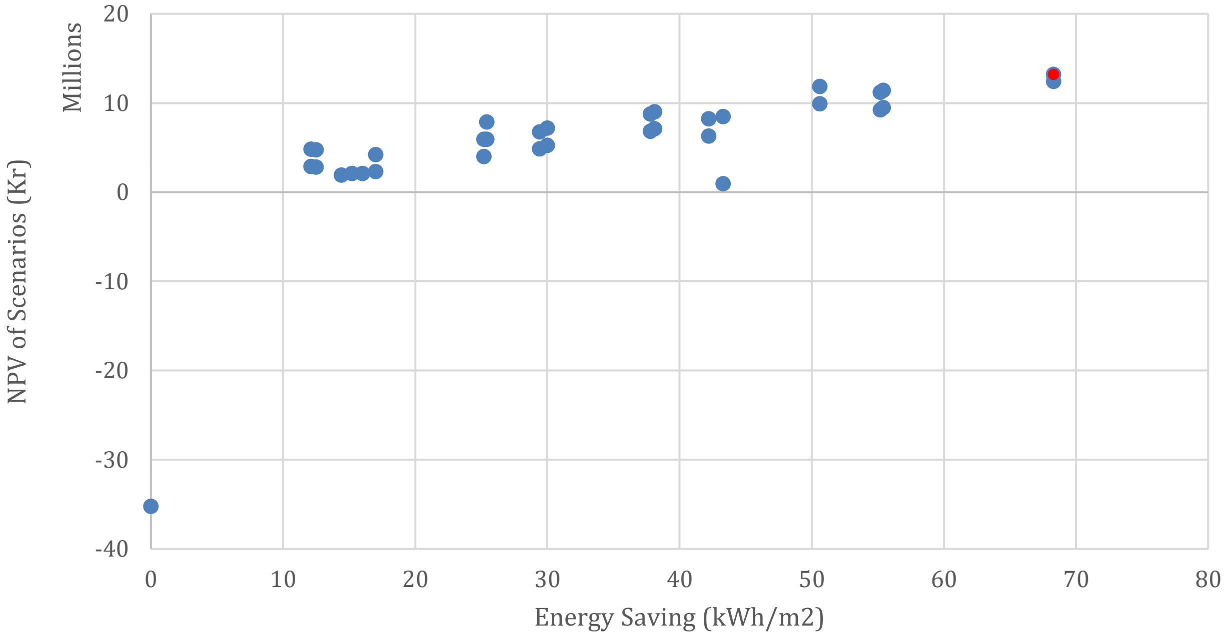

Figure 50- Comparison between NPV of Saved money and Saved Energy in 35 Years at Byalagsgatan 8.

<u>50 Years:</u>

Eventually, when evaluating the scenarios over more extended period, Scenario 31 stands out as the most advantageous option for a 50-year lifespan. By employing all of measures, Scenario 31 achieves an IRR of 14% at Blåsutgatan 8, and 12.9% at Byalagsgatan 8, making it the best choice for long-term energy efficiency improvements. Figure 51, Figure 52 depict each scenarios' spot after 50 years.

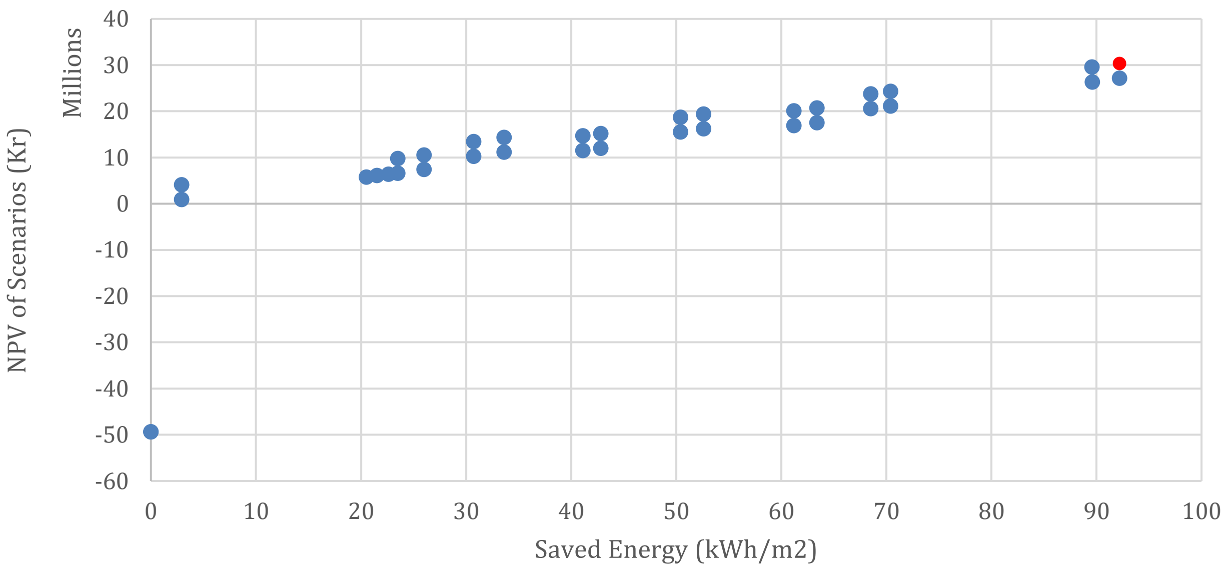

Figure 51- Comparison between NPV of Saved money and Saved Energy in 50 Years at Blåsutgatan 8.

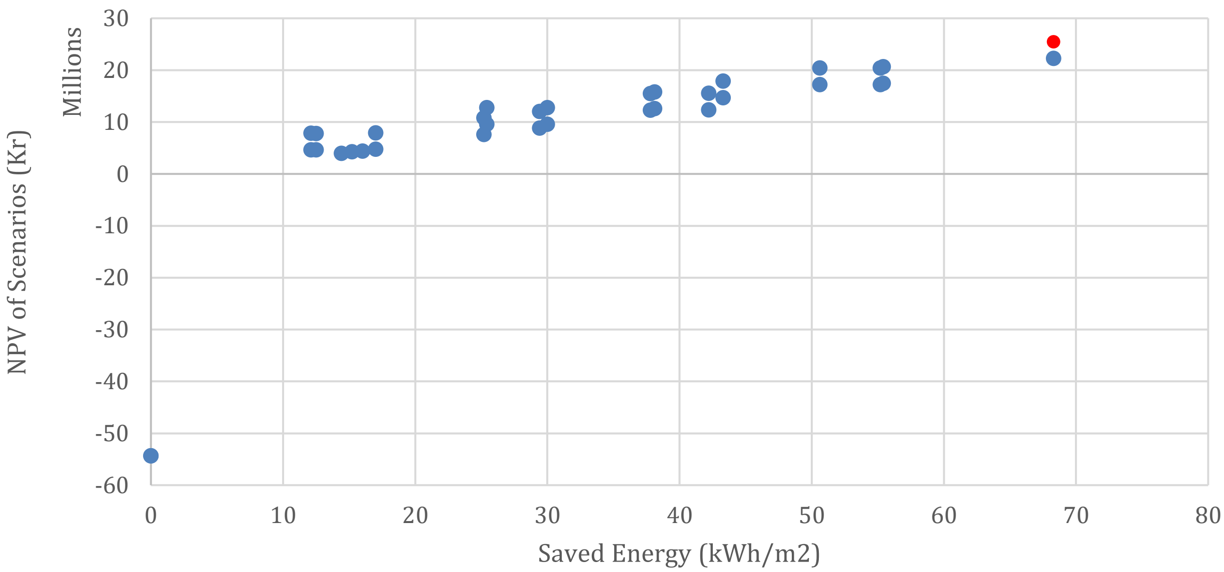

Figure 52- Comparison between NPV of Saved money and Saved Energy in 50 Years at Byalagsgatan 8.

Conclusion:

Investors often prioritise investments with shorter payback periods, making the 10- and 15-year lifespans particularly significant. However, given that the building is expected to last at least 50 years, the 50-year lifespan is critically important. From a Life Cycle Cost (LCC) perspective, Scenario 31 has been identified as the best choice for both buildings. This scenario proves to be the most advantageous for Blåsutgatan 8 over 15, 20, and 50 years, and for Byalagsgatan 8 over 20, 35, and 50 years, covering three out of the five evaluated lifespans. Its comprehensive effectiveness across multiple time frames underscores its suitability for long-term investment in energy-efficient building renovations.

Method 2: Comparing NPV of Saving and Initial Cost

The analysis of initial cost versus NPV of money saved through various renovation measures over different lifespans provides a comprehensive view of the cost-effectiveness of each scenario. Evaluating these scenarios by simply dividing NPV by initial cost might initially suggest that Scenario 4 at Blåsutgatan 8, which involves installing smart technology to improve ventilation, and Scenario 3 at Byalagsgatan 8, which involves roof improvements, are the best choices across all considered lifespans. However, this method does not necessarily identify the best scenario, as it fails to simultaneously account for the maximum energy and monetary savings.

Incorporating the Initial Cost into the NPV calculation is crucial, as it reflects the true investment efficiency over time. Therefore, the scenario with the highest NPV, after considering the Initial Cost, should ideally be selected as the best. This approach ensures that both the expenditure and the returns are balanced, leading to a more sustainable investment decision.

Blåsutgatan 8:

The graphical representations in Figure 53 to Figure 57 illustrate the comparisons of Initial Cost versus NPV over various lifespans—10, 15, 20, 35, and 50 years. These figures consistently identify the best scenarios based on the highest NPV values adjusted for Initial Costs. For instance, Figure 53 highlights that the best scenario over a 10-year period aligns with the first method, identifying Scenario 25 as the best option. Similarly, Figure 54 and Figure 55, which cover 15 and 20-year spans respectively, both suggest that Scenario 31 is the most advantageous. This scenario remains the preferred choice in Figure 56 for a 35-year lifespan and is again confirmed in Figure 57 for a 50-year period.

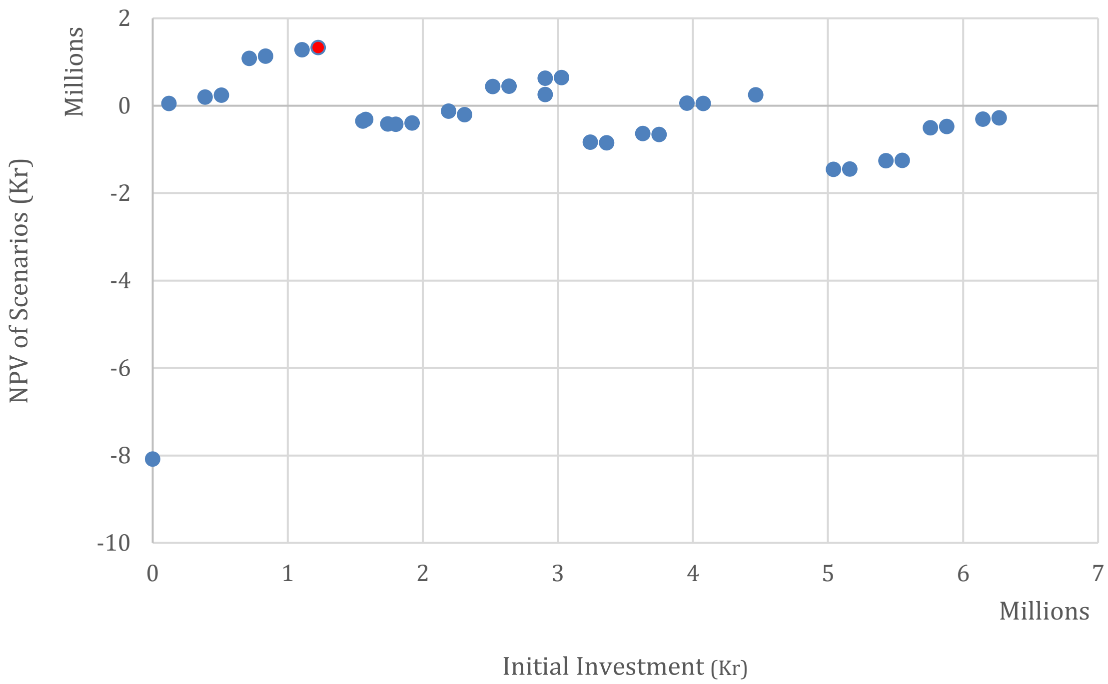

Figure 53- Comparing NPV savings to initial investment over 10 years at Blåsutgatan 8

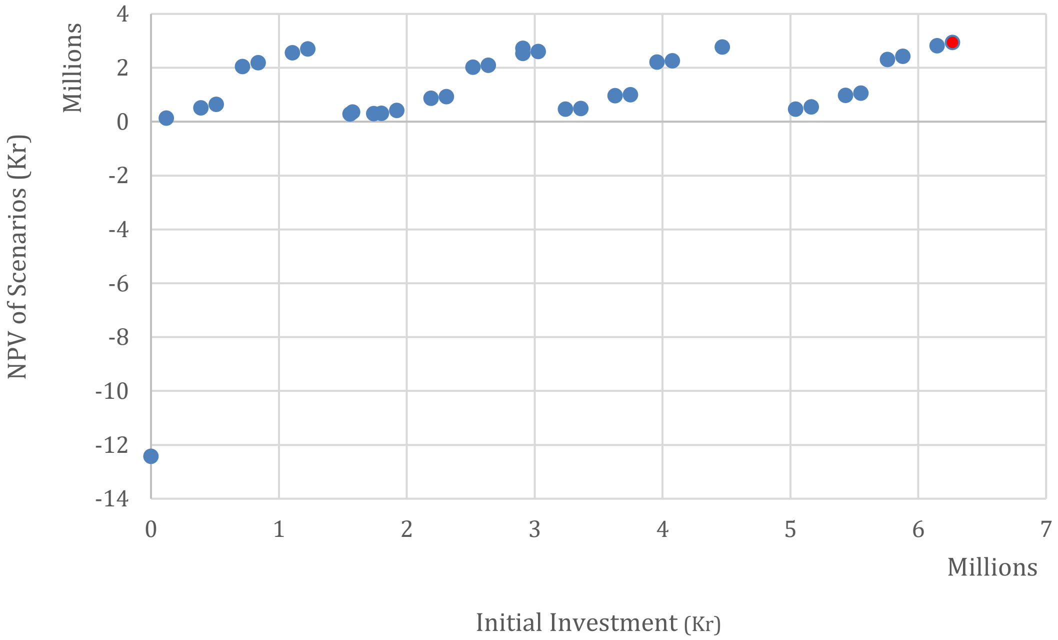

Figure 54- Comparing NPV savings to initial investment over 15 years at Blåsutgatan 8

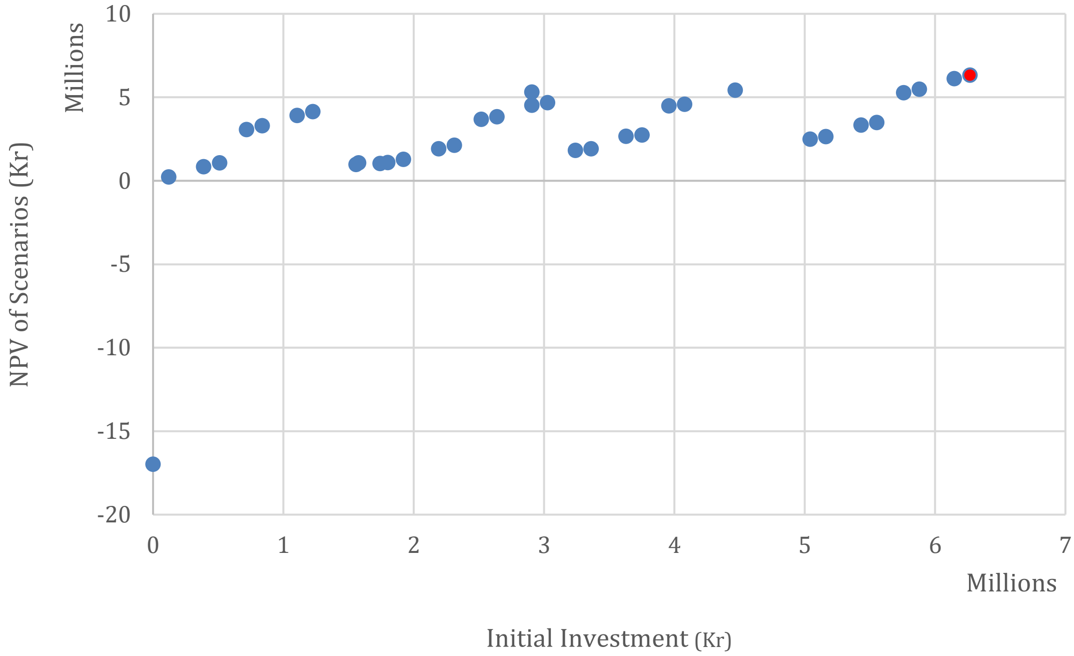

Figure 55- Comparing NPV savings to initial investment over 20 years at Blåsutgatan 8

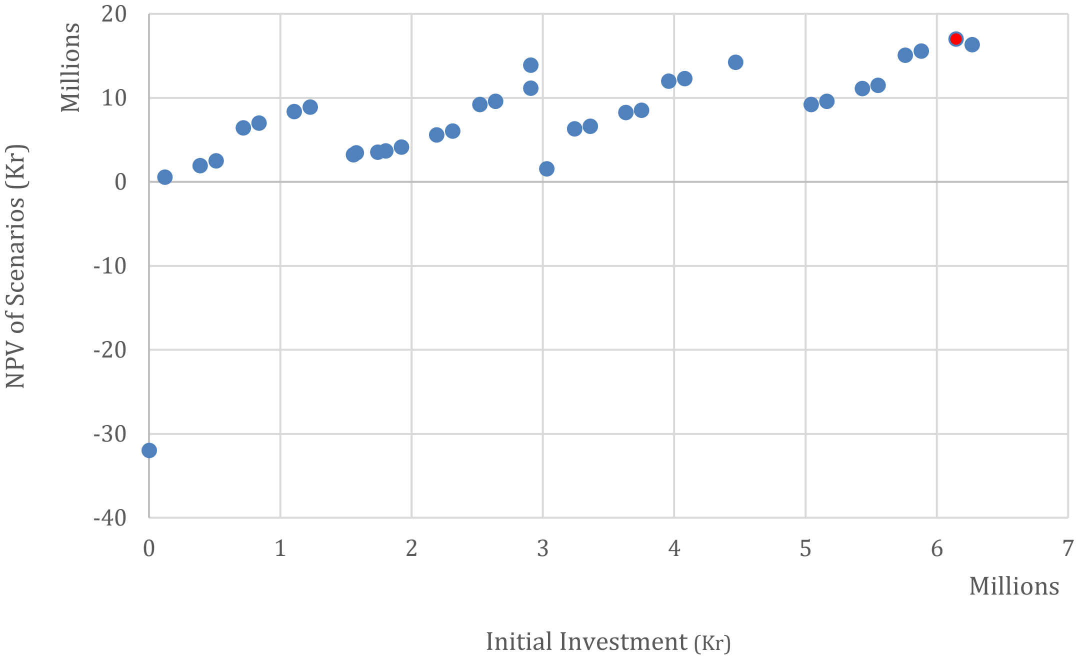

Figure 56- Comparing NPV savings to initial investment over 35 years at Blåsutgatan 8

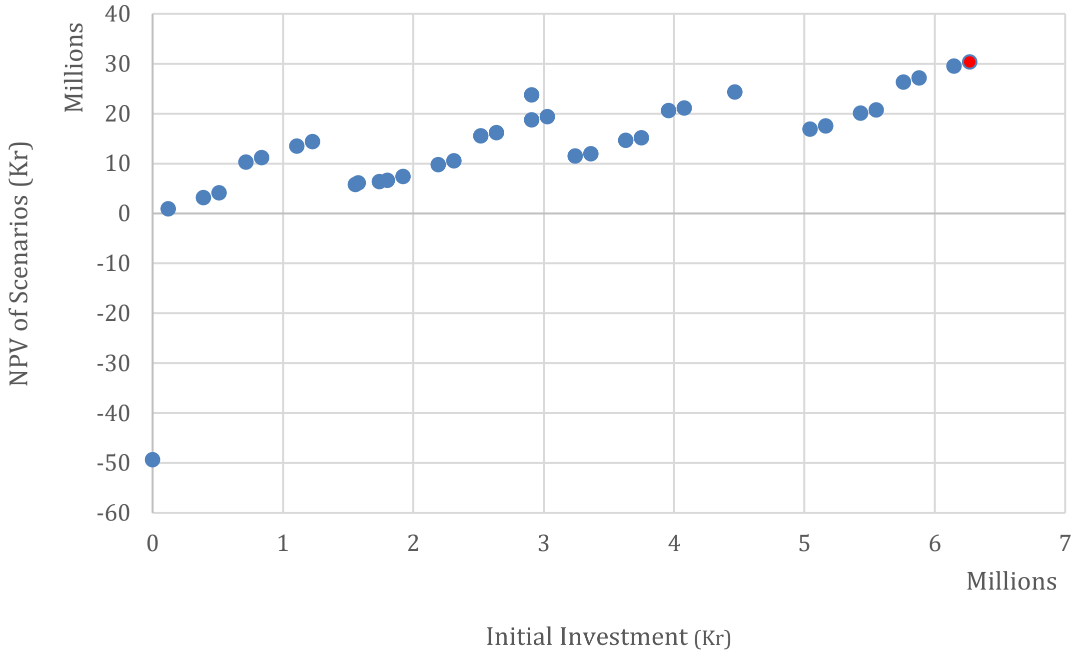

Figure 57- Comparing NPV savings to initial investment over 50 years at Blåsutgatan 8

<u>Byalagsgatan 8:</u>

Figure 58, Figure 59, Figure 60, Figure 61, and Figure 62 depicting the same comparison in Byalagsgatan 8. The results obtained using the second method are similar to those of the first method. Scenario 25 performs the best at the 10-year and 15-year marks. Scenario 31 performs the best at the 20-year, 35-year, and 50-year marks.

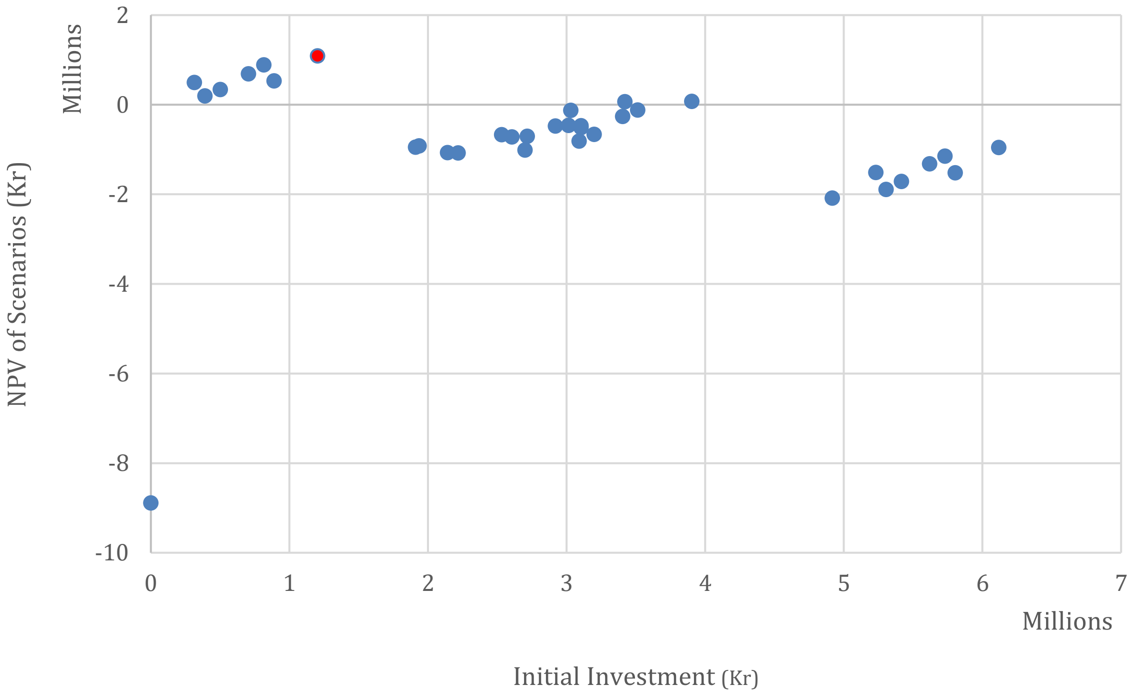

Figure 58- Comparing NPV savings to initial investment over 10 years at Byalagsgatan 8.

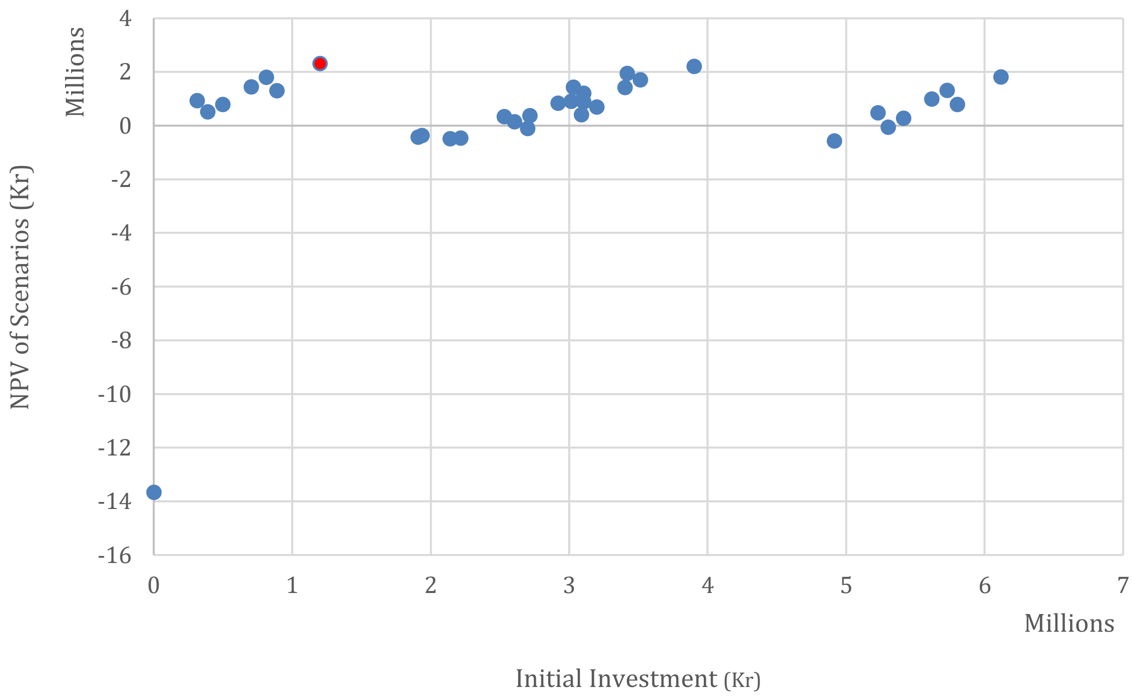

Figure 59- Comparing NPV savings to initial investment over 15 years at Byalagsgatan 8.

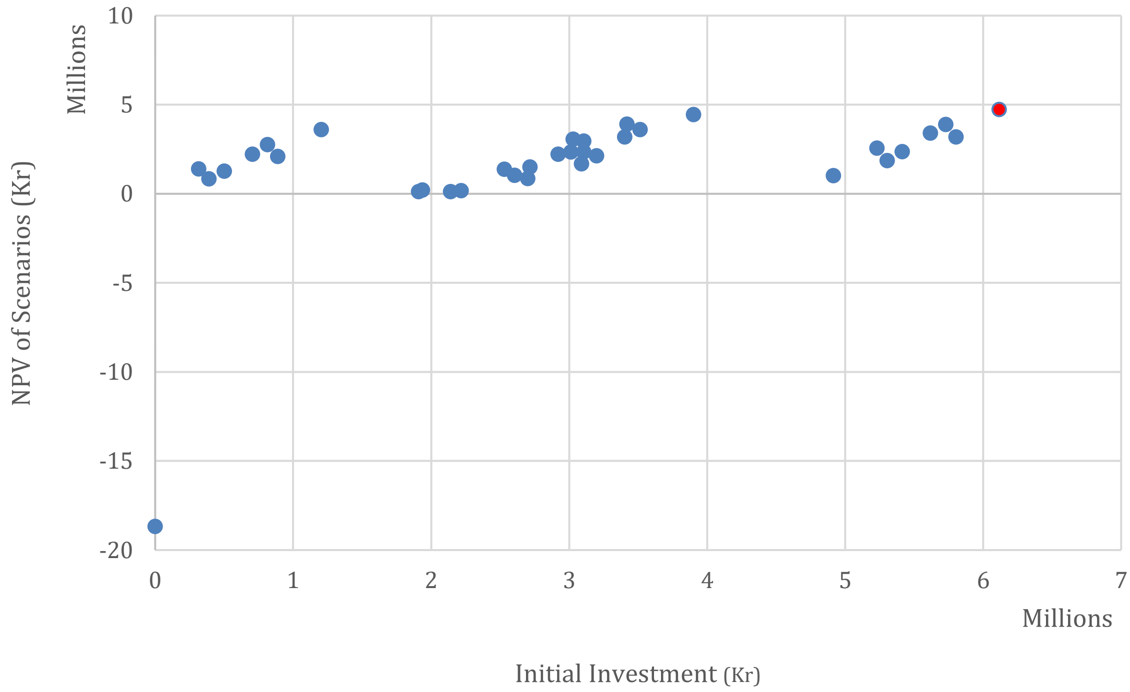

Figure 60- Comparing NPV savings to initial investment over 20 years at Byalagsgatan 8.

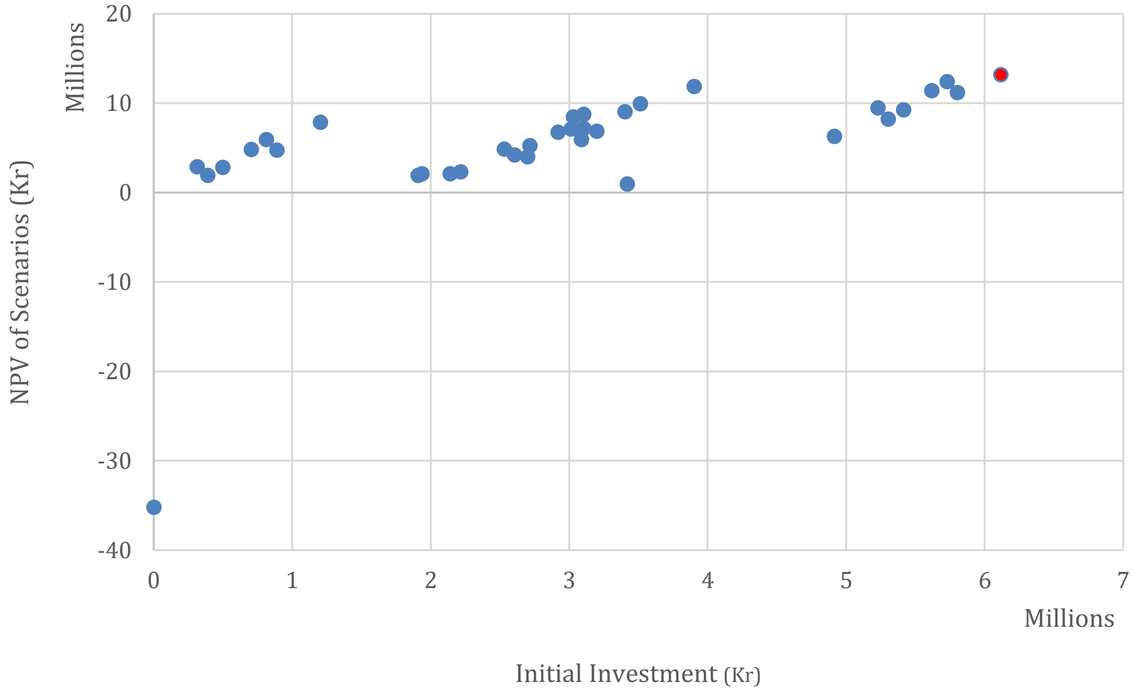

Figure 61- Comparing NPV savings to initial investment over 35 years at Byalagsgatan 8.

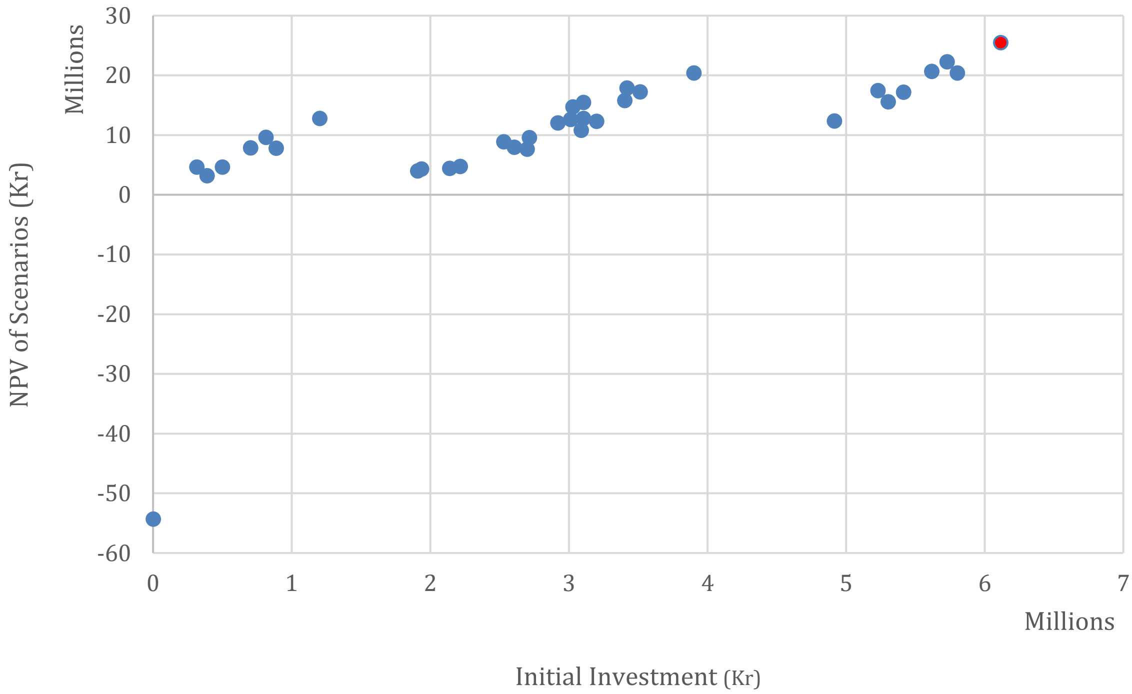

Figure 62- Comparing NPV savings to initial investment over 50 years at Byalagsgatan 8.

As a result, from an LCC perspective, for both buildings Scenario 31 is best for long-term investments in energy-efficient renovations, proving effective across multiple time frames and ensuring sustainable returns. This scenario's consistent performance across various analyses underscores its suitability for long-term energy efficiency improvements.

5.4. LCA Results

The forthcoming section will present the results for the climate change impact category. Like the LCC section, each scenario yields distinct outcomes, with each contributing its own share to CO_2 emissions. The environmental performance of each renovation scenario is evaluated across stages A1-A3, A4, B4, B6, C2, and C3-C4 in different lifespans similar to LCC part. On one hand, these assessments provide total CO_2 equivalent emissions for each of the 31 scenarios, allowing for comprehensive comparisons. On the other hand, they facilitate stage-to-stage comparisons, aiding in the identification of hotspots.

5.4.1. LCA of Scenarios

In some scenarios, despite higher initial environmental impacts due to the use of advanced sustainable technologies or materials, the long-term benefits in terms of reduced emissions and energy savings justify the initial environmental impact. Similar to NPV in financial assessments, where the long-term financial savings or benefits are considered against the initial costs.

Sensitivity analysis within the LCA framework further clarifies how variations in material sourcing or energy demand influence total CO_2 equivalent. As all stages, except B6 remained intact in different lifespans, detailed results for 50 years will be presented as our main lifespan in Table 54 for Blåsutgatan 8, and Table 55 related to Byalagsgatan 8. Details results related to other lifespans will be presented in Appendix 9.3 and 9.6. Ultimately, LCA results assist stakeholders in choosing renovation scenarios with lower CO_2 emissions.

Table 54- GWP of renovation Scenarios at Blåsutgatan 8

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-	-	-	1,030,826.26	-	-	1,030,826
1a	100mm EPS	9,479.79	206.44	-	877,474.02	52.05	3,123.22	890,336
1b	120mm EPS	11,375.75	247.72	-	869,993.42	62.46	3,747.87	885,427
1c	150mm EPS	14,219.69	309.65	-	861,764.77	78.08	4,684.83	881,057
1d	200mm EPS	18,959.59	412.87	-	855,032.23	104.11	6,246.45	880,755
2	Change windows PVC	43,154.60	1,183.98	-	723,373.72	157.78	-	767,870
3	Improving roof	4,481.82	79.70	-	1,009,132.53	7.97	122.48	1,013,824
4	Ventilation	1,013.00	36.53	-	801,171.93	4.19	488.99	802,715
5	PV panels	40,969.05	160.04	41,129.09	956,020.29	12.80	-	1,038,291
6	Improving wall + Change windows	62,114.19	1,596.85	-	573,013.72	261.88	6246.4462	643,233
7	Improving wall + Improving roof	23,441.41	492.57	-	836,330.74	112.08	6,368.93	866,746
8	Improving wall + Ventilation	19,972.59	449.41	-	653,804.17	108.30	6,735.44	681,070
9	Improving wall + PV panels	59,928.64	572.91	41,129.09	780,226.26	116.91	6,246.45	888,220
10	Change windows + Improving roof	47,636.42	1,263.67	-	710,656.71	165.75	122.48	759,845
11	Change windows + Ventilation	44,167.60	1,220.51	-	518,405.37	161.97	488.99	564,444
12	Change windows + PV panels	59,928.64	572.91	41,129.09	648,567.75	116.91	6,246.45	756,562
13	Improving roof + Ventilation	5,494.82	116.23	-	779,478.20	12.16	611.47	785,713
14	Improving roof + PV panels	45,450.87	239.74	41,129.09	934,326.56	20.78	122.48	1,021,290

15	Ventilation + PV panels	41,982.05	196.58	41,129.09	801,171.93	16.99	488.99	884,986
16	Improving wall + Change windows + Improving roof	66,596.01	1,676.55	-	556,556.41	269.86	6,368.93	631,468
17	Improving wall + Change windows + Ventilation	63,127.19	1,633.38	-	360,564.77	266.07	6,735.44	432,327
18	Improving wall + Change windows + PV panels	103,083.24	1,756.89	41,129.09	498,207.76	274.69	6,246.45	650,698
19	Improving wall + Improving roof + Ventilation	24,454.41	529.10	-	637,346.86	116.27	6,857.92	669,305
20	Improving wall + Improving roof + PV panels	64,410.46	652.61	41,129.09	761,524.77	124.88	6,368.93	874,211
21	Improving wall + Ventilation + PV panels	60,941.64	609.45	41,129.09	578,998.20	121.10	6,735.44	688,535
22	Change windows + Improving roof + Ventilation	48,649.42	1,300.21	-	504,192.23	169.94	611.47	554,923
23	Change windows + Improving roof + PV panels	88,605.47	1,423.71	41,129.09	635,850.74	178.55	122.48	767,310
24	Change windows + Ventilation + PV panels	85,136.65	1,380.55	41,129.09	518,405.37	174.77	488.99	646,715
25	Improving roof + Ventilation + PV panels	46,463.87	276.27	41,129.09	704,672.23	24.97	611.47	793,178
26	Improving wall + Change windows + Improving roof + Ventilation	67,609.01	1,713.08	-	341,115.22	274.05	6,857.92	417,569
27	Improving wall + Change windows + Improving roof + PV panels	107,565.06	1,836.59	41,129.09	481,750.44	282.66	6,368.93	638,933
28	Change windows + Improving roof + Ventilation + PV panels	89,618.47	1,460.25	41,129.09	429,386.26	182.74	611.47	562,388
29	Improving wall + PV panels + Improving roof + Ventilation	65,423.46	689.14	41,129.09	637,346.86	129.07	6,857.92	751,576
30	Improving wall + Change windows + Ventilation + PV panels	104,096.24	1,793.42	41,129.09	285,758.80	278.88	6,735.44	439,792
31	All	108,578.06	1,873.12	41,129.09	266,309.25	286.85	6,857.92	425,034

Table 55- GWP of renovation Scenarios at Byalagsgatan 8.

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-		-	1,133,984.41	-		1,133,984.41
1a	100mm EPS	12,021.50	261.80	-	1,010,836.78	52.05	3,116.23	1,026,288.36
1b	120mm EPS	14,425.80	314.16	-	1,003,995.24	62.46	3,739.47	1,022,537.14
1c	150mm EPS	18,032.25	392.71	-	997,153.71	78.08	4,674.34	1,020,331.09
1d	200mm EPS	24,043.00	523.61	-	988,601.79	104.11	6,232.45	1,019,504.96
2	Change windows PVC	37,896.00	1,037.35	-	918,476.06	157.78	-	957,567.19
3	Improving roof	11,664.00	207.41	-	1,030,506.19	7.97	318.67	1,042,704.24
4	Ventilation	548.90	19.86	-	1,027,085.43	4.19	264.87	1,027,923.24
5	PV panels	40,957.80	160.04	41,129.09	1,039,913.30	12.80	-	1,122,173.04
6	Improving wall + Change windows	61,939.00	1,560.96	-	773,093.44	261.88	6,232.45	843,087.74
7	Improving wall + Improving roof	35,707.00	731.01	-	882,558.00	112.08	6,551.12	925,659.22
8	Improving wall + Ventilation	24,591.90	543.47	-	877,426.85	108.30	6,497.32	909,167.84
9	Improving wall + PV panels	65,000.80	683.65	41,129.09	894,530.69	116.91	6,232.45	1,007,693.59
10	Change windows + Improving roof	49,560.00	1,244.76	-	808,156.31	165.75	318.67	859,445.49
11	Change windows + Ventilation	38,444.90	1,057.21	-	810,721.88	161.97	264.87	850,650.84
12	Change windows + PV panels	78,853.80	1,197.39	41,129.09	824,404.95	170.58		945,755.82
13	Improving roof + Ventilation	12,212.90	227.27	-	916,765.67	12.16	583.54	929,801.55

14	Improving roof + PV panels	52,621.80	367.45	41,129.09	936,435.09	20.78	318.67	1,030,892.87
15	Ventilation + PV panels	41,506.70	179.90	41,129.09	933,014.32	16.99	264.87	1,016,111.87
16	Improving wall + Change windows + Improving roof	73,603.00	1,768.37	-	660,208.12	269.86	6,551.12	742,400.47
17	Improving wall + Change windows + Ventilation	62,487.90	1,580.82	-	661,918.50	266.07	6,497.32	732,750.62
18	Improving wall + Change windows + PV panels	102,896.80	1,721.00	41,129.09	679,022.34	274.69	6,232.45	831,276.37
19	Improving wall + Improving roof + Ventilation	36,255.90	750.87	-	763,686.33	116.27	6,815.99	807,625.37
20	Improving wall + Improving roof + PV panels	76,664.80	891.05	41,129.09	788,486.90	124.88	6,551.12	913,847.85
21	Improving wall + Ventilation + PV panels	65,549.70	703.51	41,129.09	783,355.74	121.10	6,497.32	897,356.46
22	Change windows + Improving roof + Ventilation	50,108.90	1,264.62	-	701,257.33	169.94	583.54	753,384.33
23	Change windows + Improving roof + PV panels	90,517.80	1,404.80	41,129.09	714,085.20	178.55	318.67	847,634.12
24	Change windows + Ventilation + PV panels	79,402.70	1,217.25	41,129.09	716,650.78	174.77	264.87	838,839.46
25	Improving roof + Ventilation + PV panels	53,170.70	387.31	41,129.09	822,694.57	24.97	583.54	917,990.17
26	Improving wall + Change windows + Improving roof + Ventilation	74,151.90	1,788.23	-	549,888.37	274.05	6,815.99	632,918.54
27	Improving wall + Change windows + Improving roof + PV panels	114,560.80	1,928.41	41,129.09	566,137.01	282.66	6,497.32	730,535.29
28	Change windows + Improving roof + Ventilation + PV panels	91,066.70	1,424.66	41,129.09	607,186.22	182.74	583.54	741,572.96
29	Improving wall + PV panels + Improving roof + Ventilation	77,213.70	910.91	41,129.09	669,615.23	129.07	6,815.99	795,814.00
30	Improving wall + Change windows + Ventilation + PV panels	103,445.70	1,740.86	41,129.09	567,847.40	278.88	6,497.32	720,939.25
31	All	115,109.70	1,948.27	41,129.09	455,817.26	286.85	6,815.99	621,107.16

To analyse the tables above, it is essential to consider the key points outlined within.

Baseline Scenario 0 (No Renovation):

Blåsutgatan 8: 1,030,826 kg CO_2 eq

Byalagsgatan 8: 1,133,984.41 kg CO_2 eq

Without any renovation, both buildings exhibit significantly high emissions, serving as reference points for the effectiveness of various renovation measures.

Most Effective Individual Measures: Scenario 2 (Change Windows PVC):

Blåsutgatan 8: 767,870 kg CO_2 eq

Byalagsgatan 8: 957,567.19 kg CO_2 eq

Changing to PVC windows substantially reduces emissions at both case studies. The initial CO_2 emissions are offset by the long-term energy savings, making this scenario highly effective.

Most Effective Combination Scenarios:

Blåsutgatan 8: Scenario 26 (Improving wall + Change windows + Improving roof + Ventilation): 417,569 kg CO_2 eq

Byalagsgatan 8: Scenario 31 (All Measures): 621,107 kg CO_2 eq

This combination achieves the lowest emissions among all scenarios in each building, indicating a synergistic effect when these specific measures are combined.

Least Effective Measures:

Scenario 5 (PV Panels Alone):

Blåsutgatan 8: 1,038,291 kg CO_2 eq

Byalagsgatan 8: 1,122,173.04 kg CO_2 eq

While incorporating renewable energy technology, this scenario results in high emissions due to the embodied emissions from the production and installation of PV panels. This indicates that PV panels alone are not sufficient to achieve substantial emission reductions.

Comprehensive Renovation: Scenario 31 (All Measures):

Blåsutgatan 8: 425,034 kg CO_2 eq

Byalagsgatan 8: 621,107.16 kg CO_2 eq

Incorporating all proposed measures results in the most significant reduction in emissions for Byalagsgatan 8 and second effective scenario for Blåsutgatan 8. This scenario demonstrates the extensive potential of integrated approaches to renovation for minimising environmental impact.

Conclusion:

The analysis reveals that scenarios involving a combination of improving insulation (walls and roof), upgrading windows, and enhancing ventilation systems are the most effective in reducing emissions. The comprehensive renovation scenario (Scenario 31) also highlights the substantial environmental benefits that can be achieved through holistic buildings upgrades.

5.4.2. Finding Hotspots

Figure 63 and Figure 63 are pie charts offering a visual comparison of the CO_2 emissions associated with five main renovation measures. Each segment of the pie represents the percentage contribution of a specific renovation measure to the total CO_2 emissions.

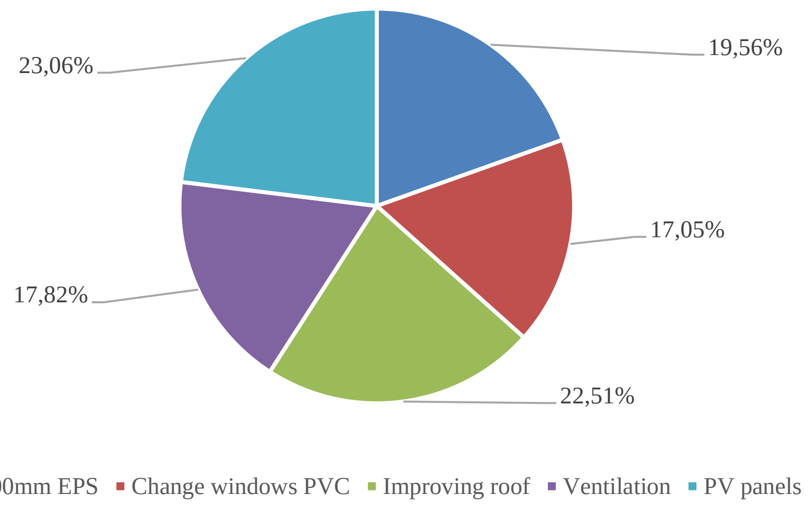

Figure 63- contribution of main five renovation measurement at Blåsutgatan 8

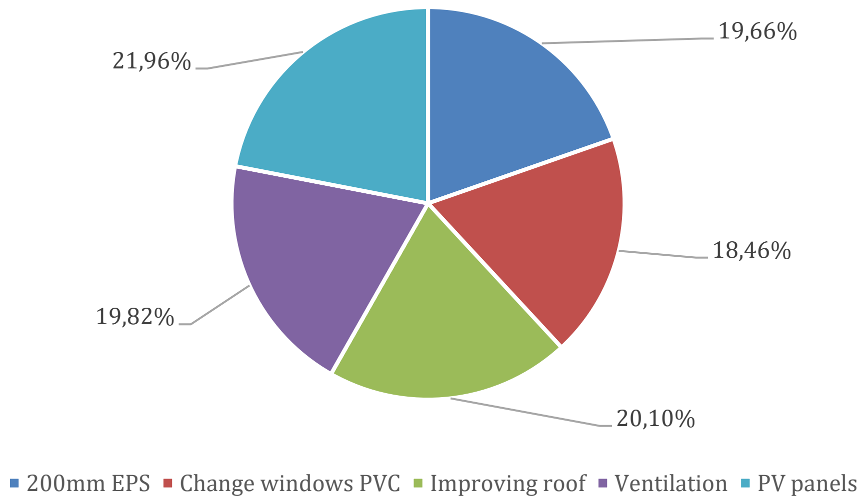

Figure 64- contribution of main five renovation measurement at Byalagsgatan 8

The installation of PV panels leads with approximately 23%, and 22% of total emissions (1,038,291 and 1,138,947 kg CO_2-eq), followed closely by roof improvements by 22.51%, and 20.10% (1,013,824, and 1,042,704 kg CO_2-eq) at Blåsutgatan 8, and Byalagsgatan 8. Both measures have significant emissions during the B6 stage, which likely encompasses the use phase, indicating the long-term impact of these renovations. The predominant contribution of PV panels can be attributed to the assumption that they can generate nearly 10 kWh/m_2 of energy which was assumed as 10 kWh/m_2 saving energy. Consequently, their effectiveness in reducing energy demand was comparatively lower than other measures. At Blåsutgatan 8 Insulation with 200mm EPS for the exterior walls contributes to 19.56% of emissions (880,755 kg CO_2-eq), with the B6 stage being the predominant source, suggesting that the material's operational impact is considerable. However, at Byalagsgatan 8 improving walls placed at 4^{th} place by emitting 19.66% (1,019,505 kg CO_2 eq), because its impact on reducing energy demand was considerable. Upgrading the ventilation system represents 19.82% (1,027,923 kg CO_2-eq) at Byalagsgatan 8. Its impact regarding energy demand reduction at Byalagsgatan 8 is not as much as Blåsutgatan 8. Ventilation's share at Blåsutgatan 8 is 17.82% of emissions (802,715 kg CO_2-eq), with the B6 stage again being a significant contributor, highlighting the operational impact of the system over time. The least producer of CO_2 is PVC window replacement accounts for 17.05% of emissions (767,870 kg CO_2-eq), and 18.46% (957,567.19 kg CO_2-eq) at Blåsutgatan 8, and Byalagsgatan 8 respectively with production and disposal processes contributing notably to the B6 stage.

This analysis underscores the importance of considering the life cycle stages of building components, particularly the use phase, to understand and mitigate their environmental footprint effectively. The pie charts provide insight into identifying the primary stage responsible for emissions and pinpointing areas with potential for CO_2 reduction. Figure 65 , and Figure 66 provide bar charts illustrating the CO_2 emissions across various stages.

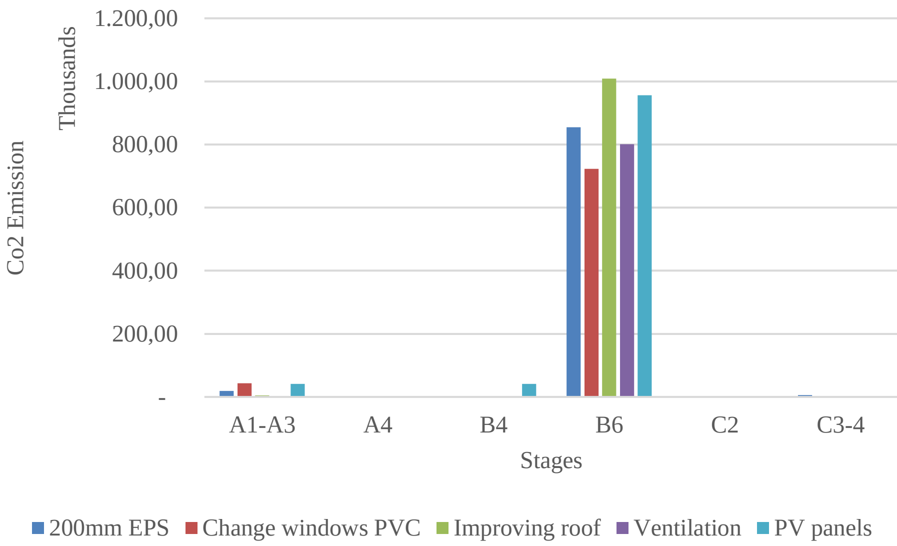

Figure 65- CO_2 emission in each stage among five main renovation measures at Blåsutgatan 8

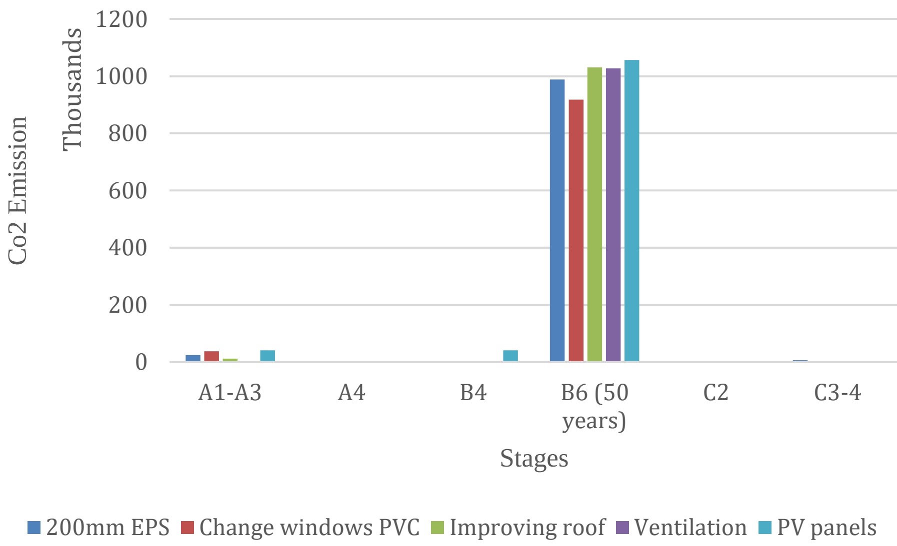

Figure 66- CO_2 emission in each stage among five main renovation measures at Byalagsgatan 8

The bar charts detail the emissions in thousands of kilograms of CO_2 equivalent with the B6 stage showing the highest emissions for all measures, indicating the significant impact of the use phase on the building's environmental footprint.

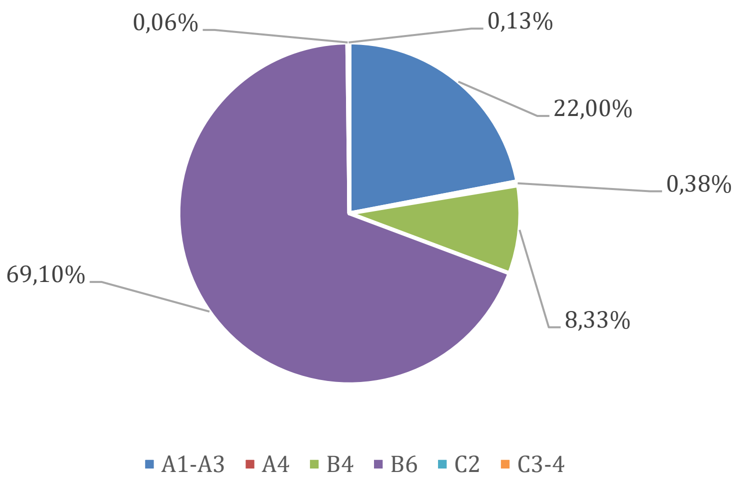

Figure 67- Distribution of CO_2-eq among five main renovation measures at Blåsutgatan 8

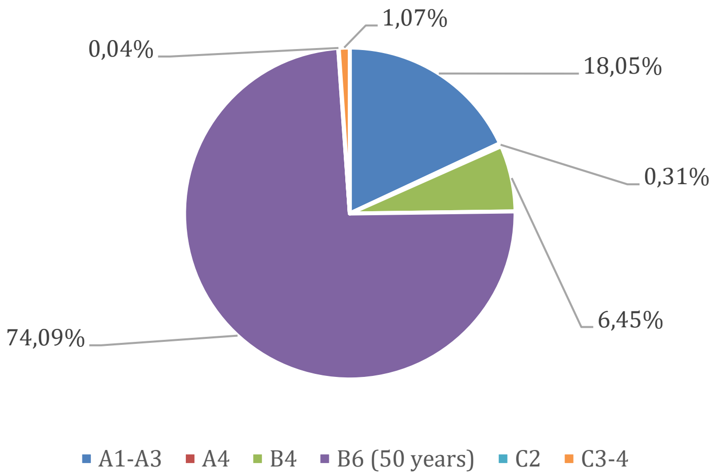

Figure 68- Distribution of CO_2-eq among five main renovation measures at Byalagsgatan 8

The pie charts above confirm same conclusion by providing a percentage breakdown of the emissions, with the majority occurring in usage phase including B6 (69% at Blåsutgatan 8, and 74% at Byalagsgatan 8), followed by production stage including A1-A3 (22% at Blåsutgatan 8, and 18% at Byalagsgatan 8). The remaining stages contributing less than 9%, and 8% combined at Blåsutgatan 8 and Byalagsgatan 8, respectively.

A key point from the above charts is the significant role of the "usage" stage as the primary contributor, attributed to the building's energy demand over its 50-year lifespan. This underscores its importance as a focal point for potential CO_2 emissions reduction efforts.

5.4.3. The Best Scenario from LCA Perspective

The best choice is determined by comparing the Total (kg CO_2 eq) of each scenario from cradle to grave, considering the stages mentioned before, across different lifespans, similar to the LCC part, shown in Table 56, and Table 57.

Table 56- CO_2 kg eq in different lifespans at Blåsutgatan 8

Scenario	Renovation Measures	CO_2 eq-10Y	CO_2 eq-15Y	CO_2 eq-20Y	CO_2 eq-35Y	CO_2 eq-50Y
0	Nothing	206165.25	309247.88	412330.50	721578.3	1030826.3
1a	100mm EPS	188356.31	276103.71	363851.12	627093.3	890335.53

1b	120mm EPS	189432.49	276431.84	363431.18	624429.2	885427.23
1c	150mm EPS	191645.21	277821.69	363998.17	622527.6	881057.03
1d	200mm EPS	196729.46	282232.68	367735.91	624245.6	880755.24
2	Change windows PVC	189171.10	261508.47	333845.84	550858	767870.08
3	Improving roof	206518.47	307431.73	408344.98	711084.7	1013824.5
4	Ventilation	161777.10	241894.29	322011.49	562363.1	802714.65
5	PV panels	273475.04	369077.07	464679.10	751485.2	1038291.2
6	Improving wall + Change windows	184822.11	242123.49	299424.86	471329	643233.09
7	Improving wall + Improving roof	197681.13	281314.21	364947.28	615846.5	866745.72
8	Improving wall + Ventilation	158026.56	223406.98	288787.40	484928.6	681069.90
9	Improving wall + PV panels	264039.25	342061.88	420084.50	654152.4	888220.26
10	Change windows + Improving roof	191319.67	262385.34	333451.01	546648	759845.03
11	Change windows + Ventilation	149720.14	201560.68	253401.22	408922.8	564444.44
12	Change windows + PV panels	237707.55	302564.32	367421.10	561991.4	756561.75
13	Improving roof + Ventilation	162130.32	240078.14	318025.96	551869.4	785712.88
14	Improving roof + PV panels	273828.26	367260.92	460693.58	740991.5	1021289.5
15	Ventilation + PV panels	244048.08	324165.28	404282.47	644634	884985.63
16	Improving wall + Change windows + Improving roof	186222.62	241878.26	297533.90	464500.8	631467.75
17	Improving wall + Change windows + Ventilation	143875.04	179931.52	215987.99	324157.4	432326.86
18	Improving wall + Change windows + PV panels	252131.90	301952.68	351773.46	501235.8	650698.11
19	Improving wall + Improving roof + Ventilation	159427.07	223161.76	286896.44	478100.6	669304.56
20	Improving wall + Improving roof + PV panels	264990.92	341143.40	417295.87	645753.3	874210.74
21	Improving wall + Ventilation + PV panels	225336.35	283236.17	341135.99	514835.4	688534.92
22	Change windows + Improving roof + Ventilation	151569.49	201988.71	252407.93	403665.6	554923.27
23	Change windows + Improving roof + PV panels	258629.45	322214.53	385799.60	576554.9	767310.05
24	Change windows + Ventilation + PV panels	231991.13	283831.66	335672.20	491193.8	646715.42
25	Improving roof + Ventilation + PV panels	229440.11	299907.34	370374.56	581776.2	793177.90
26	Improving wall + Change windows + Improving roof + Ventilation	144677.10	178788.62	212900.14	315234.7	417569.27
27	Improving wall + Change windows + Improving roof + PV panels	253532.41	301707.46	349882.50	494407.6	638932.76
28	Change windows + Improving roof + Ventilation + PV panels	218879.27	261817.90	304756.53	433572.4	562388.29
29	Improving wall + PV panels + Improving roof + Ventilation	241698.05	305432.74	369167.43	560371.5	751575.54
30	Improving wall + Change windows + Ventilation + PV panels	211184.83	239760.71	268336.59	354064.2	439791.87
31	All	211986.89	238617.81	265248.74	345141.5	425034.29

Table 57- CO_2 kg eq in different lifespans at Byalagsgatan 8

Scenario	Renovation Measures	CO_2 eq-10Y	CO_2 eq-15Y	CO_2 eq-20Y	CO_2 eq-35Y	CO_2 eq-50Y
0	Nothing	226796.88	340195.32	453593.76	793789.09	1133984.41
1a	100mm EPS	217618.94	318702.62	419786.30	723037.33	1026288.36
1b	120mm EPS	219340.95	319740.47	420140.00	721338.57	1022537.14
1c	150mm EPS	222608.12	322323.49	422038.86	721184.97	1020331.09
1d	200mm EPS	228623.53	327483.70	426343.88	722924.42	1019504.96
2	Change windows PVC	222786.34	314633.95	406481.55	682024.37	957567.19
3	Improving roof	218299.29	321349.91	424400.53	733552.39	1042704.24
4	Ventilation	206254.90	308963.45	411671.99	719797.62	1027923.24
5	PV panels	290242.39	394233.72	498225.05	810199.05	1122173.04
6	Improving wall + Change windows	224612.99	301922.33	379231.68	611159.71	843087.74
7	Improving wall + Improving roof	219612.82	307868.62	396124.42	660891.82	925659.22
8	Improving wall + Ventilation	207226.36	294969.04	382711.73	645939.78	909167.84
9	Improving wall + PV panels	292069.04	381522.11	470975.18	739334.38	1007693.59
10	Change windows + Improving roof	212920.44	293736.07	374551.71	616998.60	859445.49
11	Change windows + Ventilation	202073.33	283145.52	364217.70	607434.27	850650.84
12	Change windows + PV panels	286231.86	368672.35	451112.85	698434.33	945755.82
13	Improving roof + Ventilation	196389.01	288065.57	379742.14	654771.84	929801.55
14	Improving roof + PV panels	281744.80	375388.31	469031.82	749962.35	1030892.87
15	Ventilation + PV panels	269700.42	363001.85	456303.28	736207.58	1016111.87
16	Improving wall + Change windows + Improving roof	214233.97	280254.78	346275.60	544338.03	742400.47

17	Improving wall + Change windows + Ventilation	203215.82	269407.67	335599.52	534175.07	732750.62
18	Improving wall + Change windows + PV panels	288058.50	355960.73	423862.97	627569.67	831276.37
19	Improving wall + Improving roof + Ventilation	196676.30	273044.94	349413.57	578519.47	807625.37
20	Improving wall + Improving roof + PV panels	283058.33	361907.02	440755.71	677301.78	913847.85
21	Improving wall + Ventilation + PV panels	270671.87	349007.44	427343.02	662349.74	897356.46
22	Change windows + Improving roof + Ventilation	192378.47	262504.20	332629.93	543007.13	753384.33
23	Change windows + Improving roof + PV panels	276365.96	347774.48	419183.00	633408.56	847634.12
24	Change windows + Ventilation + PV panels	265518.84	337183.92	408849.00	623844.23	838839.46
25	Improving roof + Ventilation + PV panels	259834.52	342103.98	424373.43	671181.80	917990.17
26	Improving wall + Change windows + Improving roof + Ventilation	193007.84	247996.68	302985.52	467952.03	632918.54
27	Improving wall + Change windows + Improving roof + PV panels	277625.68	334239.38	390853.09	560694.19	730535.29
28	Change windows + Improving roof + Ventilation + PV panels	255823.98	316542.60	377261.22	559417.09	741572.96
29	Improving wall + PV panels + Improving roof + Ventilation	260121.82	327083.34	394044.86	594929.43	795814.00
30	Improving wall + Change windows + Ventilation + PV panels	266661.33	323446.07	380230.81	550585.03	720939.25
31	All	256453.35	302035.08	347616.81	484361.99	621107.16

The baseline scenario (0), with no renovations, serves as a control, showing the highest emissions across all periods and highlighting the effectiveness of the renovation The data clearly illustrates that strategic renovation measures, especially when combined, can significantly reduce CO_2 emissions over time. The effectiveness of each measure or combination thereof varies, with some being more beneficial in the short term and others yielding greater long-term reductions.

Notably, insulation improvements (Scenarios 1a to 1d) demonstrate that increasing the thickness of EPS insulation consistently reduces CO_2 emissions, with the 200mm EPS in Scenario 1d achieving the most significant reductions. Similarly, replacing windows with PVC (Scenario 2) and improving roof insulation (Scenario 3) both result in notable decreases in emissions, particularly over longer spans of 35 and 50 years, underscoring their effectiveness in long-term sustainability efforts. The addition of ventilation systems (Scenario 4) also shows a progressive reduction in emissions, indicating growing benefits over time. Interestingly, the installation of photovoltaic (PV) panels (Scenario 5) initially increases CO_2 emissions, likely due to the embodied energy of the panels, but ultimately leads to substantial reductions, especially after 50 years.

When measures are combined, at Blåsutgatan 8, Scenario 17, which includes improving walls, changing windows, and ventilation, and at Byalagsgatan 8, Scenario 22, which includes changing windows, improving rood, and ventilation emits the least CO_2 in the shortest term. Additionally, Scenario 17 ranks second in 15, 20, and 35 years, and third in 50 years at Blåsutgatan 8. Scenario 22 at Byalagsgatan 8 placed at the second rank in 15 years, and 20 years.

Meanwhile, Scenario 26 has the lowest emissions during 15, 20, 35, and 50 years at Blåsutgatan 8, and during 15, 20, and 35 years at Byalagsgatan 8. It also ranked the second lowest in 10 years at both buildings. The best Scenario during 50 years at Byalagsgatan 8 is Scenario 31.

The reason PV panels are not included in the best scenario discussed earlier is due to possible errors in calculations and assumptions. However, it may be beneficial to include PV panels as well, as previous studies have identified them as one of the most effective solutions for enhancing the environmental sustainability of buildings, given their ability to generate renewable energy (See section 2.7.5). In other words, Scenario 31, which is already ranked third and second in 35 and 50 years at Blåsutgatan 8, and second and first during 35, and 50 years at Byalagsgatan 8 has the potential to be considered the best scenario even from an LCA perspective in long-term assessments. Nevertheless, these results will serve as the basis for further analysis to determine the best scenario. Consequently, Scenario 26 is selected as the best choice from an LCA perspective for both buildings.

5.5. Exploring the Best Scenario by Integrating LCC and LCA

In this section, the best scenario in different lifespans well be explored. According to the method outlined in section 3.8, the process begins with normalising all values. Next, the percentage contribution of each scenario in each lifespan is calculated. Then, the ratio is obtained by dividing NPV by CO_2 equivalent. Ultimately, the scenario with the highest ratio is identified as the best choice. Table 58 is representing the final values.

Table 58- NPV to CO_2-eq ratio at Blåsutgatan 8

Scenario	Renovation Measures	10 Years	15 Years	20 Years	35 Years	50 Years
0	Nothing	-23.3336	-10.2355	-5.46418	-3.34188	-2.69166
1a	100mm EPS	-1.11991	0.268848	0.353346	0.385105	0.365374
1b	120mm EPS	-0.99571	0.332132	0.39102	0.412222	0.388798
1c	150mm EPS	-1.29102	0.271646	0.380278	0.424646	0.405452
1d	200mm EPS	-1.28212	0.285694	0.394458	0.441363	0.422283
2	Change windows PVC	-2.61536	0.451493	0.724106	0.862439	0.840529
3	Improving roof	0.142658	0.116732	0.076922	0.058596	0.050913
4	Ventilation	3.986651	2.159986	1.263261	0.85929	0.719887
5	PV panels	0.426295	0.352137	0.239823	0.193281	0.172383
6	Improving wall + Change windows	-4.68383	0.498103	1.10614	1.466285	1.47518
7	Improving wall + Improving roof	-1.19755	0.381535	0.465621	0.503674	0.479368
8	Improving wall + Ventilation	1.645672	2.30894	1.695748	1.427538	1.282215
9	Improving wall + PV panels	-0.27283	0.648354	0.603569	0.643225	0.620242
10	Change windows + Improving roof	-2.65096	0.481704	0.760322	0.906888	0.885538
11	Change windows + Ventilation	0.233745	2.801914	2.346354	2.202289	2.049511
12	Change windows + PV panels	-1.5909	0.819776	0.961242	1.103806	1.089667
13	Improving roof + Ventilation	4.159681	2.325807	1.37786	0.95113	0.801159
14	Improving roof + PV panels	0.533337	0.451594	0.310079	0.252249	0.225793
15	Ventilation + PV panels	3.12041	2.01272	1.28184	0.974942	0.855209
16	Improving wall + Change windows + Improving roof	-4.62162	0.5805	1.180273	1.551169	1.562086
17	Improving wall + Change windows + Ventilation	-2.09222	3.280465	3.242704	3.498568	3.424349
18	Improving wall + Change windows + PV panels	-2.97104	0.829825	1.258329	1.668577	1.73332
19	Improving wall + Improving roof + Ventilation	1.662733	2.400237	1.776516	1.509455	1.360816
20	Improving wall + Improving roof + PV panels	-0.45342	0.695592	0.674265	0.705275	0.680012
21	Improving wall + Ventilation + PV panels	1.671462	2.280072	1.762205	1.626737	1.528262
22	Change windows + Improving roof + Ventilation	0.194947	2.859925	2.415255	2.29084	2.141407
23	Change windows + Improving roof + PV panels	-1.51027	0.795612	0.946012	1.111771	1.110183
24	Change windows + Ventilation + PV panels	0.653376	2.447652	2.103272	2.129128	2.065543
25	Improving roof + Ventilation + PV panels	3.447486	2.295179	1.484	1.151899	1.019272
26	Improving wall + Change windows + Improving roof + Ventilation	-1.94938	3.463616	3.414233	3.713117	3.654517
27	Improving wall + Change windows + Improving roof + PV panels	-2.93481	0.896152	1.322193	1.751121	1.823964
28	Change windows + Improving roof + Ventilation + PV panels	0.667625	2.702787	2.366054	2.467826	2.431238
29	Improving wall + PV panels + Improving roof + Ventilation	1.579102	2.179225	1.68248	0.207362	1.449999
30	Improving wall + Change windows + Ventilation + PV panels	-0.87335	3.00393	3.025402	3.613284	3.773197
31	All	-0.78047	3.139835	3.160549	3.559934	4.011435

As evident from the table above, Scenario 13, which includes improving the roof and ventilation, emerges as the best choice for the 10-year timeframe. For the 15, 20, and 35-year durations, Scenario 26, incorporating improvements to the wall, windows, roof, and ventilation, is deemed best. Lastly, for the 50-year period, Scenario 31, encompassing all measurements, is selected as the best scenario.

Table 59 illustrates the final values at Byalagsgatan 8.

Table 59- NPV to CO_2-eq ratio at Byalagsgatan 8

Scenario	Renovation Measures	10 Years	15 Years	20 Years	35 Years	50 Years
0	Nothing	-11.904546	-34.507412	-10.393599	-5.383022	-4.144693
1a	100mm EPS	-1.317515	-1.147233	0.071158	0.321373	0.336348
1b	120mm EPS	-1.269531	-0.993069	0.122902	0.353420	0.363075
1c	150mm EPS	-1.456378	-1.309775	0.067556	0.354881	0.374331
1d	200mm EPS	-1.430134	-1.218527	0.105181	0.385825	0.402940
2	Change windows PVC	-1.376898	-0.280424	0.527414	0.710441	0.688869
3	Improving roof	0.691431	2.493443	0.826736	0.479575	0.385245
4	Ventilation	0.498782	2.193402	0.773339	0.475452	0.388999
5	PV panels	0.204927	1.111419	0.425461	0.288771	0.245599
6	Improving wall + Change windows	-2.821371	-1.613921	0.683559	1.249199	1.269664
7	Improving wall + Improving roof	-0.926600	0.918512	0.877866	0.888559	0.826088
8	Improving wall + Ventilation	-1.032231	1.094687	0.995481	0.986569	0.911144
9	Improving wall + PV panels	-0.749760	0.316192	0.559715	0.693711	0.681163
10	Change windows + Improving roof	-0.655297	2.668592	1.585081	1.397266	1.267900
11	Change windows + Ventilation	-0.998854	2.113059	1.472475	1.366386	1.249683
12	Change windows + PV panels	-0.863900	0.949157	0.945129	1.028729	0.988884
13	Improving roof + Ventilation	1.375353	5.379934	1.837227	1.099318	0.892571
14	Improving roof + PV panels	0.746837	3.301718	1.200010	0.781047	0.657004
15	Ventilation + PV panels	0.601981	3.073923	1.162247	0.782648	0.664755
16	Improving wall + Change windows + Improving roof	-2.148959	1.467855	1.874819	2.113946	2.035457
17	Improving wall + Change windows + Ventilation	-2.562102	0.871051	1.774038	2.100065	2.030734
18	Improving wall + Change windows + PV panels	-1.993477	-0.137993	1.111687	1.589341	1.619247
19	Improving wall + Improving roof + Ventilation	-0.195921	4.506233	2.216612	1.776479	1.575747
20	Improving wall + Improving roof + PV panels	-0.508781	1.992058	1.269909	1.212463	1.138352
21	Improving wall + Ventilation + PV panels	-0.570532	2.180634	1.387545	1.315357	1.230266
22	Change windows + Improving roof + Ventilation	-0.190510	5.567693	2.741956	2.217909	1.977148
23	Change windows + Improving roof + PV panels	-0.289644	3.513830	1.922001	1.730436	1.610713
24	Change windows + Ventilation + PV panels	-0.536171	3.073877	1.830204	1.705477	1.595834
25	Improving roof + Ventilation + PV panels	1.268433	5.810902	2.143508	1.421023	1.204281
26	Improving wall + Change windows + Improving roof + Ventilation	-1.810078	4.534201	3.240378	3.217895	3.041723
27	Improving wall + Change windows + Improving roof + PV panels	-1.444037	2.541687	2.203333	2.469551	2.445779
28	Change windows + Improving roof + Ventilation + PV panels	0.089235	6.001409	2.979453	2.571074	2.380287
29	Improving wall + PV panels + Improving roof + Ventilation	0.080522	5.101339	2.503496	0.194019	1.945452
30	Improving wall + Change windows + Ventilation + PV panels	-1.729464	2.080182	2.123294	2.462406	2.446289
31	All	-1.130346	5.173656	3.434135	3.302347	3.543297

The results for Byalagsgatan 8 are easier to analyse. Over a 10-year period, the best scenario is similar to that of Blåsutgatan 8, which is Scenario 13. However, for a 15-year lifespan, the best scenario is Scenario 28, which includes changing windows, improving the roof, enhancing ventilation, and installing PV panels. For longer periods of 20, 35, and 50 years, Scenario 31, which encompasses all measures, is the best scenario.

<u>Visual Comparison:</u>

<u>Blåsutgatan 8:</u>

Figure 69, Figure 70, Figure 71, Figure 72, and Figure 73 are showing the comparison between LCA and LCC results in different lifespans at Blåsutgatan 8. The best scenario is marked in red.

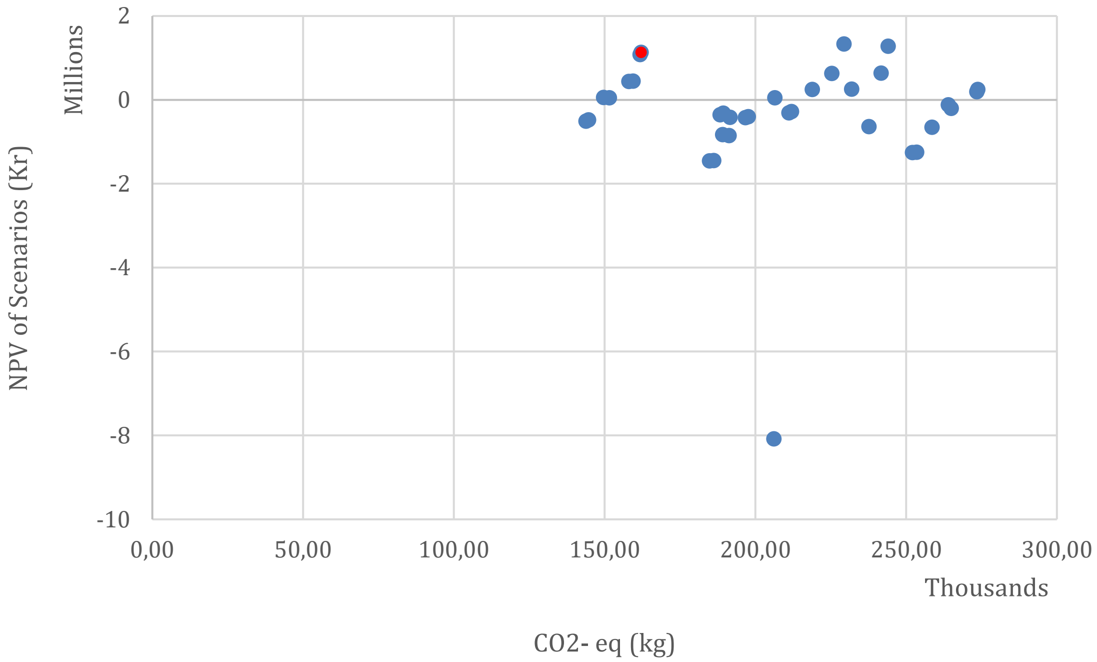

Figure 69- Relationship between CO_2-eq and NPV of Scenarios in 10 years at Blåsutgatan 8.

Best Scenario:

Scenario 13: Improving roof + ventilation.

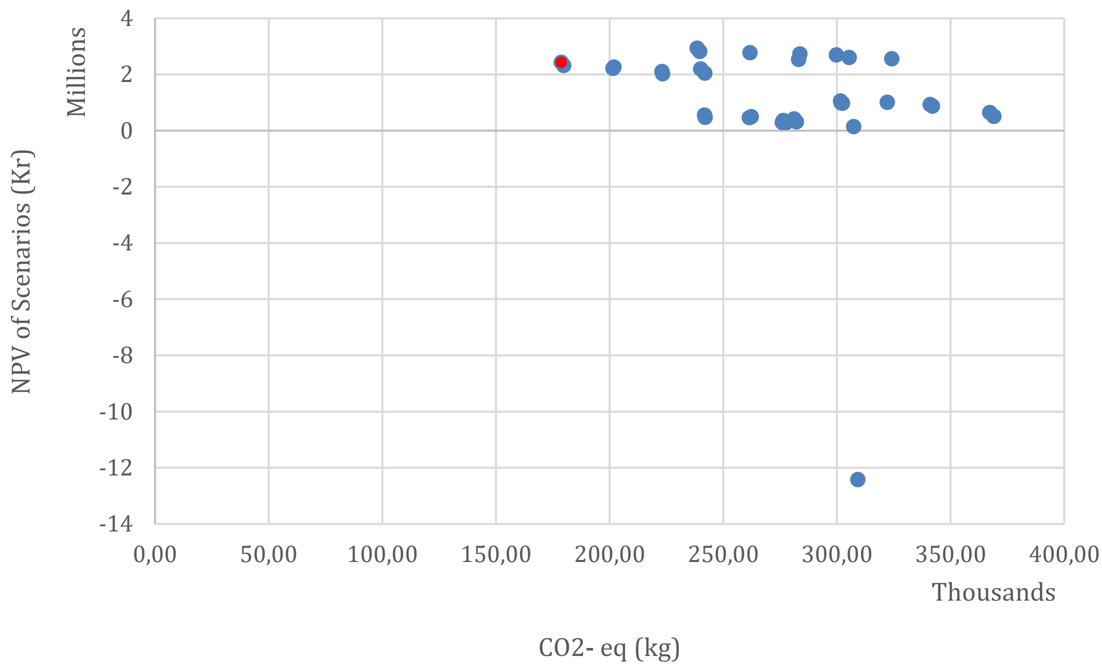

Figure 70- Relationship between CO_2-eq and NPV of Scenarios in 15 years at Blåsutgatan 8.

Best Scenario:

Scenario 26: Improving wall + Change windows + Improving roof + Ventilation.

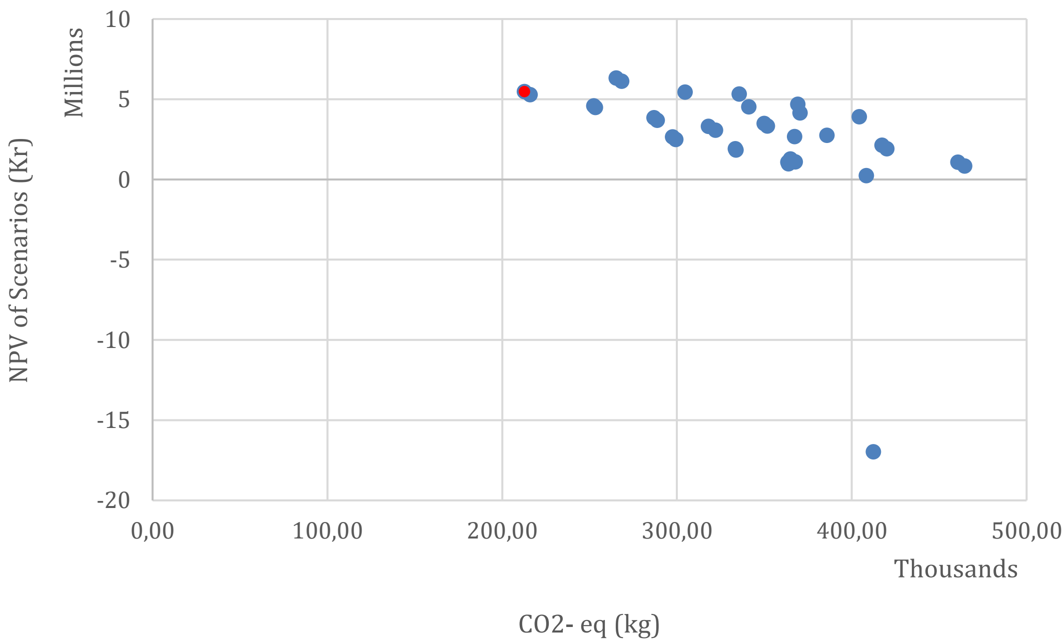

Figure 71- Relationship between CO_2-eq and NPV of Scenarios in 20 years at Blåsutgatan 8.

Best Scenario:

Scenario 26: Improving wall + Change windows + Improving roof + Ventilation.

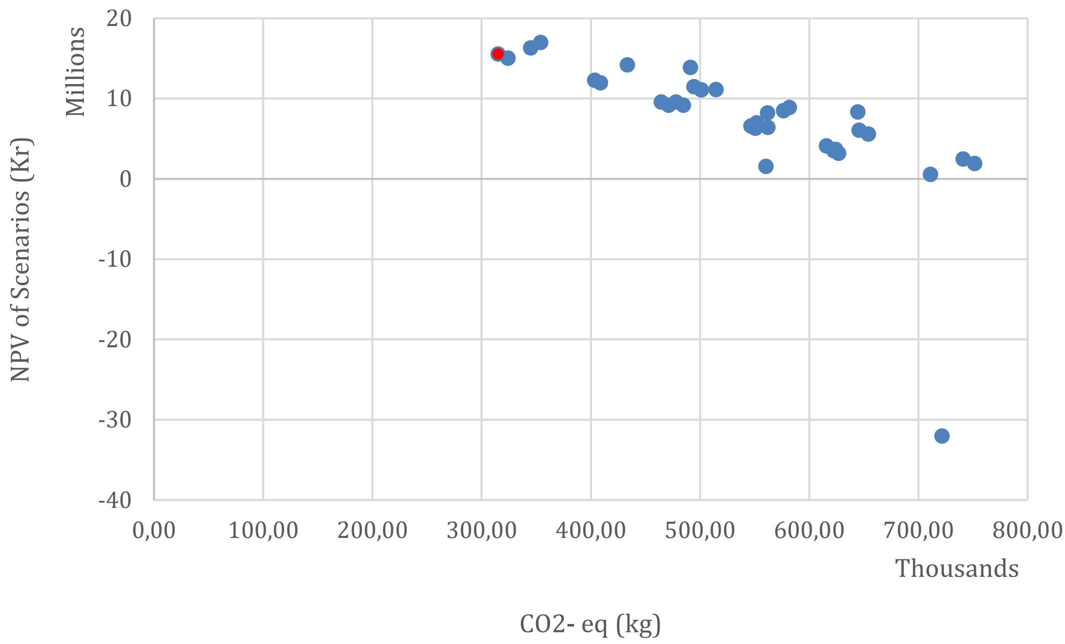

Figure 72- Relationship between CO_2-eq and NPV of Scenarios in 35 years at Blåsutgatan 8.

Best Scenario:

Scenario 26: Improving wall + Change windows + Improving roof + Ventilation.

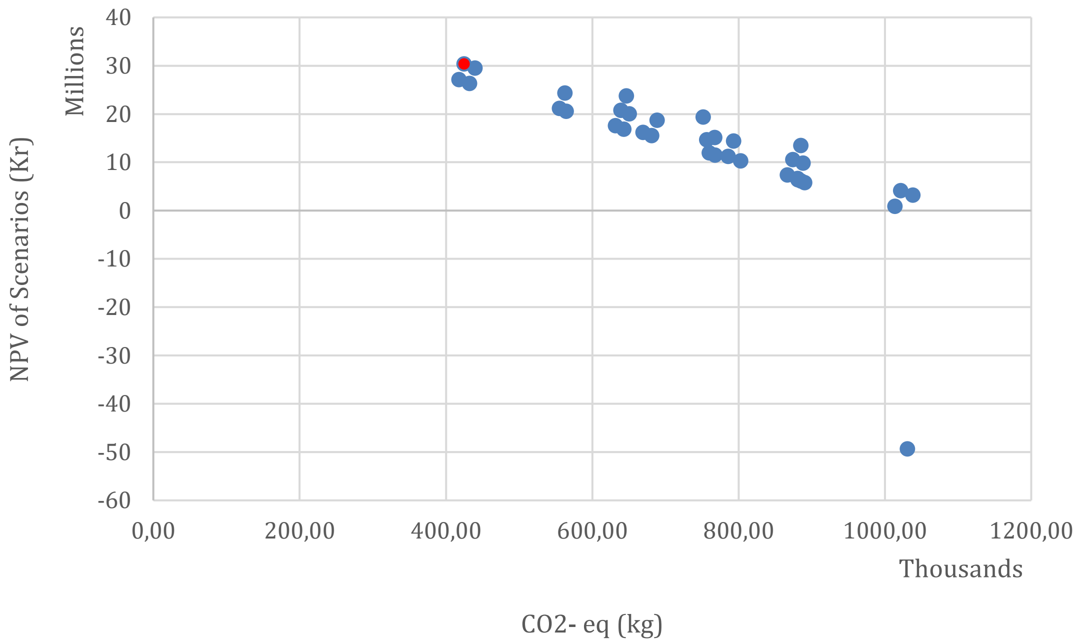

Figure 73- Relationship between CO_2-eq and NPV of Scenarios in 50 years at Blåsutgatan 8.

Best Scenario:

Scenario 31: Improving wall + Change windows + Improving roof + Ventilation+ PV Panels

Byalagsgatan 8:

Figure 74, Figure 75, Figure 76, Figure 77, and Figure 78 are showing the comparison between LCA and LCC results in different lifespans at Byalagsgatan 8. The best scenario is marked in red.

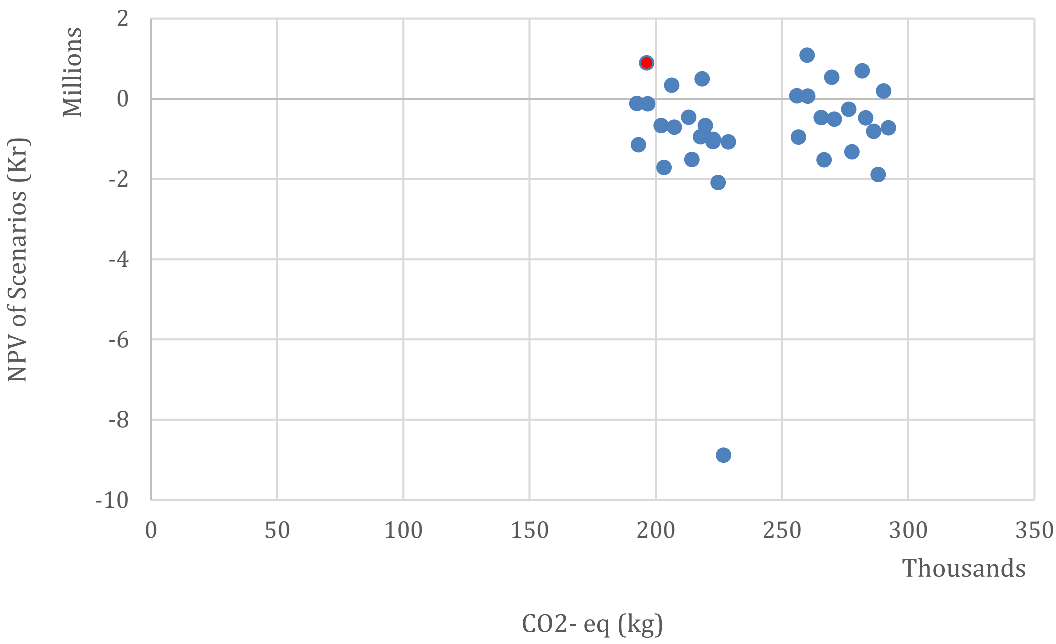

Figure 74- Relationship between CO_2-eq and NPV of Scenarios in 10 years at Byalagsgatan 8.

Best Scenario:

Scenario 13: Improving roof + ventilation.

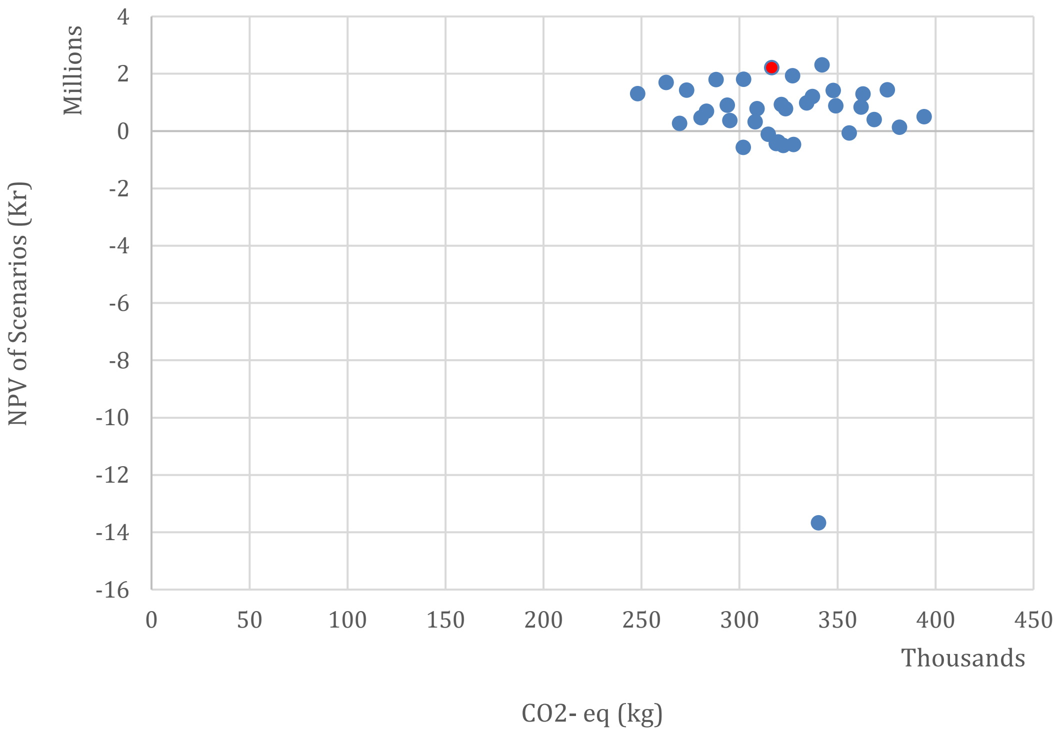

Figure 75- Relationship between CO_2-eq and NPV of Scenarios in 15 years at Byalagsgatan 8

Best Scenario:

Scenario 28: Change windows + Improving roof + Ventilation + PV panels.

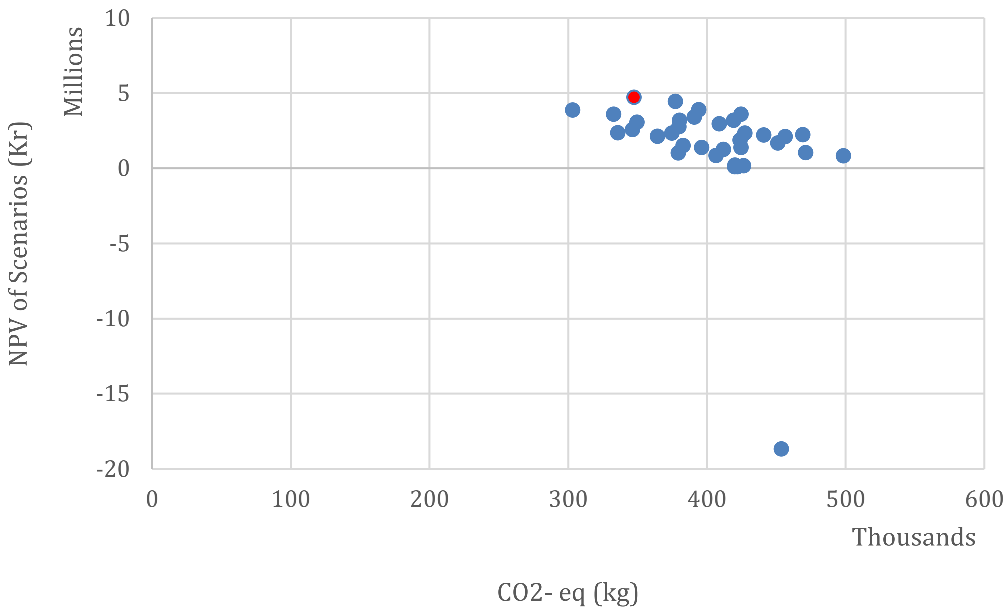

Figure 76- Relationship between CO_2-eq and NPV of Scenarios in 20 years at Byalagsgatan 8

Best Scenario:

Scenario 31: Improving wall + Change windows + Improving roof + Ventilation+ PV Panels

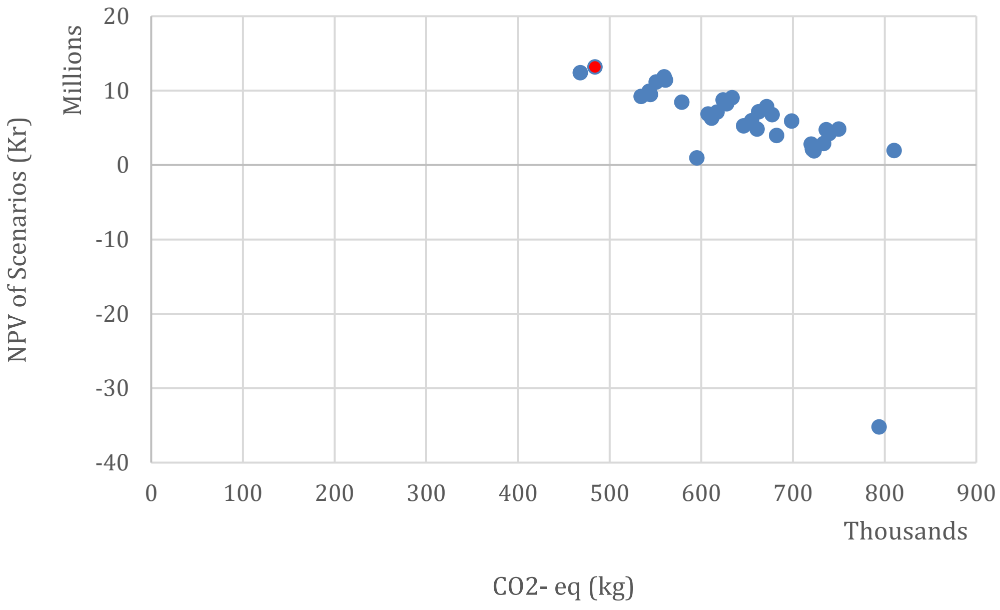

Figure 77- Relationship between CO_2-eq and NPV of Scenarios in 35 years at Byalagsgatan 8

Best Scenario:

Scenario 31: Improving wall + Change windows + Improving roof + Ventilation+ PV Panels

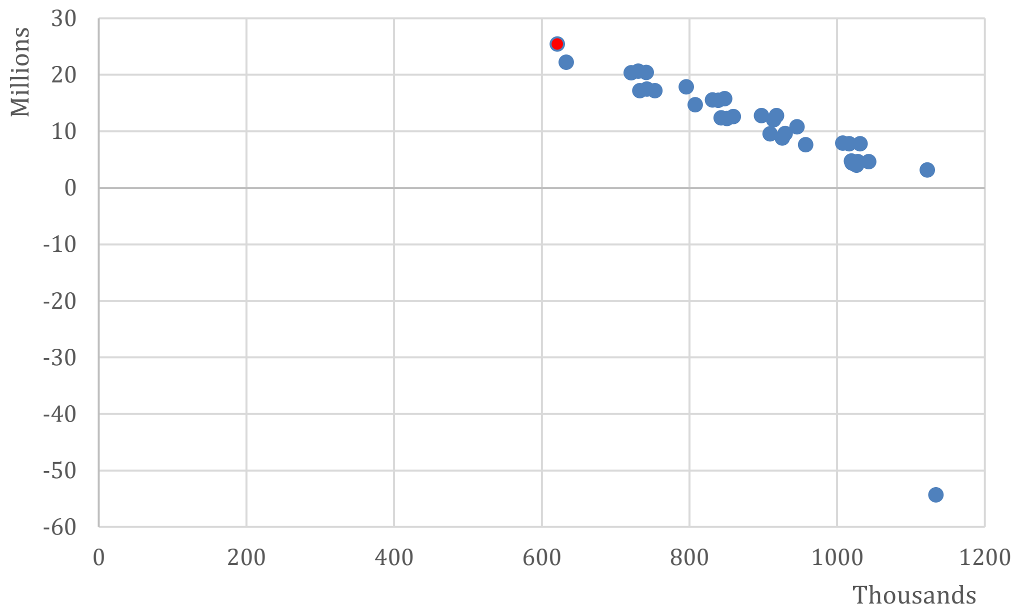

Figure 78- Relationship between CO_2-eq and NPV of Scenarios in 50 years at Byalagsgatan 8

Best Scenario:

Scenario 31: Improving wall + Change windows + Improving roof + Ventilation+ PV Panels

5.6. Added Floors

As described in the methodology, the best scenario should be selected for inclusion in the added floor scenario, known as Scenario 32. A lifespan of 50 years has been chosen for both LCA and LCC perspectives because it allows for a comprehensive evaluation of the building's costs and benefits over its expected operational life. This duration encompasses maintenance cycles, providing a realistic assessment of long-term financial and environmental impacts. Within this timeframe, Scenario 31, which includes all proposed measures, demonstrates the best performance. Consequently, Scenario 31 will be selected as the foundational scenario for conducting the LCC and LCA calculations for Scenario 32.

5.6.1. Energy Demand

Table 60 describes the changes in area, heating demand, and energy savings before and after Scenario 32, which is applying all renovation measures + adding floors.

Table 60- Energy performance before and after Scenario 32.

Building Name	Items	Existing Building	Added Floor	Unit
Blåsutgatan 8	Area	2807	3480	m^2
	Heating demand	137.8	45.1	kWh/m^2
	Saved Energy annually	0	229,857	kWh
Byalagsgatan 8	Area	3209	4139	$W/m^2/K$
	Heating demand	132.6	58.5	kWh/m^2
	Saved Energy annually	0	183,382	kWh

Reviewing Table 60 reveals that implementing Scenario 32 at Blåsutgatan 8 and Byalagsgatan 8 significantly reduces space heating energy demand—by approximately 67% at Blåsutgatan 8 and 56% at Byalagsgatan 8. These reductions exceed those achieved in Scenario 31. However, the total energy requirement for Scenario 32 is 156,948 kWh at Blåsutgatan 8 and 242,131 kWh at Byalagsgatan 8, which are 28,948 kWh and 35,793 kWh higher than Scenario 31, respectively. This increase is primarily due to the expansion of the building areas, with Blåsutgatan 8 increasing by 673 m² and Byalagsgatan 8 by 930 m², which consequently raises the overall heating load of the buildings.

5.6.2. LCC

In the design of the two additional floors, detailed in Section 4.6.1, the costs associated with roof improvements from the renovation scenarios were excluded. Instead, the expenses for demolishing the existing roof and constructing a new one were considered. The costs for photovoltaic (PV) panels; however, remained unchanged.

In Scenario 32, the rent for the newly added apartments, which represents a source of revenue for the company, was evaluated. Consultations with real estate experts in the area helped establish the base rent. To minimise the risk of overly optimistic projections, the lowest figure mentioned by the experts was chosen as the base rent. The inflation rate for rent was also considered, similar to the escalation rate for energy at an annual rate of 5%. Table 61 presents details related to added apartments.

Table 61- Details of Newly Added Apartments

Building	Apartment Number	Total Apartment	Area (m²)	Total Area (m²)	Rent (SEK)
Blåsutgatan 8	8	8	84.2	673.6	13,000
Byalagsgatan 8	1	13	27	815	5,000
	11		65		10,000
	1		75		12,000

Table 62 provides a breakdown of the LCC for adding floors across mentioned five lifespans.

Table 62- LCC of Scenario 32

Buildings	Lifespan (Years)	Investment Cost (SEK)	NPV of Energy Cost (SEK)	NPV of Rent (SEK)	Final NPV (SEK)	IRR
Blåsutgatan 8	50	11,807,573	16,218,168	79,641,386	104,168,272	19.89%
	5		1,351,242	6,361,159	-2958129	-5.95%
	7		1,884,997	8,992,078	887,940	4.83%
	10		2,705,029	13,034,082	6796838	12.29%
	15		4,125,166	20,034,047	17029899	16.95%
	20		5,614,905	27,377,083	27,764,488	18.61%
	35		10,536,686	51,636,921	61,941,126	19.76%
Byalagsgatan 8	50	11,807,573	18,555,314	97,254,384	126,859,298	23.37%
	5		1,559,246	7,767,954	-849617	0.45%
	6		1,862,884	9,366,646	143192	6.46%
	10		3,106,914	15,916,619	10779601	17.31%
	15		4,730,433	24,464,653	22978771	21.25%
	20		6,433,522	33,431,630	35,775,827	22.54%
	35		12,060,168	63,056,624	76,766,424	23.31%

According to Table 62, it takes only after 7 years at Blåsutgatan 8, and 6 years at Byalagsgatan 8 that the final NPV becomes positive, achieving an IRR of 4.83% and 6.46%, respectively. These milestones can serve as a significant incentive for investor companies, indicating a turning point where the investment starts yielding financial gains.

5.6.3. LCA

Table 63 shows each stage's CO_2-eq in Scenario 32.

Table 63- CO_2-eq of all stages individually

Buildings Name	Lifespan	Product	Construction	Use		End of Life		Total (kg CO_2-eq)
Blåsutgatan 8		A1-A3	A4	B4	B6	C2	C3-4	
	10	151 751	6 915	42 095	65 104	530	3017	269 412
	15				97 656			301 964
	20				130 208			323 516
	35				227 865			432 174
	50				325 522			529 830
Byalagsgatan 8	10	180 428	9807	43 633	109 200	1185	9825	354 078
	15				163 800			408 678
	20				218 400			463 278
	35				382 201			627 079
	50				546 002			790 880

To effectively assess the LCA of Scenario 32, it is crucial to identify the stage with the most significant environmental impact. Figure 79, provides a visual representation of the contribution of each stage across various lifespans.

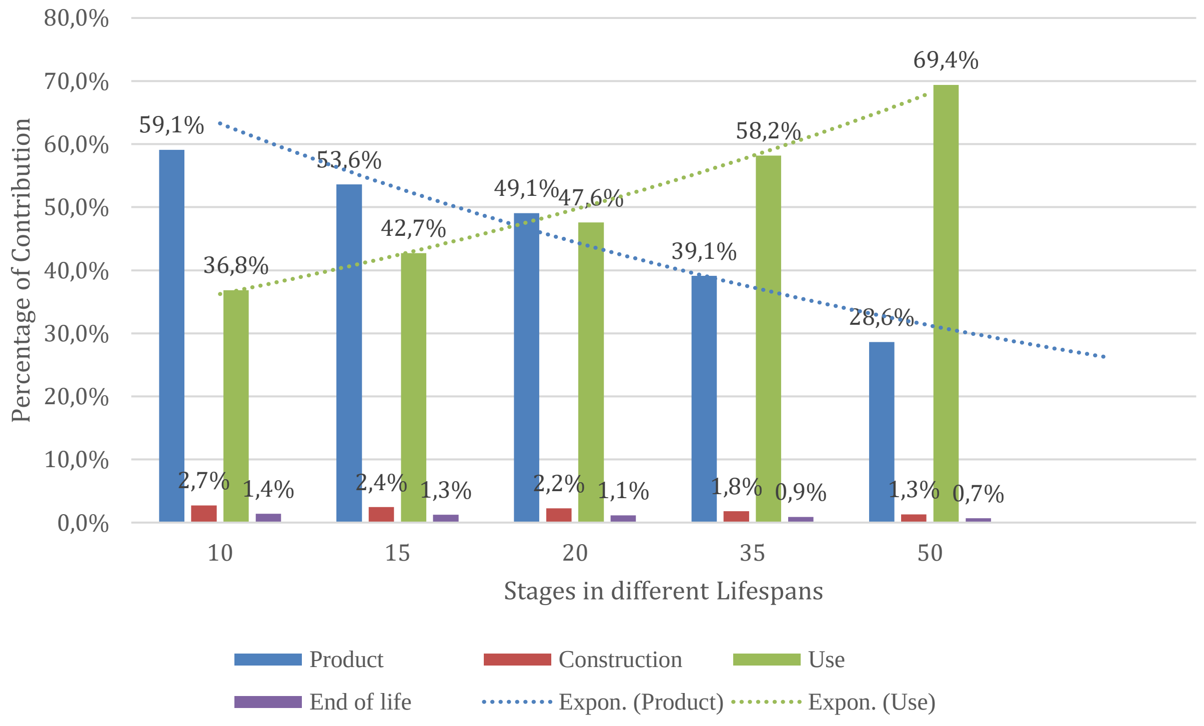

Figure 79- contribution of each stage across different lifespans at Blåsutgatan 8.

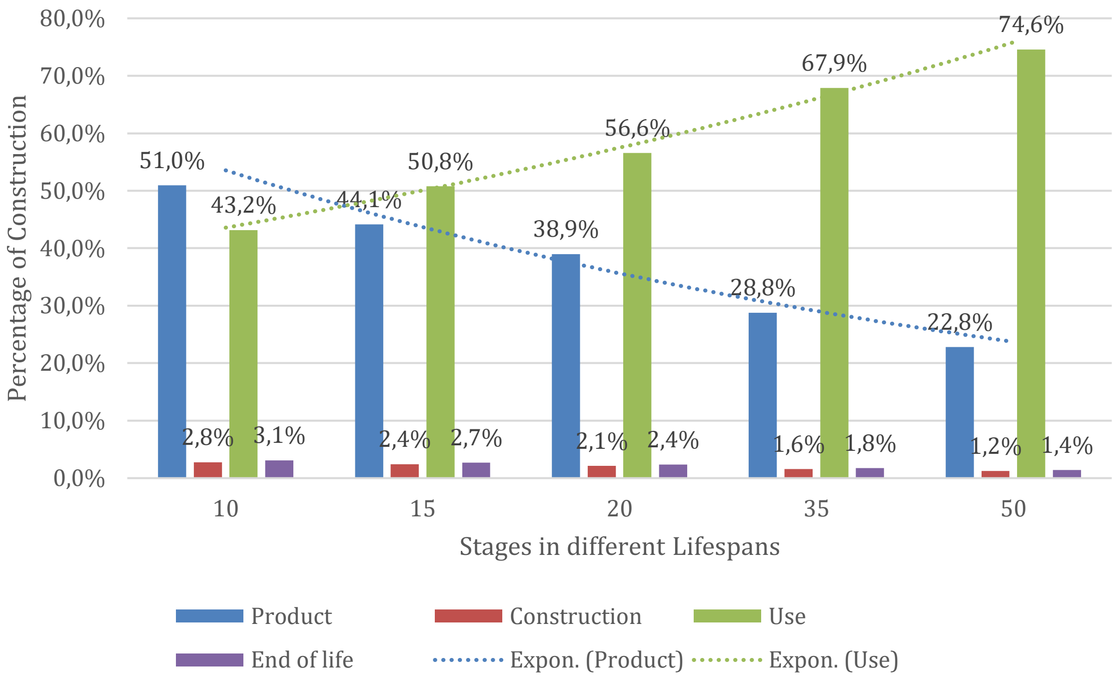

Figure 80 - Contribution of each stage across different lifespans at Byalagsgatan 8.

As depicted in the bar chart for Blåsutgatan 8, the Product stage (A1-A3) emerges as the primary contributor to emissions during the 10, 15, and 20-year lifespans, accounting for approximately 60%, 54%, and 50% of total emissions, respectively. However, during the 35 and 50-year lifespans, the Use stage becomes the predominant hotspot, constituting about 58% and 70% of emissions, respectively.

A similar trend can be observed at Byalagsgatan 8. While the Product stage is the primary contributor during the 10-year lifespan, accounting for 51% of total emissions, the Use stage becomes the main contributor during the longer lifespans, encompassing 50.8%, 56.6%, 67.9%, and 47.6% of the total emissions during the 15, 20, 35, and 50-year lifespans, respectively.

The bar charts demonstrate a clear trend where, over time, the impact of energy demand during the Use stage increasingly surpasses that of the Product stage. This shift highlights the growing significance of managing energy use as the lifespan extends.

As the Product stage is identified as one the main contributors for environmental impact in short terms, detailed analysis is beneficial. Table 64 displays the CO_2 emissions associated with each module of the product stage.

Table 64- CO_2- eq in each module of the product stage (A1-A3).

Process	**Amount (kg CO_2-eq)**	
	Blåsutgatan 8	**Byalagsgatan 8**
Ceilings	10239.03	15111.84
Doors	4897.72	6513.96
Exterior Walls	4897.72	10699.96
Interior Walls	4758.033	8129.2
Roof	4222.09	11719.9
Ventilation	129.15	104.92
Staircase	1759.22	879.11
Windows	10805.79	12294.58

Figures 83 and 84 depict the distribution of CO_2-equivalent emissions as percentages across various modules in the product stage at Blåsutgatan 8 and Byalagsgatan 8, respectively.

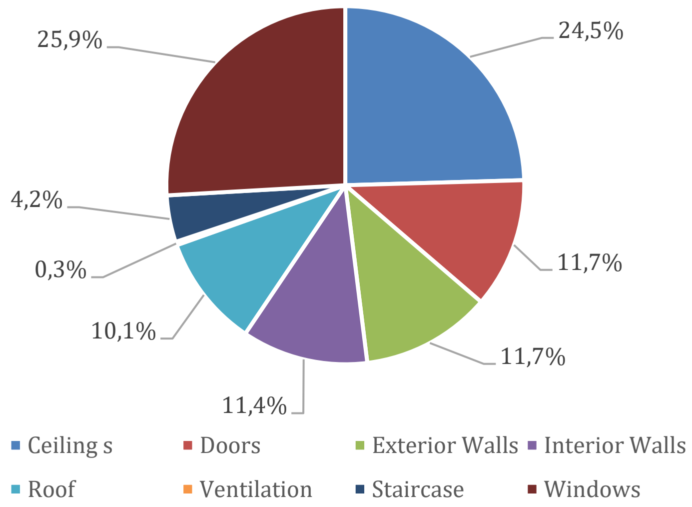

Figure 81- Distribution of CO_2-eq in the Product stage's modules at Blåsutgatan 8.

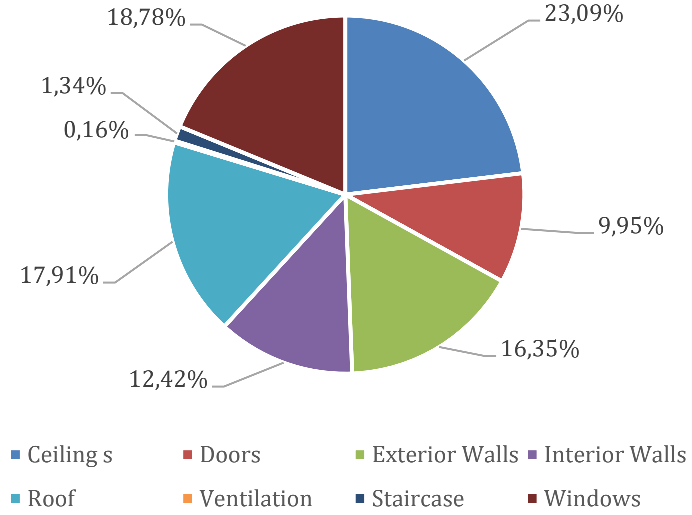

Figure 82- Distribution of CO_2-eq in the Product stage's modules at Byalagsgatan 8.

At Blåsutgatan 8, the pie chart reveals that the largest share of emissions is attributed to windows, accounting for 25.9%, closely followed by ceilings at 24.5%. Exterior walls and doors each contribute 11.7% of the emissions, while the roof is associated with 10.1%. The staircase has a smaller impact at 4.2%, and ventilation has the least effect, representing only 0.3% of the emissions.

At Byalagsgatan 8, the pie chart shows that the largest share of emissions is attributed to ceilings, which account for 23.09%, closely followed by windows at 18.78%. The roof is associated with 17.91% of emissions. The larger area of the roof and ceiling at Byalagsgatan 8 compared to Blåsutgatan 8 results in their higher contribution to CO_2 emissions. Ventilation has the least effect here as well, representing only 0.16% of the emissions.

This distribution highlights areas where environmental impact reduction efforts could be most effective, particularly focusing on windows and ceilings, which are the major contributors to the building's carbon footprint during the product stage.

6. Discussion

This chapter discusses about the analysis of the findings obtained from the energy demand simulations, financial viability assessments, and environmental impact evaluations conducted for the renovation of Blåsutgatan 8 and Byalagsgatan 8. The results were derived through a combination of LCC analysis, LCA, and energy performance simulations using software. The study also compares these findings with existing literature to contextualise the results and identifies practical implications and limitations.

6.1. Analysis of the Findings

Energy Demand Reduction

The energy demand simulations for Blåsutgatan 8 and Byalagsgatan 8 revealed substantial reductions post-renovation. Blåsutgatan 8's energy demand decreased from 137.8 kWh/m² to 45.6 kWh/m², and Byalagsgatan 8's from 132.6 kWh/m² to 64.3 kWh/m². These reductions of approximately 67% and 51% respectively demonstrate the effectiveness of comprehensive renovation strategies.

Financial Viability

LCC analysis identified Scenario 31 as the most financially viable for both buildings. Blåsutgatan 8 achieved an IRR of 14% and an NPV of 30,336,440 SEK, with a payback period of under 11 years. Byalagsgatan 8 showed an IRR of 12.9% and an NPV of 25,429,752 SEK, with a payback period of 12 years. These results underscore the financial benefits of extensive renovations.

Environmental Impact

Scenario 31 also proved to be the most environmentally beneficial, reducing the Global Warming Potential (GWP) to 151 kg CO_2-eq/m² for Blåsutgatan 8 and 194 kg CO_2-eq/m² for Byalagsgatan 8 over 50 years. These reductions highlight the significant environmental benefits of the renovation measures.

Table 65 shows a summary of results demonstrating the best scenario from the combination of LCC and LCA perspectives for each lifespan.

Table 65- Summary of results

Buildings	Lifespan (Years)	Best Scenario	Improvements Included
Blåsutgatan 8	10	13	Improving roof + Ventilation
Byalagsgatan 8			
Blåsutgatan 8	15	26	Improving wall + Change windows + Improving roof + Ventilation
Byalagsgatan 8		28	Change windows + Improving roof + Ventilation + PV panels
Blåsutgatan 8	20	26	Improving wall + Change windows + Improving roof + Ventilation
Byalagsgatan 8		31	All measurements (Wall, Windows, Roof, Ventilation, PV)
Blåsutgatan 8	35	26	Improving wall + Change windows + Improving roof + Ventilation
Byalagsgatan 8		31	All measurements (Wall, Windows, Roof, Ventilation, PV)
Blåsutgatan 8	50	31	All measurements (Wall, Windows, Roof, Ventilation, PV)
Byalagsgatan 8			

Efficiency of Added Floors

The energy demand for the added floors was significantly lower than the initial consumption of the existing buildings: 45.1 kWh/m² for Blåsutgatan 8 and 58.5 kWh/m² for Byalagsgatan 8. Financially, the added floors were highly viable, with Blåsutgatan 8 achieving an NPV of 104,168,272 SEK and an IRR of 19.9%, and Byalagsgatan 8 an NPV of 126,859,298 SEK and an IRR of 23.4%. The GWP for the added floors was also lower, reinforcing their environmental benefits.

6.2. Comparison with Literature

The findings of this study align with existing literature on energy efficiency improvements. Previous studies have shown that measures such as improved insulation, upgraded windows, and enhanced ventilation systems lead to substantial energy savings. For example, external wall insulation has been shown to reduce space heating energy use by about 29%, similar to the reductions observed here. The integration of PV panels for electricity generation, which exceeded consumption needs by 38.5% in Blåsutgatan 8 and 19.7% in Byalagsgatan 8, aligns with literature emphasising the potential of renewable energy sources.

Financially, the study's LCC analysis concurs with previous research that demonstrates the economic viability of energy-efficient renovations. Positive NPVs and IRRs underscore the long-term financial benefits. Environmentally, the significant reductions in GWP are consistent with findings that highlight the potential of comprehensive renovations to reduce carbon emissions and support sustainability goals.

Building-Specific Considerations

One notable deviation from the literature is the varying impact of roof improvements between the two buildings, likely due to differences in dimensions and roof areas. This highlights the importance of considering building-specific factors when evaluating renovation measures, an aspect not always prominently discussed in broader literature.

6.3. Limitations

Data Limitations

Incomplete Building Information:

For Blåsutgatan 8, specific details such as the section of the building and digital maps were unavailable. This necessitated assumptions and estimations regarding the building's dimensions and construction details, which may have introduced inaccuracies into the analysis. for Windows' U-values, and construction details of the buildings data about Miljonprogrammet in Sweden was used (Cecilia Björk, 2021, Friberg and Karlin, 2015, Laven and Strandberg, 2019, Mälardalen, 2013).

Data Gaps:

There were discrepancies between different data sources (e.g., BRF Blåsutgatan, Sweco, and DTE).

Material Specifications:

Some materials specified in the renovation scenarios were not directly available in the Ecoinvent database used for the LCA. Consequently, the closest available equivalents were used, which might not perfectly match the actual materials in terms of environmental impact and performance.

Assumptions in LCA and LCC:

Assumptions had to be made regarding the lifespan of building components, maintenance schedules, rents, and energy price escalation rates. These assumptions, while based on industry standards and expert recommendations, introduce a degree of uncertainty into the Life Cycle Cost (LCC) and LCA results.

Methodological Constraints

The methodologies employed in this study also presented certain constraints:

Simulation Tools:

The initial energy simulations were conducted using OpenStudio, but discrepancies with actual data led to a shift to BIM-Energy software.

LCA Database Limitations:

The Ecoinvent database, used for the LCA, did not contain all the specific materials and processes relevant to the renovation scenarios. This necessitated the use of proxy data, which may not fully capture the environmental impacts of the actual materials used.

Simplified Building Models:

To streamline the simulation process, certain simplifications were made in the building models. For example, the interior details of apartments were not modelled. These simplifications, while necessary for practical reasons, may have affected the accuracy of the energy demand simulations.

Exclusion of Certain LCA Phases:

The LCA focused on specific life cycle phases (A1-A3, A4, B4, B6, C2, C3, and C4) and excluded others (A5, B1-B3, B5, and C1). While this approach was based on previous studies indicating the major contributors to environmental impact, it may have overlooked some relevant impacts associated with the excluded phases.

Financial Analysis Assumptions:

The LCC analysis assumed constant energy price inflation and did not consider possible future fluctuations. Additionally, the analysis did not consider potential changes in regulatory frameworks or market conditions that could affect the financial viability of the renovation scenarios.

7. Conclusion

This study provides a thorough analysis that examines the financial and environmental advantages of different renovation strategies for existing multi-family residential buildings in Sweden, specifically looking at the potential benefits of expanding the floor (s). The study has conducted a comprehensive evaluation of the effects on energy demand, carbon emissions, and economic viability by combining Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) methodologies.

The recommended renovation strategy consists of implementing a range of energy-efficient measures, such as enhancing wall insulation, replacing windows, improving roof insulation, installing a heat recovery ventilation system, and integrating photovoltaic (PV) panels. In addition, the study investigated the advantages of incorporating additional level(s) into the renovation procedure. This comprehensive approach not only optimises energy conservation and cost-efficiency but also substantially diminishes the overall carbon emissions, bolstering Sweden's dedication to sustainable growth and efforts to mitigate climate change.

Among the renovation scenarios, Scenario 31 emerged as the best choice for both Blåsutgatan 8 and Byalagsgatan 8 over multiple lifespans. This scenario consistently provided the highest Net Present Value (NPV) after accounting for initial costs, ensuring a balanced approach to investment efficiency and sustainability. The integration of vertical expansion into the renovation process further enhanced the financial and environmental benefits by increasing rental space and property value while maintaining a lower carbon footprint compared to new constructions.

The LCA findings indicate that the usage phase (B6) is the main source of CO_2 emissions, emphasising the significance of implementing energy efficiency measures to decrease operational energy demand. The study's findings highlight the crucial importance of implementing comprehensive renovation strategies to successfully achieve long-term sustainability objectives for the Swedish residential sector. Stakeholders can make well-informed decisions that align with broader climate objectives and regulatory requirements by adopting an integrated approach that balances economic viability with environmental responsibility.

Practical Implications

The study's findings have significant practical implications for policymakers, property owners, and stakeholders in the building sector. Governments should provide financial incentives, such as tax credits, rebates, and low-interest loans, to encourage energy-efficient renovations. Updating building codes and standards to require higher energy efficiency in renovations is essential. Public awareness campaigns and training programs should educate stakeholders about the benefits of energy-efficient renovations. A comprehensive planning and assessment approach, including initial energy audits and integrated renovation plans, should be adopted. A phased renovation approach can help manage costs and minimize disruption to residents. Stakeholder engagement is crucial for the successful implementation of renovation projects.

Future Research

Further studies are needed to explore alternative renovation strategies, such as green roofs, advanced building automation systems, and innovative materials with superior thermal properties. Extending the analysis to other building typologies, such as single-family homes, commercial buildings, and offices, would provide a more comprehensive understanding of renovation strategies across diverse building stocks. Regional variations within Sweden should be considered, as climatic conditions, energy sources, and construction practices vary. Incorporating occupant behaviour patterns, comfort preferences, and their impact on energy demand could enhance the accuracy of energy simulations and provide insights into potential energy-saving measures through occupant engagement. Exploring the integration of renovated buildings with district heating and cooling systems, and the potential for energy exchange between buildings, could lead to more efficient and sustainable energy management strategies at a larger scale.

Technological advancements will play a crucial role in the future effectiveness of renovation strategies. Advanced building materials, such as aerogel insulation, phase change materials, or vacuum insulation panels, can improve energy efficiency while reducing insulation thickness. Smart building technologies, including IoT devices, sensors, and advanced building automation systems, enable real-time monitoring, control, and optimisation of building systems. The integration of renewable energy technologies, such as building-integrated photovoltaic (BIPV) systems, small-scale wind turbines, and energy storage solutions, should be further explored. Digital twins and Building Information Modelling (BIM) can facilitate accurate simulations, virtual testing of renovation scenarios, and data-driven decision-making throughout the building's lifecycle. The application of AI and machine learning algorithms can optimise building operations, predict maintenance needs, and identify energy-saving opportunities based on historical data and real-time monitoring.

8. References

ÅBERG, M. & HENNING, D. 2011. Optimisation of a Swedish district heating system with reduced heat demand due to energy efficiency measures in residential buildings. *Energy Policy,* 39**,** 7839-7852.

ADALBERTH, K. 2000. Energy use and environmental impact of new residential buildings.

ADL-ZARRABI, B., JOHANSSON, P., BATARD, A., BRUNNER, S., CAPOZZOLI, A., GALLIANO, R., HEINEMANN, U., GUDMUNSSON, K., FANTUCCI, S., KARAMI, P., MUKHOPADHYAYA, P., LORENZATI, A., PERINO, M., QUENARD, D., SPRENGARD, C., TREML, S. & YRIEIX, B. Annex 65, Long-Term Performance of Super-Insulating-Materials in Building Components and Systems. Report of Subtask III: Practical Applications – Retrofitting at the Building Scale – Field scale. 2020.

ADOLFSSON, L. & ANDERSSON, C. 2016. Multi-active Façades for Renovation of Million Program Houses.

ALASMARI, E., MARTINEZ-VAZQUEZ, P. & BANIOTOPOULOS, C. 2022. A Systematic Literature Review of the Adoption of Building Information Modelling (BIM) on Life Cycle Cost (LCC). *Buildings,* 12**,** 1829.

ALMEIDA, M., ASCIONE, F., BIANCO, N., IOVANE, T., MASTELLONE, M. & MATEUS, R. Weights of embodied energy and carbon emissions in an energy retrofit of the building envelope: Assessment for a Mediterranean residential building. 2023 8th International Conference on Smart and Sustainable Technologies (SpliTech), 2023. IEEE, 1-6.

ALMEIDA, M. & FERREIRA, M. 2018. Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation. *Building and Environment,* 143**,** 15-23.

ANDALORO, A., SALVALAI, G., FREGONESE, G., TSO, L. & PAOLETTI, G. 2021. Framework for Evaluating Financial Impacts of Technical Risks Related to Energy-Efficient Renovation of Commercial Office Buildings. *Environmental Sciences Proceedings,* 11**,** 32.

ANU, S. & KIMMO, I. 2015. Sustainable Buildings for the High North. Energy performance of current building stock in Scandinavia and Russia. *ePooki-Oulun ammattikorkeakoulun tutkimus-ja kehitystyön julkaisut*.

ASHRAFIAN, T., YILMAZ, Z. & MOAZZEN, N. A long-term strategy for energy and cost performance improvement of existing residential buildings: step-by-step renovation in Turkey. E3S Web of Conferences, 2019. EDP Sciences, 03040.

AXON, C. & DARTON, R. 2023. Energy Demand Reduction: supply chains and risk analysis. *Energy Efficiency,* 16**,** 84.

BAGINSKI, J. P. 2019. *Key drivers and barriers for energy efficient and sustainable household investments*. Dissertation, Duisburg, Essen, Universität Duisburg-Essen, 2019.

BANKVALL, C. G. 2013. *Luftboken: Luftrörelser och täthet i byggnader*, Studentlitteratur.

BATTISTI, F. & CAMPO, O. 2021. The assessment of density bonus in building renovation interventions. the case of the city of Florence in Italy. *Land,* 10**,** 1391.

BEEMSTERBOER, S. 2019. *Simplifying LCA use in the life cycle of residential buildings in Sweden*, Chalmers Tekniska Hogskola (Sweden).

BELAÏD, F., RANJBAR, Z. & MASSIÉ, C. 2021. Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. *Energy Policy,* 150**,** 112122.

BERGGREN, B. & WALL, M. 2019. Review of constructions and materials used in Swedish residential buildings during the post-war peak of production. *Buildings,* 9**,** 99.

BOJIĆ, M., MILETIĆ, M., MALEŠEVIĆ, J., DJORDJEVIĆ, S. & CVETKOVIĆ, D. 2012. Influence of additional storey construction to space heating of a residential building. *Energy and buildings,* 54**,** 511-518.

BOVERKET 2019. Boverket´ s Mandatory Provisions and General Recommendations, BBR, BFS 2011: 6 with Amendments up to BFS 2018: 4. Boverket Karlskrona, Sweden.

BOVERKET 2023. Utsläpp av växthusgaser från bygg- och fastighetssektorn.

BOVERKET, A. 2014. Under miljonprogrammet byggdes en miljon bostäder. Boverket Karlskrona, Sweden.
BROWN, N. W., MALMQVIST, T., BAI, W. & MOLINARI, M. 2013. Sustainability assessment of renovation packages for increased energy efficiency for multi-family buildings in Sweden. *Building and Environment,* 61**,** 140-148.
CARUSO, M., PINHO, R., BIANCHI, F., CAVALIERI, F. & LEMMO, M. T. 2020. A life cycle framework for the identification of optimal building renovation strategies considering economic and environmental impacts. *Sustainability,* 12**,** 10221.
CECILIA BJÖRK, P. K., LAILA REPPEN 2021. Så byggdes husen 1880-2020. 172.
CENTRALBYRÅN(SCB), S. 2023. Almost 5.2 million homes in the country.
CHERSONI, G., DELLAVALLE, N. & FONTANA, M. An agent-based model of retrofit diffusion.
CHRISTIS Z, C., RENOS, V., NICHOLAS, K., ROGIROS, I., CHRISTIANA A, F. & STATHIS, B. 2023. Seismic and energy upgrading of existing buildings—full‐scale testing of retrofitted masonry‐infilled RC frames. *Earthquake Engineering & Structural Dynamics,* 52**,** 4489-4517.
COMA, J., MALDONADO, J. M., DE GRACIA, A., GIMBERNAT, T., BOTARGUES, T. & CABEZA, L. F. 2019. Comparative analysis of energy demand and CO2 emissions on different typologies of residential buildings in Europe. *Energies,* 12**,** 2436.
COMMISSION, E. R.-E. 2010. Energy Performance of Buildings Directive 2010/31. *EU of the European Parliament and of the Council of,* 19.
CUCE, E. 2017. Role of airtightness in energy loss from windows: Experimental results from in-situ tests. *Energy and Buildings,* 139**,** 449-455.
DINEEN, D. & GALLACHÓIR, B. Ó. 2011. Modelling the impacts of building regulations and a property bubble on residential space and water heating. *Energy and Buildings,* 43**,** 166-178.
DODOO, A., GUSTAVSSON, L. & SATHRE, R. 2011. Primary energy implications of ventilation heat recovery in residential buildings. *Energy and Buildings,* 43**,** 1566-1572.
DOLGE, K. & BLUMBERGA, D. 2023. Transitioning to Clean Energy: A Comprehensive Analysis of Renewable Electricity Generation in the EU-27. *Energies,* 16**,** 6415.
DOLŠAK, J., HROVATIN, N. & ZORIĆ, J. Factors Impacting Energy Efficient Renovations In The Residential Sector: The Effectiveness Of The Slovenian Grant Program. Transforming Energy Markets, 41st IAEE International Conference, Jun 10-13, 2018, 2018. International Association for Energy Economics.
ECOINVENT 2024. System Models. Ecoinvent.
ENERGIMYNDIGHETEN 2021. Energy statistics for apartment buildings. *Swedish Energy Agency*.
ERIK BRADLEY, P. & KOHLER, N. 2007. Methodology for the survival analysis of urban building stocks. *Building Research & Information,* 35**,** 529-542.
FARAHANI, A., WALLBAUM, H. & DALENBÄCK, J.-O. 2019. Optimized maintenance and renovation scheduling in multifamily buildings–a systematic approach based on condition state and life cycle cost of building components. *Construction management and economics,* 37**,** 139-155.
FRIBERG, R. & KARLIN, V. 2015. Påbyggnad av miljonprogrammets flervåningshus ur ett bärförmågeperspektiv.
GAMAYUNOVA, O., RADAEV, A., PETRICHENKO, M. & DMITRIEVA, E. The increase in energy efficiency of residential buildings of military towns. E3S web of conferences, 2019. EDP Sciences, 02144.
GEORGESCU, E.-S., GEORGESCU, M. S., MACRI, Z., MARINO, E. M., MARGANI, G., MEITA, V., PANA, R., CASCONE, S. M., PETRAN, H. & ROSSI, P. P. 2018. Seismic and energy renovation: A review of the code requirements and solutions in Italy and Romania. *Sustainability,* 10**,** 1561.
GONTKOVIČOVÁ, B. & SPIŠÁKOVÁ, E. D. 2023. Climate and energy targets under Europe 2020 strategy and their fulfillment by member states. *Frontiers in Environmental Science*.
GOTA, S., HUIZENGA, C. & PEET, K. 2015. Emission reduction potential in the transport sector by 2030. *SLOCAT. Bejing: SLOCAT.*

GUSTAFSSON, M., DIPASQUALE, C., POPPI, S., BELLINI, A., FEDRIZZI, R., BALES, C., OCHS, F., SIÉ, M. & HOLMBERG, S. 2017. Economic and environmental analysis of energy renovation packages for European office buildings. *Energy and Buildings,* 148**,** 155-165.
HARTMANN, M., ALSAAD, H., MOSAYEBZADEH, M. & VOELKER, C. 2023. The reduction of building energy demand by a living wall system in a Central European climate. *Proceedings of Building Simulation 2023*.
HOLLBERG, A., KLÜBER, N., SCHNEIDER, S., RUTH, J. & DONATH, D. A method for evaluating the environmental life cycle potential of building geometry. Systems Thinking in the Built Environment. Sustainable Built Environment (SBE) Regional Conference Zurich, 2016. 590-595.
HUANG, L., KRIGSVOLL, G., JOHANSEN, F., LIU, Y. & ZHANG, X. 2018. Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews,* 81**,** 1906-1916.
HUANG, W., LI, F., CUI, S.-H., HUANG, L. & LIN, J.-Y. 2017. Carbon footprint and carbon emission reduction of urban buildings: a case in Xiamen City, China. *Procedia Engineering,* 198**,** 1007-1017.
JEROME, A., FEMENÍAS, P., THUVANDER, L., WAHLGREN, P. & JOHANSSON, P. 2021. Exploring the Relationship between Environmental and Economic Payback Times, and Heritage Values in an Energy Renovation of a Multi-Residential Pre-War Building. *Heritage,* 4**,** 3652-3675.
KARJALAINEN, M., ILGıN, H. E., METSÄRANTA, L. & NORVASUO, M. 2022. Wooden Facade Renovation and Additional Floor Construction for Suburban Development in Finland. *Nearly Zero Energy Building (NZEB): Materials, Design and New Approaches***,** 57.
KÜHN, L., FUCHS, N., BRAUN, L., MAIER, L. & MÜLLER, D. 2024. Landlord–Tenant Dilemma: How Does the Conflict Affect the Design of Building Energy Systems? *Energies,* 17**,** 686.
LA FLEUR, L., MOSHFEGH, B. & ROHDIN, P. 2017. Measured and predicted energy use and indoor climate before and after a major renovation of an apartment building in Sweden. *Energy and Buildings,* 146**,** 98-110.
LABARAN, Y. H., MATHUR, V. S., MUHAMMAD, S. U. & MUSA, A. A. 2022. Carbon footprint management: A review of construction industry. *Cleaner Engineering and Technology,* 9**,** 100531.
LANDWEHR, A. 2013. How can local governments push for ambitious energy-efficient renovation of privately owned million-program houses? : Malmö högskola/Kultur och samhälle.
LARSSON, M., ERLANDSSON, M., MALMQVIST, T. & KELLNER, J. 2016. Byggandets klimatpåverkan: Livscykelberäkning av klimatpåverkan för ett nyproducerat flerbostadshus med massiv stomme av trä.
LAVEN, F. & STRANDBERG, B. 2019. Bygga hus-illustrerad bygglära. Lund: Studentlitteratur AB.
LIU, W., YU, Z., WU, J., LI, H., GAO, C. & GONG, H. Influence of building air tightness on energy consumption of ventilation system in nearly zero energy residential buildings. E3S Web of Conferences, 2019. EDP Sciences, 03074.
MAGHRABIE, H. M., ABDELKAREEM, M. A., AL-ALAMI, A. H., RAMADAN, M., MUSHTAHA, E., WILBERFORCE, T. & OLABI, A. G. 2021. State-of-the-art technologies for building-integrated photovoltaic systems. *Buildings,* 11**,** 383.
MÄLARDALEN, U. O. 2013. Byggnadstypologier Sverige

TABULA. *Mälardalen university***,** 95.
MANDINEC, J. & JOHANSSON, P. 2022. Towards an automatized and objective assessment of data from visual inspections of building envelopes.
MANGOLD, M., BOHMAN, H., JOHANSSON, T. & VON PLATTEN, J. 2023. Increased rent misspent? How ownership matters for renovation and rent increases in rental housing in Sweden. *International journal of housing policy***,** 1-23.
MANGOLD, M., ÖSTERBRING, M. & WALLBAUM, H. 2015. A review of Swedish residential building stock research. *International Journal of Environmental Sustainability,* 11.

MATA, É., KALAGASIDIS, A. S. & JOHNSSON, F. 2013. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. *Energy Policy,* 55**,** 404-414.
MEIJER, F., ITARD, L. & SUNIKKA-BLANK, M. 2009. Comparing European residential building stocks: performance, renovation and policy opportunities. *Building Research & Information,* 37**,** 533-551.
MY, L., GE, J., TT, S. & XY, L. 2015. Strategies for energy efficiency renovation and evaluation system of existing residential building in hot summer and cold winter zone. *Lowland Technology International,* 17**,** 111-120.
NARDI, I. & LUCCHI, E. 2023. In Situ Thermal Transmittance Assessment of the Building Envelope: Practical Advice and Outlooks for Standard and Innovative Procedures. *Energies,* 16**,** 3319.
NÄSSÉN, J., HOLMBERG, J., WADESKOG, A. & NYMAN, M. 2007. Direct and indirect energy use and carbon emissions in the production phase of buildings: an input–output analysis. *Energy,* 32**,** 1593-1602.
NATURVÅRDSVERKET, N. D. 2023. Bygg- och rivningsavfall. Naturvårdsverket.
NEVES, T. I., UYEDA, C. A., CARVALHO, M. & ABRAHÃO, R. 2018. Environmental evaluation of the life cycle of elephant grass fertilization—Cenchrus purpureus (Schumach.) Morrone—using chemical fertilization and biosolids. *Environmental monitoring and assessment,* 190**,** 1-8.
NILSSON, M., DZEBO, A., SAVVIDOU, G. & AXELSSON, K. 2020. A bridging framework for studying transition pathways–From systems models to local action in the Swedish heating domain. *Technological Forecasting and Social Change,* 151**,** 119260.
OLIN, J. 2023. Renovation for the future An investigation of environmental impact and lifecycle costs from design choices during a renovation project.
PARTILLEENERGI 2023. District heating. Partille Energi.
PEETERS, M. & ATHANASIADOU, N. 2020. The continued effort sharing approach in EU climate law: Binding targets, challenging enforcement? *Review of European, Comparative & International Environmental Law,* 29**,** 201-211.
PEREIRA SANCHES, A. 2004. The financial benefits of building? green? An analysis of New York City high performance law.
PERSSON, U. & MÜNSTER, M. 2016. Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review. *Energy,* 110**,** 116-128.
RAMÍREZ-VILLEGAS, R., ERIKSSON, O. & OLOFSSON, T. 2019. Life cycle assessment of building renovation measures–trade-off between building materials and energy. *Energies,* 12**,** 344.
REGERINGSKANSLIET, S. 2010. The Swedish National Action Plan for the promotion of the use of renewable energy in accordance with Directive 2009/28/EC and the Commission Decision of 30.06. 2009. *URL: http://ec. europa. eu/energy/renewables/action_plan_en. htm, Abrufdatum,* 3**,** 2013.
REHFELDT, M., FLEITER, T. & TORO, F. 2018. A bottom-up estimation of the heating and cooling demand in European industry. *Energy Efficiency,* 11**,** 1057-1082.
ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN III, F. S., LAMBIN, E., LENTON, T. M., SCHEFFER, M., FOLKE, C. & SCHELLNHUBER, H. J. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society,* 14.
RUGGIERI, G., ANDREOLLI, F. & ZANGHERI, P. 2023. A policy roadmap for the energy renovation of the residential and educational building stock in Italy. *Energies,* 16**,** 1319.
SARTORI, I., WACHENFELDT, B. J. & HESTNES, A. G. 2009. Energy demand in the Norwegian building stock: Scenarios on potential reduction. *Energy Policy,* 37**,** 1614-1627.
SAVICKIS, J., ZEMITE, L., ZELTINS, N., BODE, I. & JANSONS, L. 2020. Natural gas and biomethane in the european road transport: The Latvian perspective. *Latvian Journal of Physics and Technical Sciences,* 57**,** 57-72.
SAVVIDOU, G. & NYKVIST, B. 2020. Heat demand in the Swedish residential building stock-pathways on demand reduction potential based on socio-technical analysis. *Energy Policy,* 144**,** 111679.

SCHERZ, M., HOXHA, E., MAIERHOFER, D., KREINER, H. & PASSER, A. 2023. Strategies to improve building environmental and economic performance: an exploratory study on 37 residential building scenarios. *The International Journal of Life Cycle Assessment,* 28**,** 828-842.

SCHNEISING, O., BUCHWITZ, M., REUTER, M., VANSELOW, S., BOVENSMANN, H. & BURROWS, J. P. 2020. Remote sensing of methane leakage from natural gas and petroleum systems revisited. *Atmospheric Chemistry and Physics,* 20**,** 9169-9182.

SELVAKKUMARAN, S., AXELSSON, L. & SVENSSON, I.-L. 2021. Drivers and barriers for prosumer integration in the Swedish district heating sector. *Energy Reports,* 7**,** 193-202.

SG, B. O. 2021. COMMISSION STAFF WORKING DOCUMENT EVALUATION of the.

SG, P. E. C. 2020. COMMISSION STAFF WORKING DOCUMENT Country Report Belgium 2020 Accompanying the document.

SHAMSUDDIN, S. M., ZAKARIA, R., HASHIM, N., YUSUWAN, N. M., SAHAMIR, S. R. & ABIDIN, N. I. A framework of initiatives for successful application of life cycle costing (LCC) in industrialised building system (IBS) in Malaysian construction industry. MATEC Web of Conferences, 2017. EDP Sciences, 05002.

SHARIF, S. A. & HAMMAD, A. 2019. Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment. *Journal of Building Engineering,* 21**,** 429-445.

SKULLESTAD, J. L., BOHNE, R. A. & LOHNE, J. 2016. High-rise timber buildings as a climate change mitigation measure–A comparative LCA of structural system alternatives. *Energy Procedia,* 96**,** 112-123.

SLAUGHTER, E. S. 2001. Design strategies to increase building flexibility. *Building Research & Information,* 29**,** 208-217.

SMARTVENT 2023. Smart One.

STEFFEN, W., RICHARDSON, K., ROCKSTRÖM, J., CORNELL, S. E., FETZER, I., BENNETT, E. M., BIGGS, R., CARPENTER, S. R., DE VRIES, W. & DE WIT, C. A. 2015. Planetary boundaries: Guiding human development on a changing planet. *science,* 347**,** 1259855.

STENBERG, J. 2020. The zero option–tenant experiences from an experiment to renovate apartments without increasing rent. *Cogent Social Sciences,* 6**,** 1848500.

SUHÁNYIOVÁ, A., KOREČKO, J. & SUHÁNYI, L. 2023. Renewable energy sources management in the EU-27 countries. *Acta Montanistica Slovaca,* 28.

TRAFIKVERKET 2021. Livscykelanalys i byggprocessen *Bransch. Trafikverket.se*.

UNEP, U. 2020. 2020 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. *Renewables global status report*.

VAN GULCK, L., WASTIELS, L. & STEEMAN, M. 2022. How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978. *The International Journal of Life Cycle Assessment,* 27**,** 1249-1266.

XIAO, Z., GE, H., LACASSE, M. A., WANG, L. & ZMEUREANU, R. 2023. Nature-based solutions for carbon neutral climate resilient buildings and communities: A review of technical evidence, design guidelines, and policies. *Buildings,* 13**,** 1389.

YANG, Y., CAMPANA, P. E., STRIDH, B. & YAN, J. 2020. Potential analysis of roof-mounted solar photovoltaics in Sweden. *Applied Energy,* 279**,** 115786.

YAO, Q. & HU, Y. 2023. Spatial–Temporal Variation and Influencing Factors on Housing Prices of Resource-Based City: A Case Study of Xuzhou, China. *Sustainability,* 15**,** 7026.

9. Appendix

9.1. Detailed Renovation Cost at Blåsutgatan 8

Table 66- Cost of renovated wall components.

Items	BSAB	Area Wall (m2)	Material cost (Kr/m2)	Labor cost (Kr/m2)	Cost (Kr/m2)	Total cost
Scaffolding	AFG.51	1168	81.4	126.21	207.61	242,488.5
Surface cleaning & brushing	LBS	1168	23	215.76	238.76	278,871.7
Vapor barrier	JSF.54	1168	11	77.67	88.67	103,566.6
Insulation EPS 100mm	IBE.252	1168	106.4	103.56	209.96	245,233.3
Insulation EPS 120mm	IBE.252	1168	124.5	103.56	228.06	266,374.1
Insulation EPS 150mm	IBE.252	1168	160.7	207.13	367.83	429,625.4
Insulation EPS 200mm	IBE.252	1168	212.8	207.13	419.93	490,478.2
Mortar	LBS	1168	29	129.46	158.46	185,081.3
Finishing mortar	LBS	1168	21	327.96	348.96	407,585.3

Table - Investment costs for improving wall.

Wall Insulation EPS	Area (m2)	Scaffolding (kr)	Surface cleaning and brushing (kr)	Vapor barrier cost (kr)	Insulation cost (kr)	Base mortar (kr)	Finishing mortar (kr)	Total cost (kr)
100mm	1168	335912.98	278871.68	103566.56	245233.28	185081.28	407585.28	1556251.06
120mm	1168	335912.98	278871.68	103566.56	266374.08	185081.28	407585.28	1577391.86
150mm	1168	335912.98	278871.68	103566.56	429625.44	185081.28	407585.28	1740643.22
200mm	1168	335912.98	278871.68	103566.56	490478.24	185081.28	407585.28	1801496.02

Table 67- Cost of previous windows demolition

Type of Window	Area old windows (m2)	Quantity	Total area (m2)	Demolition cost per window (kr)	Weight per window (kg)	Total weight of windows (kg)	Tipping fee old windows (kr/kg)	Tipping fee old windows total (kr)	Total demolition cost (kr)
BRF Blåsut small window tvåglasfönster Entreplan 9x6	0.558	34	18.972	431.52	20	680	1.1	748	15419.68
BRF Blåsut Window tvåglasfönster Balcony 8x15	1.2	28	33.6	431.52	55	1540	1.1	1694	13776.56
BRF Blåsut window tvåglasfönster Entreplan 11x15	1.65	6	9.9	517.82	59	354	1.1	389.4	3496.32
BRF Blåsut Window tvåglasfönster Longsides 15x15	2.25	84	189	517.82	100	8400	1.1	9240	52736.88
BRF Blåsut Window tvåglasfönster Longsides 12x15	1.8	56	100.8	690.43	74	4144	1.1	4558.4	43222.48
BRF Blåsut Window tvåglasfönster shortsides 12x14	1.75	56	98	517.82	69	3864	1.1	4250.4	33248.32
Grand total	9.208	264	450.272	3106.93	377	18982		20,880.20	161,900.24

Table 68- PVC window mean calculation for 1m2.

PVC	BSAB	Area (m2)	Material price	Total cost	PVC mean cost per 1m2
PVC window 12x12 inward side NSC.114	-	3700.00	5339.78	-	
20 PP-laminate 150x1200 NSC.72	-	449.00	837.37	-	
Internal casing of MDF 16x150, white painted NSC.71	-	326.88	906.84	-	
Casing, 12x43 white painted NSC.71	-	126.36	575.14	-	
22x145 external casing HSD.167	-	96.20	544.98	-	
Acrylic sealant with backing strip ZSB.11	-	60.96	433.79	-	
Double-sided sealing with glass wool NSC.11	-	43.20	374.61	-	
22x70 external casing board HSD.167	-	24.84	257.86	-	
Pre-lacquered drip edge B=250 JTB.5221	-	0.00	385.44	-	
Pre-lacquered window edge B=250 JTB.521	-	0.00	500.28	-	
Total	16.038	1.44	4827.44	10156	7052.84

Table 69- Investment cost of changing windows

New window	Area new windows (m2)	Quantity	Total area (m2)	Total cost (including labour)
1. PVC window 0,9x0,5 three-glass painted	0.45	34	15.3	107908.4563
2. PVC window 0,9x1,3 three-glass painted	1.17	28	32.76	231051.0475
3. PVC window 1,2x1,3 three-glass painted	1.56	6	9.36	66014.585
4. PVC window 1,5x1,4 three-glass painted	2.1	84	176.4	1244121.025
5. PVC window 1,4x1,3 three-glass painted	1.82	56	101.92	718825.4811
6. PVC window 1,2x1,5 three-glass painted	1.8	56	100.8	710926.3
Total			436.54	3,078,846.89 Kr

Table 70- Investment cost for improving roof.

Wall renovation	Area (m2)	Labor cost	Material cost	Total cost
EPS 200	363	91040.4	29511.9	120552.3

Table 71-Investment cost for ventilation

Ventilation	Cost per unit	Quantity	Total cost
Smart 1	4200	112	470400
Hole drilling	500	112	56000
Installation	1000	112	112000
Adjustment	700	112	78400
Total	-	-	716800 Kr

Table 72- Investment cost for PV panel

PV panels	Quantity	Area (m2)	Total cost including labour
DMEGC Mono All Black 535W	69	178	-
Inverter Solis 30kW	1	-	-
Fireproof panel behind the inverter	1	-	-
Scaffolding, fall protection, and safety equipment	1	-	-
Total	-	-	389,060.00 SEK

9.2. Detailed Cost Added Floors at Blåsutgatan 8

Table 73 exterior walls, Table 74 interior walls, Table 75intermediate floor (8th floor), Table 76 attic floor (9th floor), Table 77 existing roof demolition, Table 78new roof, Table 79 ventilation, Table 80 new windows, Table 81 new doors, Table 82 staircase, Table 83toilets, Table 84 kitchens, respectively.

Table 73- The cost of constructing Exterior walls.

Exterior Walls	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
70-story high climate board-33	IBE.251	298	m²	54534	35.76	30,860.88	85,394.88
22 profiled panel primed	HSD.16	298	m²	53014.20	134.10	115,728.3	168,742.50
195 stone wool board-36	IBE.24	298	m²	52865.2	29.8	25,717.40	78,582.60
45x195 studs C24 c 600	HSD.113	1043	m	43075.9	104.3	90,010.90	133,086.80
145 stone wool board-36	IBE.24	298	m²	40200.2	29.8	25,717.40	65,917.60
70 stone wool board-36 (B=410)	IBE.24	298	m²	21754	26.82	23,145.66	44,899.66
45x70 studs c 450	HSD.113	1043	m	16166.5	83.44	72,008.72	88,175.22
13 gypsum boards (B=900)	KBC.321	298	m²	12516	59.6	51,434.80	63,950.80
Scaffolding	AFG.51	342.7	m²	11994.5	61.69	53,238.47	65,232.97
34x70 laths c 600	HSD.151	894	m	11264.4	26.82	23,145.66	34,410.06
0.20 plastic film incl. tape	JSF.54	298	m²	3278	26.82	23,145.66	26,423.66
70 spacer sleeves	HSD.151	298	pcs	745	2.98	2,571.74	3,316.74
Total	7.089	-	-	321407.9	621.93	536,725.59	858,133.49

Table 74- The cost of constructing Interior wall.

Interior load-bearing wall	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
11 OSB chipboards (B=900)	KEL.21	746	m²	55950	164.12	141,643.77	197,593.77
13 gypsum boards (B=900)	KBC.321	746	m²	31332.00	149.20	128,767.06	160,099.06
45x70 studs c 450	HSD.113	1492	m	23126	119.36	103,013.65	126,139.65

45 stone wool board-36 (B=410)	IBE.24	373	m²	19582.5	29.84	25,753.41	45,335.91
GPD 70/100 polyethylene sheet	IG	373	m	2275.3	11.19	9,657.53	11,932.83
Total	8.051	-	-	132265.8	473.71	408,835.42	541,101.22

Table 75- The cost of constructing Intermediate floors.

Intermediate floor (363 m2)	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
AP 25 acoustic profile	HSB.1666	1306.8	m	58048.06	104.54	90,223.25	148,271.31
22 chipboards	KEJ.23	363	m²	48859.80	90.75	78,321.79	127,181.59
45x220 beams C24 c 600	HSD.122	834.9	m	38822.85	91.84	79,262.51	118,085.36
45 stone wool board-36	IBF.21	363	m²	17968.5	21.78	18,797.23	36,765.73
13 gypsum boards (B=900)	KBC.322	363	m²	15246	79.86	68,923.17	84,169.17
0.20 safety film	JSF.52	363	m²	8929.8	29.04	25,062.97	33,992.77
Cross bracing	HSD.122	90.75	m	1815	24.5	21,144.73	22,959.73
Beam alignment	HSD.122	363	m²	0	29.04	25,062.97	25,062.97
Total	9.039	-	-	189690.01	471.35	406,798.62	596,488.63

Table 76- The cost constructing attic floor.

Attic floor (363 m2)	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
195 stone wool boards-36	IBF.31	726	m²	128792.4	58.08	50,123.04	178,915.44
100 stone wool mats-37	IBF.31	363	m²	32161.80	25.41	21,928.83	54,090.63
13 lightweight gypsum boards (B=900)	KBC.322	363	m²	19529.4	79.86	68,919.18	88,448.58
28x95 stud panel c 300	HSD.1531	1306.8	m	17119.08	78.41	67,667.83	84,786.91
0.20 safety film	JSF.55	363	m²	8929.8	29.04	25,061.52	33,991.32
Total	9.073	-	-	206532.48	270.8	233,700.40	440,232.88

Table 77- The cost of demolishing existing roof.

Existing Roof Demolition	BSAB	Area (m2)	Demolition cost	Weight (kg)	Tipping fee old roof total	Total demolition cost
0.15 plastic film removal	BED.4	363	3,884	63	69.3	3953.3
Roofing felt removal	BED.4	363	19,418	3870	4257	23675
22 raw panel removal	BED.4	363	31,070	4653	5118.3	36188.3
Truss-3 gr removal	BED.4	363	62,139	4500	4950	67089
120 mineral wool removal	BED.4	363	15,534	1566	1722.6	17256.6
Total	11.003	-	132,045	14652	16,117.20	148,162.20

Table 78- The cost of constructing roof.

Roof	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
Prefabricated timber truss - 27 degrees	GSN.17	363	m²	45012	39.93	34,459.59	79,471.59
23 rough sawn panels	HSD.1331	363	m²	40910.10	72.60	62,653.80	103,563.90
Concrete roof tiles, surface-treated, black	JUC.1	363	m²	25010.7	65.34	56,388.42	81,399.12
Underlay paper YAP 2200	JSC.112	363	m²	13140.6	29.04	25,061.52	38,202.12
25x50 load-bearing batten	HSD.141	1089	m	5880.6	21.78	18,796.14	24,676.74
Freight for concrete roof tiles	JUC.1	363	m²	5844.3	0	-	5,844.30
25x50 counter batten	HSD.141	726	m	3920.4	7.26	6,265.38	10,185.78
Total	11.040	-	-	139718.7	235.95	203,624.85	343,343.55

Table 79- Ventilation cost

Ventilation	Cost per unit	Quantity	Total cost
Smart 1	4200	32	134,400
Hole Drilling	500	32	16,000
Installation	1000	32	32,000
Adjustment	700	32	22,400
Total			204,800

Table 80- The cost of windows

New window	Area windows added floor	Quantity	Total area (m2)	Cost/m2 (including labour)	Total cost (including labour)
PVC window 0.9x1.3 three-glass painted	1.17	8	9.36	7052.84	66,014.5824
PVC window 1.5x1.4 three-glass painted	2.1	24	50.4	7052.84	355,463.136
PVC window 1.4x1.3 three-glass painted	1.82	16	29.12	7052.84	205,378.7008
PVC window 1.2x1.5 three-glass painted	1.8	16	28.8	7052.84	203,121.792
Total			117.68		829,978.21

Table 81- Door's cost

Doors	BSAB	Quantity	Total cost

Entrance door Climate door 9x21 painted EI 30, 36dB	16.053	8	122,458
Interior door 9x21 rustic, lacquered	16.064	32	206,300
Total			328,758

Table 82- The cost of building staircase

Stairwell	BSAB	Quantity	Total cost
Staircase of pine with integrated resting place	NSK.122	2	85,549.04
Interior wooden railing with pine infill	NSK.3112	20	55,733.44
Total			141,282.48

Table 83- The cost of building toilets

WC	BSAB	Quantity	Unit	Material Cost	Total Labor Time	Labor Cost	Total Cost
Corner shower wall 900x900 clear glass	NSG.1	8	pcs	60760	32	hrs	88,377.28
Mirror with spotlights 600x834	XBD.1	8	pcs	38008.00	4.40	hrs	41,805.38
Under-cabinet B=600	XBD.1	8	pcs	22920	8	hrs	29,824.32
Built-in washbasin 560x400	XBD.1	8	pcs	19664	4.4	hrs	23,461.38
Tall cabinet B=300	XBD.1	8	pcs	15744	8.8	hrs	23,338.75
Countertop with sink cutout L=600	XBD.1	8	pcs	7584	4	hrs	11,036.16
Soap holder	XBD.5	8	pcs	2576	1.36	hrs	3,749.73
Toilet paper holder	XBD.5	8	pcs	1848.00	1.36	hrs	3,021.73
Towel rack, 5-hook	XBD.5	8	pcs	792	1.36	hrs	1,965.73
30 reinforced self-levelling compounds in slope	MHJ.12	7.2	m²				14,652.00
Floor levelling compound 1.0 kg/m²	MHJ.11	40	m²				6,600.00
Tile skirting H=100	MBE.42	64	m				17,388.80
Waterproofing membrane	MBE.222	168	m²				63,756.00
Coloured ceramic tiles	MBE.22	168	m²				112,358.40
Waterproofing membrane	MBE.1212	56	m²				22,853.60
Standard ceramic tiles	MBE.121	40	m²				42,152.00
Paint panels 56-03512 System VA	LCS.22	40	m²				8,184.00
Total		18,007					514,525.26

Table 84- The cost of building kitchens

Kitchen 15 m²	BSAB	Quantity	Unit	Material cost	Total labour time	Labor cost	Total cost
Pantry Cabinet B=600	XBD.1	8	pcs	66,624.00	8.80	7,594.75	74,218.75
Fridge-freezer 183/140 l	XKG.0	8	pcs	66,000.00	8.00	6,904.32	72,904.32
Wall cabinet B=800	XBD.1	24	pcs	63,384.00	21.60	18,641.66	82,025.66
Dishwasher	XKF	8	pcs	60,000.00	8.00	6,904.32	66,904.32
Sink L=1600	XBE.6	8	pcs	51,704.00	4.40	3,797.38	55,501.38
Built-in cabinet-2 drawers B=600	XBD.1	8	pcs	48,568.00	8.80	7,594.75	56,162.75
Drawer unit B=400	XBD.1	8	pcs	46,584.00	7.60	6,559.10	53,143.10
Cabinet-3 drawers B=800	XBD.1	8	pcs	45,816.00	8.00	6,904.32	52,720.32
Sink cabinet-1 drawer B=800	XBD.1	8	pcs	44,880.00	8.00	6,904.32	51,784.32
Built-in oven	XKC.2	8	pcs	44,400.00	8.00	6,904.32	51,304.32
Cooktop	XKC.1	8	pcs	43,200.00	5.60	4,833.02	48,033.02
Cooktop cabinet-3 drawers B=600	XBD.1	8	pcs	39,000.00	7.60	6,559.10	45,559.10
Hood over stove	XKC.1	8	pcs	16,800.00	8.00	6,904.32	23,704.32
Hood cabinet B=600	XBD.1	8	pcs	16,592.00	6.80	5,868.67	22,460.67
Cabinet over fridge-freezer B=600	XBD.1	8	pcs	13,392.00	7.20	6,213.89	19,605.89
Towel cabinet B=200	XBD.1	8	pcs	12,160.00	6.80	5,868.67	18,028.67
Wall cabinet B=400	XBD.1	8	pcs	11,976.00	6.80	5,868.67	17,844.67
Stainless steel bow handles	XBD.1	200	pcs	8,800.00	30.00	25,891.20	34,691.20
Filler piece painted white B=54	XBD.1	32.8	m	7,150.40	3.61	3,113.85	10,264.25
Side panel high cabinet 585x2112 painted white	XBD.1	8	pcs	6,120.00	1.60	1,380.86	7,500.86
PP Countertop L=800	XBE.2	8	pcs	4,440.00	4.40	3,797.38	8,237.38
Side panel countertop 585x870 painted white	XBD.1	8	pcs	3,568.00	1.36	1,173.73	4,741.73
Side panel wall cabinet 350x864 painted white	XBD.1	8	pcs	2,728.00	1.36	1,173.73	3,901.73
Tile backsplash, H=450 white	MBE.22	32	m	2,688.00	25.60	22,093.82	24,781.82
Ceiling trim, 21x33 shadow trim painted white	NSM.2	80	m	2,472.00	8.80	7,594.75	10,066.75
Enclosure upper cabinet H=150	KBC.323	49.6	m	2,360.96	17.86	15,410.44	17,771.40
Tile trim, 16x55 painted white	NSM.2	32	m	2,252.80	4.48	3,866.42	6,119.22
PP Countertop L=400	XBE.2	8	pcs	2,216.00	3.60	3,106.94	5,322.94
Baseboard, 12x56 painted white	NSM.2	72	m	1,980.00	7.20	6,213.89	8,193.89
3 underlayment foam, sound insulation	IG	120	m²	1,560.00	6.00	5,178.24	6,738.24

0.20 plastic sheeting	IG	120	m²	1,320.00	7.20	6,213.89	7,533.89
15 oak parquet-lay glue less	MCC.2	120	m²	-	-	79,200.00	79,200.00
Acrylic panels 56-03510	LCS.22	408	m²	-	-	54,753.60	54,753.60
Total		18,006		740,736.16	263.07	360,988.32	1,101,724.48

9.3. Detailed LCA of Blåsutgatan 8

Table 85 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 10 years)

Scenario	**Renovation Measure**	**A1-A3**	**A4**	**B4**	**B6**	**C2**	**C3-4**	**Total (kg CO_2 eq)**
0	Nothing	-	-	-	206 165,25	-	-	206 165
1a	100mm EPS	9 479,79	206,44	-	175 494,80	52,05	3 123,22	188 356
1b	120mm EPS	11 375,75	247,72	-	173 998,68	62,46	3 747,87	189 432
1c	150mm EPS	14 219,69	309,65	-	172 352,95	78,08	4 684,83	191 645
1d	200mm EPS	18 959,59	412,87	-	171 006,45	104,11	6 246,45	196 729
2	Change windows PVC	43 154,60	1 183,98	-	144 674,74	157,78	-	189 171
3	Improving roof	4 481,82	79,70	-	201 826,51	7,97	122,48	206 518
4	Ventilation	1 013,00	36,53	-	160 234,39	4,19	488,99	161 777
5	PV panels	40 969,05	160,04	41 129,09	191 204,06	12,80	-	273 475
6	Improving wall + Change windows	62 114,19	1 596,85	-	114 602,74	261,88	6246,44 618	184 822
7	Improving wall + Improving roof	23 441,41	492,57	-	167 266,15	112,08	6 368,93	197 681
8	Improving wall + Ventilation	19 972,59	449,41	-	130 760,83	108,30	6 735,44	158 027
9	Improving wall + PV panels	59 928,64	572,91	41 129,09	156 045,25	116,91	6 246,45	264 039
10	Change windows + Improving roof	47 636,42	1 263,67	-	142 131,34	165,75	122,48	191 320
11	Change windows + Ventilation	44 167,60	1 220,51	-	103 681,07	161,97	488,99	149 720
12	Change windows + PV panels	59 928,64	572,91	41 129,09	129 713,55	116,91	6 246,45	237 708
13	Improving roof + Ventilation	5 494,82	116,23	-	155 895,64	12,16	611,47	162 130
14	Improving roof + PV panels	45 450,87	239,74	41 129,09	186 865,31	20,78	122,48	273 828
15	Ventilation + PV panels	41 982,05	196,58	41 129,09	160 234,39	16,99	488,99	244 048
16	Improving wall + Change windows + Improving roof	66 596,01	1 676,55	-	111 311,28	269,86	6 368,93	186 223
17	Improving wall + Change windows + Ventilation	63 127,19	1 633,38	-	72 112,95	266,07	6 735,44	143 875
18	Improving wall + Change windows + PV panels	103 083,24	1 756,89	41 129,09	99 641,55	274,69	6 246,45	252 132
19	Improving wall + Improving roof + Ventilation	24 454,41	529,10	-	127 469,37	116,27	6 857,92	159 427
20	Improving wall + Improving roof + PV panels	64 410,46	652,61	41 129,09	152 304,95	124,88	6 368,93	264 991
21	Improving wall + Ventilation + PV panels	60 941,64	609,45	41 129,09	115 799,64	121,10	6 735,44	225 336
22	Change windows + Improving roof + Ventilation	48 649,42	1 300,21	-	100 838,45	169,94	611,47	151 569

23	Change windows + Improving roof + PV panels	88 605,47	1 423,71	41 129,09	127 170,15	178,55	122,48	258 629
24	Change windows + Ventilation + PV panels	85 136,65	1 380,55	41 129,09	103 681,07	174,77	488,99	231 991
25	Improving roof + Ventilation + PV panels	46 463,87	276,27	41 129,09	140 934,45	24,97	611,47	229 440
26	Improving wall + Change windows + Improving roof + Ventilation	67 609,01	1 713,08	-	68 223,04	274,05	6 857,92	144 677
27	Improving wall + Change windows + Improving roof + PV panels	107 565,06	1 836,59	41 129,09	96 350,09	282,66	6 368,93	253 532
28	Change windows + Improving roof + Ventilation + PV panels	89 618,47	1 460,25	41 129,09	85 877,25	182,74	611,47	218 879
29	Improving wall + PV panels + Improving roof + Ventilation	65 423,46	689,14	41 129,09	127 469,37	129,07	6 857,92	241 698
30	Improving wall + Change windows + Ventilation + PV panels	104 096,24	1 793,42	41 129,09	57 151,76	278,88	6 735,44	211 185
31	All	108 578,06	1 873,12	41 129,09	53 261,85	286,85	6 857,92	211 987

Table 86 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 15 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-	-	-	309 247,88	-	-	309 248
1a	100mm EPS	9 479,79	206,44	-	263 242,21	52,05	3 123,22	276 104
1b	120mm EPS	11 375,75	247,72	-	260 998,03	62,46	3 747,87	276 432
1c	150mm EPS	14 219,69	309,65	-	258 529,43	78,08	4 684,83	277 822
1d	200mm EPS	18 959,59	412,87	-	256 509,67	104,11	6 246,45	282 233
2	Change windows PVC	43 154,60	1 183,98	-	217 012,12	157,78	-	261 508
3	Improving roof	4 481,82	79,70	-	302 739,76	7,97	122,48	307 432
4	Ventilation	1 013,00	36,53	-	240 351,58	4,19	488,99	241 894
5	PV panels	40 969,05	160,04	41 129,09	286 806,09	12,80	-	369 077
6	Improving wall + Change windows	62 114,19	1 596,85	-	171 904,12	261,88	6246,44618	242 123
7	Improving wall + Improving roof	23 441,41	492,57	-	250 899,22	112,08	6 368,93	281 314
8	Improving wall + Ventilation	19 972,59	449,41	-	196 141,25	108,30	6 735,44	223 407
9	Improving wall + PV panels	59 928,64	572,91	41 129,09	234 067,88	116,91	6 246,45	342 062
10	Change windows + Improving roof	47 636,42	1 263,67	-	213 197,01	165,75	122,48	262 385
11	Change windows + Ventilation	44 167,60	1 220,51	-	155 521,61	161,97	488,99	201 561
12	Change windows + PV panels	59 928,64	572,91	41 129,09	194 570,33	116,91	6 246,45	302 564
13	Improving roof + Ventilation	5 494,82	116,23	-	233 843,46	12,16	611,47	240 078
14	Improving roof + PV panels	45 450,87	239,74	41 129,09	280 297,97	20,78	122,48	367 261
15	Ventilation + PV panels	41 982,05	196,58	41 129,09	240 351,58	16,99	488,99	324 165

16	Improving wall + Change windows + Improving roof	66 596,01	1 676,55	-	166 966,92	269,86	6 368,93	241 878
17	Improving wall + Change windows + Ventilation	63 127,19	1 633,38	-	108 169,43	266,07	6 735,44	179 932
18	Improving wall + Change windows + PV panels	103 083,24	1 756,89	41 129,09	149 462,33	274,69	6 246,45	301 953
19	Improving wall + Improving roof + Ventilation	24 454,41	529,10	-	191 204,06	116,27	6 857,92	223 162
20	Improving wall + Improving roof + PV panels	64 410,46	652,61	41 129,09	228 457,43	124,88	6 368,93	341 143
21	Improving wall + Ventilation + PV panels	60 941,64	609,45	41 129,09	173 699,46	121,10	6 735,44	283 236
22	Change windows + Improving roof + Ventilation	48 649,42	1 300,21	-	151 257,67	169,94	611,47	201 989
23	Change windows + Improving roof + PV panels	88 605,47	1 423,71	41 129,09	190 755,22	178,55	122,48	322 215
24	Change windows + Ventilation + PV panels	85 136,65	1 380,55	41 129,09	155 521,61	174,77	488,99	283 832
25	Improving roof + Ventilation + PV panels	46 463,87	276,27	41 129,09	211 401,67	24,97	611,47	299 907
26	Improving wall + Change windows + Improving roof + Ventilation	67 609,01	1 713,08	-	102 334,57	274,05	6 857,92	178 789
27	Improving wall + Change windows + Improving roof + PV panels	107 565,06	1 836,59	41 129,09	144 525,13	282,66	6 368,93	301 707
28	Change windows + Improving roof + Ventilation + PV panels	89 618,47	1 460,25	41 129,09	128 815,88	182,74	611,47	261 818
29	Improving wall + PV panels + Improving roof + Ventilation	65 423,46	689,14	41 129,09	191 204,06	129,07	6 857,92	305 433
30	Improving wall + Change windows + Ventilation + PV panels	104 096,24	1 793,42	41 129,09	85 727,64	278,88	6 735,44	239 761
31	All	108 578,06	1 873,12	41 129,09	79 892,78	286,85	6 857,92	238 618

Table 87 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 20 years)

Scenario	**Renovation Measure**	**A1-A3**	**A4**	**B4**	**B6**	**C2**	**C3-4**	**Total (kg CO_2 eq)**
0	Nothing	-	-	-	412 330,50	-	-	412 331
1a	100mm EPS	9 479,79	206,44	-	350 989,61	52,05	3 123,22	363 851
1b	120mm EPS	11 375,75	247,72	-	347 997,37	62,46	3 747,87	363 431
1c	150mm EPS	14 219,69	309,65	-	344 705,91	78,08	4 684,83	363 998
1d	200mm EPS	18 959,59	412,87	-	342 012,89	104,11	6 246,45	367 736
2	Change windows PVC	43 154,60	1 183,98	-	289 349,49	157,78	-	333 846
3	Improving roof	4 481,82	79,70	-	403 653,01	7,97	122,48	408 345
4	Ventilation	1 013,00	36,53	-	320 468,77	4,19	488,99	322 011
5	PV panels	40 969,05	160,04	41 129,09	382 408,11	12,80	-	464 679
6	Improving wall + Change windows	62 114,19	1 596,85	-	229 205,49	261,88	6246,44 618	299 425
7	Improving wall + Improving roof	23 441,41	492,57	-	334 532,29	112,08	6 368,93	364 947
8	Improving wall + Ventilation	19 972,59	449,41	-	261 521,67	108,30	6 735,44	288 787
9	Improving wall + PV panels	59 928,64	572,91	41 129,09	312 090,50	116,91	6 246,45	420 085

10	Change windows + Improving roof	47 636,42	1 263,67	-	284 262,68	165,75	122,48	333 451
11	Change windows + Ventilation	44 167,60	1 220,51	-	207 362,15	161,97	488,99	253 401
12	Change windows + PV panels	59 928,64	572,91	41 129,09	259 427,10	116,91	6 246,45	367 421
13	Improving roof + Ventilation	5 494,82	116,23	-	311 791,28	12,16	611,47	318 026
14	Improving roof + PV panels	45 450,87	239,74	41 129,09	373 730,62	20,78	122,48	460 694
15	Ventilation + PV panels	41 982,05	196,58	41 129,09	320 468,77	16,99	488,99	404 282
16	Improving wall + Change windows + Improving roof	66 596,01	1 676,55	-	222 622,56	269,86	6 368,93	297 534
17	Improving wall + Change windows + Ventilation	63 127,19	1 633,38	-	144 225,91	266,07	6 735,44	215 988
18	Improving wall + Change windows + PV panels	103 083,24	1 756,89	41 129,09	199 283,10	274,69	6 246,45	351 773
19	Improving wall + Improving roof + Ventilation	24 454,41	529,10	-	254 938,74	116,27	6 857,92	286 896
20	Improving wall + Improving roof + PV panels	64 410,46	652,61	41 129,09	304 609,91	124,88	6 368,93	417 296
21	Improving wall + Ventilation + PV panels	60 941,64	609,45	41 129,09	231 599,28	121,10	6 735,44	341 136
22	Change windows + Improving roof + Ventilation	48 649,42	1 300,21	-	201 676,89	169,94	611,47	252 408
23	Change windows + Improving roof + PV panels	88 605,47	1 423,71	41 129,09	254 340,30	178,55	122,48	385 800
24	Change windows + Ventilation + PV panels	85 136,65	1 380,55	41 129,09	207 362,15	174,77	488,99	335 672
25	Improving roof + Ventilation + PV panels	46 463,87	276,27	41 129,09	281 868,89	24,97	611,47	370 375
26	Improving wall + Change windows + Improving roof + Ventilation	67 609,01	1 713,08	-	136 446,09	274,05	6 857,92	212 900
27	Improving wall + Change windows + Improving roof + PV panels	107 565,06	1 836,59	41 129,09	192 700,18	282,66	6 368,93	349 882
28	Change windows + Improving roof + Ventilation + PV panels	89 618,47	1 460,25	41 129,09	171 754,51	182,74	611,47	304 757
29	Improving wall + PV panels + Improving roof + Ventilation	65 423,46	689,14	41 129,09	254 938,74	129,07	6 857,92	369 167
30	Improving wall + Change windows + Ventilation + PV panels	104 096,24	1 793,42	41 129,09	114 303,52	278,88	6 735,44	268 337
31	All	108 578,06	1 873,12	41 129,09	106 523,70	286,85	6 857,92	265 249

Table 88 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 35 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-	-	-	721 578,38	-	-	721 578
1a	100mm EPS	9 479,79	206,44	-	614 231,81	52,05	3 123,22	627 093
1b	120mm EPS	11 375,75	247,72	-	608 995,40	62,46	3 747,87	624 429
1c	150mm EPS	14 219,69	309,65	-	603 235,34	78,08	4 684,83	622 528
1d	200mm EPS	18 959,59	412,87	-	598 522,56	104,11	6 246,45	624 246
2	Change windows PVC	43 154,60	1 183,98	-	506 361,61	157,78	-	550 858
3	Improving roof	4 481,82	79,70	-	706 392,77	7,97	122,48	711 085
4	Ventilation	1 013,00	36,53	-	560 820,35	4,19	488,99	562 363
5	PV panels	40 969,05	160,04	41 129,09	669 214,20	12,80	-	751 485
6	Improving wall + Change windows	62 114,19	1 596,85	-	401 109,61	261,88	6246,44618	471 329
7	Improving wall + Improving roof	23 441,41	492,57	-	585 431,52	112,08	6 368,93	615 847

8	Improving wall + Ventilation	19 972,59	449,41	-	457 662,92	108,30	6 735,44	484 929
9	Improving wall + PV panels	59 928,64	572,91	41 129,09	546 158,38	116,91	6 246,45	654 152
10	Change windows + Improving roof	47 636,42	1 263,67	-	497 459,70	165,75	122,48	546 648
11	Change windows + Ventilation	44 167,60	1 220,51	-	362 883,76	161,97	488,99	408 923
12	Change windows + PV panels	59 928,64	572,91	41 129,09	453 997,43	116,91	6 246,45	561 991
13	Improving roof + Ventilation	5 494,82	116,23	-	545 634,74	12,16	611,47	551 869
14	Improving roof + PV panels	45 450,87	239,74	41 129,09	654 028,59	20,78	122,48	740 992
15	Ventilation + PV panels	41 982,05	196,58	41 129,09	560 820,35	16,99	488,99	644 634
16	Improving wall + Change windows + Improving roof	66 596,01	1 676,55	-	389 589,49	269,86	6 368,93	464 501
17	Improving wall + Change windows + Ventilation	63 127,19	1 633,38	-	252 395,34	266,07	6 735,44	324 157
18	Improving wall + Change windows + PV panels	103 083,24	1 756,89	41 129,09	348 745,43	274,69	6 246,45	501 236
19	Improving wall + Improving roof + Ventilation	24 454,41	529,10	-	446 142,80	116,27	6 857,92	478 101
20	Improving wall + Improving roof + PV panels	64 410,46	652,61	41 129,09	533 067,34	124,88	6 368,93	645 753
21	Improving wall + Ventilation + PV panels	60 941,64	609,45	41 129,09	405 298,74	121,10	6 735,44	514 835
22	Change windows + Improving roof + Ventilation	48 649,42	1 300,21	-	352 934,56	169,94	611,47	403 666
23	Change windows + Improving roof + PV panels	88 605,47	1 423,71	41 129,09	445 095,52	178,55	122,48	576 555
24	Change windows + Ventilation + PV panels	85 136,65	1 380,55	41 129,09	362 883,76	174,77	488,99	491 194
25	Improving roof + Ventilation + PV panels	46 463,87	276,27	41 129,09	493 270,56	24,97	611,47	581 776
26	Improving wall + Change windows + Improving roof + Ventilation	67 609,01	1 713,08	-	238 780,65	274,05	6 857,92	315 235
27	Improving wall + Change windows + Improving roof + PV panels	107 565,06	1 836,59	41 129,09	337 225,31	282,66	6 368,93	494 408
28	Change windows + Improving roof + Ventilation + PV panels	89 618,47	1 460,25	41 129,09	300 570,38	182,74	611,47	433 572
29	Improving wall + PV panels + Improving roof + Ventilation	65 423,46	689,14	41 129,09	446 142,80	129,07	6 857,92	560 371
30	Improving wall + Change windows + Ventilation + PV panels	104 096,24	1 793,42	41 129,09	200 031,16	278,88	6 735,44	354 064
31	All	108 578,06	1 873,12	41 129,09	186 416,48	286,85	6 857,92	345 142

9.4. Detailed Renovation Cost at Byalagsgatan 8

Table X Cost of renovated wall components.

Material	**BSAB**	**Area Wall (m2)**	**Material cost (kr/m^2)**	**Labor cost (kr/m^2)**	**Cost (Kr/m^2)**	**Total cost (kr)**

Scaffolding	*AFG.51*	1461	81,4	126,21	207,61	303 318,21
Surface cleaning & brushing	*LBS*	1461	23	215,76	238,76	348 828,36
Vapor barrier	*JSF.54*	1461	11	77,67	88,67	129 546,87
Insulation EPS 100mm	*IBE.252*	1461	106,4	103,56	209,96	306 751,56
Insulation EPS 120mm	*IBE.252*	1461	124,5	103,56	228,06	333 195,66
Insulation EPS 150mm	*IBE.252*	1461	160,7	207,13	367,83	537 399,63
Insulation EPS 200mm	*IBE.252*	1461	212,8	207,13	419,93	613 517,73
Grundputs (Mortar)	*LBS*	1461	29	129,46	158,46	231 510,06
Finishing mortar	*LBS*	1461	21	327,96	348,96	509 830,56

89- The cost of constructing Exterior walls.

Table 90- Investment costs for improving wall.

Wall Insulation EPS	Area (m2)	Scaffolding (kr)	Surface cleaning and brushing (kr)	Vapor barrier cost (kr)	Insulation cost (kr)	Grundputs (kr)	Armeringsnät (kr)	Finishing mortar (kr)	Total cost (kr)
100mm	1461	382625.23	348828.36	129546.87	306751.56	231510.06	-	509830.56	1,909,092.64
120mm	1461	382625.23	348828.36	129546.87	333195.66	231510.06	-	509830.56	1,935,536.74
150mm	1461	382625.23	348828.36	129546.87	537399.63	231510.06	-	509830.56	2,139,740.71
200mm	1461	382625.23	348828.36	129546.87	613517.73	231510.06	-	509830.56	2,215,858.81

Table 91- Cost of previous windows demolition

Type of Window	**Area old windows (m2)**	**Quantity**	**Total area (m2)**	**Demolition cost per window (kr)**	**Weight per window (kg)**	**Total weight of windows (kg)**	**Tipping fee old windows (kr/kg)**	**Tipping fee old windows total (kr)**	**Total demolition cost (kr)**
BRF Blåsut small window tvåglasfönster Entreplan 9x6	0.558	34	18.972	431.52	20	680	1.1	748	15419.68
BRF Blåsut Window tvåglasfönster Balcony 8x15	1.2	28	33.6	431.52	55	1540	1.1	1694	13776.56
BRF Blåsut window tvåglasfönster Entreplan 11x15	1.65	6	9.9	517.82	59	354	1.1	389.4	3496.32
BRF Blåsut Window tvåglasfönster Longsides 15x15	2.25	84	189	517.82	100	8400	1.1	9240	52736.88
BRF Blåsut Window tvåglasfönster Longsides 12x15	1.8	56	100.8	690.43	74	4144	1.1	4558.4	43222.48
BRF Blåsut Window tvåglasfönster shortsides 12x14	1.75	56	98	517.82	69	3864	1.1	4250.4	33248.32
Grand total	9.208	264	450.272	3106.93	377	18982		20,880.20	161,900.24

Table 92- PVC window mean calculation for 1m2.

PVC	**BSAB**	**Area (m2)**	**Material price**	**Total cost**	**PVC mean cost per 1m2**
PVC window 12x12 inward side NSC.114	-	3700.00	5339.78	-	
20 PP-laminate 150x1200 NSC.72	-	449.00	837.37	-	

Internal casing of MDF 16x150, white painted NSC.71	-	326.88	906.84	-	
Casing, 12x43 white painted NSC.71	-	126.36	575.14	-	
22x145 external casing HSD.167	-	96.20	544.98	-	
Acrylic sealant with backing strip ZSB.11	-	60.96	433.79	-	
Double-sided sealing with glass wool NSC.11	-	43.20	374.61	-	
22x70 external casing board HSD.167	-	24.84	257.86	-	
Pre-lacquered drip edge B=250 JTB.5221	-	0.00	385.44	-	
Pre-lacquered window edge B=250 JTB.521	-	0.00	500.28	-	
Total	16.038	1.44	4827.44	10156	7052.84

Table 93- Investment cost of changing windows

New window	**Area new windows (m2)**	**Quantity**	**Total area (m2)**	**Total cost (including labour)**
1. PVC window 0,9x0,5 three-glass painted	0.45	34	15.3	107908.4563
2. PVC window 0,9x1,3 three-glass painted	1.17	28	32.76	231051.0475
3. PVC window 1,2x1,3 three-glass painted	1.56	6	9.36	66014.585
4. PVC window 1,5x1,4 three-glass painted	2.1	84	176.4	1244121.025
5. PVC window 1,4x1,3 three-glass painted	1.82	56	101.92	718825.4811
6. PVC window 1,2x1,5 three-glass painted	1.8	56	100.8	710926.3
Total			436.54	3,078,846.89 Kr

Table 94- Investment cost for improving roof.

Wall renovation	**Area (m2)**	**Labor cost**	**Material cost**	**Total cost**
EPS 200	363	91040.4	29511.9	120552.3

Table 95-Investment cost for ventilation

Ventilation	**Cost per unit**	**Quantity**	**Total cost**
Smart 1	4200	112	470400
Hole drilling	500	112	56000
Installation	1000	112	112000
Adjustment	700	112	78400
Total	-	-	716800 Kr

Table 96- Investment cost for PV panel

PV panels	**Quantity**	**Area (m2)**	**Total cost including labour**
DMEGC Mono All Black 535W	69	178	-
Inverter Solis 30kW	1	-	-
Fireproof panel behind the inverter	1	-	-
Scaffolding, fall protection, and safety equipment	1	-	-
Total	-	-	389,060.00 SEK

9.5. Detailed Cost Added Floors at Byalagsgatan 8

Table 73 exterior walls, Table 74 interior walls, Table 75intermediate floor (8th floor), Table 76 attic floor (9th floor), Table 77 existing roof demolition, Table 78new roof, Table 79 ventilation, Table 80 new windows, Table 81 new doors, Table 82 staircase, Table 83toilets, Table 84 kitchens, respectively.

<u>Improving wall:</u>

Table 97- The cost of constructing Exterior walls.

Exterior Walls	**BSAB**	**Quantity**	**Unit**	**Material cost**	**labour time**	**Labor cost**	**Total cost**
70-story high climate board-33	IBE.251	298	m²	54534	35.76	30,860.88	85,394.88
22 profiled panel primed	HSD.16	298	m²	53014.20	134.10	115,728.3	168,742.50
195 stone wool board-36	IBE.24	298	m²	52865.2	29.8	25,717.40	78,582.60
45x195 studs C24 c 600	HSD.113	1043	m	43075.9	104.3	90,010.90	133,086.80
145 stone wool board-36	IBE.24	298	m²	40200.2	29.8	25,717.40	65,917.60
70 stone wool board-36 (B=410)	IBE.24	298	m²	21754	26.82	23,145.66	44,899.66
45x70 studs c 450	HSD.113	1043	m	16166.5	83.44	72,008.72	88,175.22
13 gypsum boards (B=900)	KBC.321	298	m²	12516	59.6	51,434.80	63,950.80

Scaffolding	AFG.51	342.7	m²	11994.5	61.69	53,238.47	65,232.97
34x70 laths c 600	HSD.151	894	m	11264.4	26.82	23,145.66	34,410.06
0.20 plastic film incl. tape	JSF.54	298	m²	3278	26.82	23,145.66	26,423.66
70 spacer sleeves	HSD.151	298	pcs	745	2.98	2,571.74	3,316.74
Total	7.089	-	-	321407.9	621.93	536,725.59	858,133.49

Table 98- The cost of constructing Interior wall.

Interior load-bearing wall	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
11 OSB chipboards (B=900)	KEL.21	746	m²	55950	164.12	141,643.77	197,593.77
13 gypsum boards (B=900)	KBC.321	746	m²	31332.00	149.20	128,767.06	160,099.06
45x70 studs c 450	HSD.113	1492	m	23126	119.36	103,013.65	126,139.65
45 stone wool board-36 (B=410)	IBE.24	373	m²	19582.5	29.84	25,753.41	45,335.91
GPD 70/100 polyethylene sheet	IG	373	m	2275.3	11.19	9,657.53	11,932.83
Total	8.051	-	-	132265.8	473.71	408,835.42	541,101.22

Table 99- The cost of constructing Intermediate floors.

Intermediate floor (363 m2)	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
AP 25 acoustic profile	HSB.1666	1306.8	m	58048.06	104.54	90,223.25	148,271.31
22 chipboards	KEJ.23	363	m²	48859.80	90.75	78,321.79	127,181.59
45x220 beams C24 c 600	HSD.122	834.9	m	38822.85	91.84	79,262.51	118,085.36
45 stone wool board-36	IBF.21	363	m²	17968.5	21.78	18,797.23	36,765.73
13 gypsum boards (B=900)	KBC.322	363	m²	15246	79.86	68,923.17	84,169.17
0.20 safety film	JSF.52	363	m²	8929.8	29.04	25,062.97	33,992.77
Cross bracing	HSD.122	90.75	m	1815	24.5	21,144.73	22,959.73
Beam alignment	HSD.122	363	m²	0	29.04	25,062.97	25,062.97
Total	9.039	-	-	189690.01	471.35	406,798.62	596,488.63

Table 100- The cost constructing attic floor.

Attic floor (363 m2)	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
195 stone wool boards-36	IBF.31	726	m²	128792.4	58.08	50,123.04	178,915.44
100 stone wool mats-37	IBF.31	363	m²	32161.80	25.41	21,928.83	54,090.63
13 lightweight gypsum boards (B=900)	KBC.322	363	m²	19529.4	79.86	68,919.18	88,448.58
28x95 stud panel c 300	HSD.1531	1306.8	m	17119.08	78.41	67,667.83	84,786.91
0.20 safety film	JSF.55	363	m²	8929.8	29.04	25,061.52	33,991.32
Total	9.073	-	-	206532.48	270.8	233,700.40	440,232.88

Table 101- The cost of demolishing existing roof.

Existing Roof Demolition	BSAB	Area (m2)	Demolition cost	Weight (kg)	Tipping fee old roof total	Total demolition cost
0.15 plastic film removal	BED.4	363	3,884	63	69.3	3953.3
Roofing felt removal	BED.4	363	19,418	3870	4257	23675
22 raw panel removal	BED.4	363	31,070	4653	5118.3	36188.3
Truss-3 gr removal	BED.4	363	62,139	4500	4950	67089
120 mineral wool removal	BED.4	363	15,534	1566	1722.6	17256.6
Total	11.003	-	132,045	14652	16,117.20	148,162.20

Table 102- The cost of constructing roof.

Roof	BSAB	Quantity	Unit	Material cost	labour time	Labor cost	Total cost
Prefabricated timber truss - 27 degrees	GSN.17	363	m²	45012	39.93	34,459.59	79,471.59
23 rough sawn panels	HSD.1331	363	m²	40910.10	72.60	62,653.80	103,563.90
Concrete roof tiles, surface-treated, black	JUC.1	363	m²	25010.7	65.34	56,388.42	81,399.12
Underlay paper YAP 2200	JSC.112	363	m²	13140.6	29.04	25,061.52	38,202.12
25x50 load-bearing batten	HSD.141	1089	m	5880.6	21.78	18,796.14	24,676.74
Freight for concrete roof tiles	JUC.1	363	m²	5844.3	0	-	5,844.30
25x50 counter batten	HSD.141	726	m	3920.4	7.26	6,265.38	10,185.78
Total	11.040	-	-	139718.7	235.95	203,624.85	343,343.55

Table 103- Ventilation cost

Ventilation	Cost per unit	Quantity	Total cost
Smart 1	4200	32	134,400
Hole Drilling	500	32	16,000
Installation	1000	32	32,000
Adjustment	700	32	22,400
Total			204,800

Table 104- The cost of windows

New window	Area windows added floor	Quantity	Total area (m2)	Cost/m2 (including labour)	Total cost (including labour)
PVC window 0.9x1.3 three-glass painted	1.17	8	9.36	7052.84	66,014.5824
PVC window 1.5x1.4 three-glass painted	2.1	24	50.4	7052.84	355,463.136
PVC window 1.4x1.3 three-glass painted	1.82	16	29.12	7052.84	205,378.7008
PVC window 1.2x1.5 three-glass painted	1.8	16	28.8	7052.84	203,121.792
Total			117.68		829,978.21

Table 105- Door's cost

Doors	BSAB	Quantity	Total cost
Entrance door Climate door 9x21 painted EI 30, 36dB	16.053	8	122,458
Interior door 9x21 rustic, lacquered	16.064	32	206,300
Total			328,758

Table 106- The cost of building staircase

Stairwell	BSAB	Quantity	Total cost
Staircase of pine with integrated resting place	NSK.122	2	85,549.04
Interior wooden railing with pine infill	NSK.3112	20	55,733.44
Total			141,282.48

Table 107- The cost of building toilets

WC	BSAB	Quantity	Unit	Material Cost	Total Labor Time	Labor Cost	Total Cost
Corner shower wall 900x900 clear glass	NSG.1	8	pcs	60760	32	hrs	88,377.28
Mirror with spotlights 600x834	XBD.1	8	pcs	38008.00	4.40	hrs	41,805.38
Under-cabinet B=600	XBD.1	8	pcs	22920	8	hrs	29,824.32
Built-in washbasin 560x400	XBD.1	8	pcs	19664	4.4	hrs	23,461.38
Tall cabinet B=300	XBD.1	8	pcs	15744	8.8	hrs	23,338.75
Countertop with sink cutout L=600	XBD.1	8	pcs	7584	4	hrs	11,036.16
Soap holder	XBD.5	8	pcs	2576	1.36	hrs	3,749.73
Toilet paper holder	XBD.5	8	pcs	1848.00	1.36	hrs	3,021.73
Towel rack, 5-hook	XBD.5	8	pcs	792	1.36	hrs	1,965.73
30 reinforced self-levelling compounds in slope	MHJ.12	7.2	m²				14,652.00
Floor levelling compound 1.0 kg/m²	MHJ.11	40	m²				6,600.00
Tile skirting H=100	MBE.42	64	m				17,388.80
Waterproofing membrane	MBE.222	168	m²				63,756.00
Coloured ceramic tiles	MBE.22	168	m²				112,358.40
Waterproofing membrane	MBE.1212	56	m²				22,853.60
Standard ceramic tiles	MBE.121	40	m²				42,152.00
Paint panels 56-03512 System VA	LCS.22	40	m²				8,184.00
Total		18,007					514,525.26

Table 108- The cost of building kitchens

Kitchen 15 m^2	BSAB	Quantity	Unit	Material cost	Total labour time	Labor cost	Total cost
Pantry Cabinet B=600	XBD.1	8	pcs	66,624.00	8.80	7,594.75	74,218.75
Fridge-freezer 183/140 l	XKG.0	8	pcs	66,000.00	8.00	6,904.32	72,904.32
Wall cabinet B=800	XBD.1	24	pcs	63,384.00	21.60	18,641.66	82,025.66
Dishwasher	XKF	8	pcs	60,000.00	8.00	6,904.32	66,904.32
Sink L=1600	XBE.6	8	pcs	51,704.00	4.40	3,797.38	55,501.38
Built-in cabinet-2 drawers B=600	XBD.1	8	pcs	48,568.00	8.80	7,594.75	56,162.75
Drawer unit B=400	XBD.1	8	pcs	46,584.00	7.60	6,559.10	53,143.10
Cabinet-3 drawers B=800	XBD.1	8	pcs	45,816.00	8.00	6,904.32	52,720.32
Sink cabinet-1 drawer B=800	XBD.1	8	pcs	44,880.00	8.00	6,904.32	51,784.32
Built-in oven	XKC.2	8	pcs	44,400.00	8.00	6,904.32	51,304.32
Cooktop	XKC.1	8	pcs	43,200.00	5.60	4,833.02	48,033.02
Cooktop cabinet-3 drawers B=600	XBD.1	8	pcs	39,000.00	7.60	6,559.10	45,559.10
Hood over stove	XKC.1	8	pcs	16,800.00	8.00	6,904.32	23,704.32
Hood cabinet B=600	XBD.1	8	pcs	16,592.00	6.80	5,868.67	22,460.67
Cabinet over fridge-freezer B=600	XBD.1	8	pcs	13,392.00	7.20	6,213.89	19,605.89
Towel cabinet B=200	XBD.1	8	pcs	12,160.00	6.80	5,868.67	18,028.67
Wall cabinet B=400	XBD.1	8	pcs	11,976.00	6.80	5,868.67	17,844.67
Stainless steel bow handles	XBD.1	200	pcs	8,800.00	30.00	25,891.20	34,691.20
Filler piece painted white B=54	XBD.1	32.8	m	7,150.40	3.61	3,113.85	10,264.25
Side panel high cabinet 585x2112 painted white	XBD.1	8	pcs	6,120.00	1.60	1,380.86	7,500.86

PP Countertop L=800	XBE.2	8	pcs	4,440.00	4.40	3,797.38	8,237.38
Side panel countertop 585x870 painted white	XBD.1	8	pcs	3,568.00	1.36	1,173.73	4,741.73
Side panel wall cabinet 350x864 painted white	XBD.1	8	pcs	2,728.00	1.36	1,173.73	3,901.73
Tile backsplash, H=450 white	MBE.22	32	m	2,688.00	25.60	22,093.82	24,781.82
Ceiling trim, 21x33 shadow trim painted white	NSM.2	80	m	2,472.00	8.80	7,594.75	10,066.75
Enclosure upper cabinet H=150	KBC.323	49.6	m	2,360.96	17.86	15,410.44	17,771.40
Tile trim, 16x55 painted white	NSM.2	32	m	2,252.80	4.48	3,866.42	6,119.22
PP Countertop L=400	XBE.2	8	pcs	2,216.00	3.60	3,106.94	5,322.94
Baseboard, 12x56 painted white	NSM.2	72	m	1,980.00	7.20	6,213.89	8,193.89
3 underlayment foam, sound insulation	IG	120	m²	1,560.00	6.00	5,178.24	6,738.24
0.20 plastic sheeting	IG	120	m²	1,320.00	7.20	6,213.89	7,533.89
15 oak parquet-lay glue less	MCC.2	120	m²	-	-	79,200.00	79,200.00
Acrylic panels 56-03510	LCS.22	408	m²	-	-	54,753.60	54,753.60
Total		18,006		740,736.16	263.07	360,988.32	1,101,724.48

9.6. Detailed LCA of Byalagsgatan 8

Table 109 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 10 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-		-	226 796,88	-		226796,8815
1a	100mm EPS	12021,5	261,8037664	-	202 167,36	52,05360467	3116,226099	217 618,94
1b	120mm EPS	14425,8	314,1645196	-	200 799,05	62,46432561	3739,471319	219 340,95
1c	150mm EPS	18032,25	392,7056495	-	199 430,74	78,08040701	4674,339149	222 608,12
1d	200mm EPS	24043	523,6075327	-	197 720,36	104,1072093	6232,452199	228 623,53
2	Change windows PVC	37896	1037,353979	-	183 695,21	157,7773856	-	222 786,34
3	Improving roof	11664	207,4061329	-	206 101,24	7,972931001	318,6719371	218 299,29
4	Ventilation	548,9	19,85958178	-	205 417,09	4,190153519	264,8697484	206 254,90
5	PV panels	40957,8	160,0405858	41129,08999	207 982,66	12,80324686	-	290 242,39
6	Improving wall + Change windows	61939	1560,961512	-	154 618,69	261,8845949	6232,452199	224 612,99
7	Improving wall + Improving roof	35707	731,0136656	-	176 511,60	112,0801403	6551,124136	219 612,82
8	Improving wall + Ventilation	24591,9	543,4671145	-	175 485,37	108,2973629	6497,321947	207 226,36
9	Improving wall + PV panels	65000,8	683,6481185	41129,08999	178 906,14	116,9104562	6232,452199	292 069,04
10	Change windows + Improving roof	49560	1244,760112	-	161 631,26	165,7503166	318,6719371	212 920,44
11	Change windows + Ventilation	38444,9	1057,213561	-	162 144,38	161,9675391	264,8697484	202 073,33
12	Change windows + PV panels	78853,8	1197,394565	41129,08999	164 880,99	170,5806325		286 231,86
13	Improving roof + Ventilation	12212,9	227,2657147	-	183 353,13	12,16308452	583,5416856	196 389,01
14	Improving roof + PV panels	52621,8	367,4467187	41129,08999	187 287,02	20,77617786	318,6719371	281 744,80
15	Ventilation + PV panels	41506,7	179,9001676	41129,08999	186 602,86	16,99340038	264,8697484	269 700,42
16	Improving wall + Change windows + Improving roof	73603	1768,367644	-	132 041,62	269,8575259	6551,124136	214 233,97
17	Improving wall + Change windows + Ventilation	62487,9	1580,821093	-	132 383,70	266,0747485	6497,321947	203 215,82
18	Improving wall + Change windows + PV panels	102896,8	1721,002097	41129,08999	135 804,47	274,6878418	6232,452199	288 058,50
19	Improving wall + Improving roof + Ventilation	36255,9	750,8732474	-	152 737,27	116,2702939	6815,993884	196 676,30
20	Improving wall + Improving roof + PV panels	76664,8	891,0542514	41129,08999	157 697,38	124,8833872	6551,124136	283 058,33

21	Improving wall + Ventilation + PV panels	65549,7	703,5077003	41129,08999	156 671,15	121,1006097	6497,321947	270 671,87
22	Change windows + Improving roof + Ventilation	50108,9	1264,619693	-	140 251,47	169,9404701	583,5416856	192 378,47
23	Change windows + Improving roof + PV panels	90517,8	1404,800698	41129,08999	142 817,04	178,5535635	318,6719371	276 365,96
24	Change windows + Ventilation + PV panels	79402,7	1217,254146	41129,08999	143 330,16	174,770786	264,8697484	265 518,84
25	Improving roof + Ventilation + PV panels	53170,7	387,3063005	41129,08999	164 538,91	24,96633138	583,5416856	259 834,52
26	Improving wall + Change windows + Improving roof + Ventilation	74151,9	1788,227226	-	109 977,67	274,0476795	6815,993884	193 007,84
27	Improving wall + Change windows + Improving roof + PV panels	114560,8	1928,40823	41129,08999	113 227,40	282,6607728	6497,321947	277 625,68
28	Change windows + Improving roof + Ventilation + PV panels	91066,7	1424,660279	41129,08999	121 437,24	182,743717	583,5416856	255 823,98
29	Improving wall + PV panels + Improving roof + Ventilation	77213,7	910,9138332	41129,08999	133 923,05	129,0735407	6815,993884	260 121,82
30	Improving wall + Change windows + Ventilation + PV panels	103445,7	1740,861679	41129,08999	113 569,48	278,8779953	6497,321947	266 661,33
31	All	115109,7	1948,267812	41129,08999	91 163,45	286,8509263	6815,993884	256 453,35

Table 110 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 15 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-		-	340 195,32	-		340 195,32
1a	100mm EPS	12 021,50	261,80	-	303 251,03	52,05	3 116,23	318 702,62
1b	120mm EPS	14 425,80	314,16	-	301 198,57	62,46	3 739,47	319 740,47
1c	150mm EPS	18 032,25	392,71	-	299 146,11	78,08	4 674,34	322 323,49
1d	200mm EPS	24 043,00	523,61	-	296 580,54	104,11	6 232,45	327 483,70
2	Change windows PVC	37 896,00	1 037,35	-	275 542,82	157,78	-	314 633,95
3	Improving roof	11 664,00	207,41	-	309 151,86	7,97	318,67	321 349,91
4	Ventilation	548,90	19,86	-	308 125,63	4,19	264,87	308 963,45
5	PV panels	40 957,80	160,04	41 129,09	311 973,99	12,80	-	394 233,72
6	Improving wall + Change windows	61 939,00	1 560,96	-	231 928,03	261,88	6 232,45	301 922,33
7	Improving wall + Improving roof	35 707,00	731,01	-	264 767,40	112,08	6 551,12	307 868,62
8	Improving wall + Ventilation	24 591,90	543,47	-	263 228,05	108,30	6 497,32	294 969,04
9	Improving wall + PV panels	65 000,80	683,65	41 129,09	268 359,21	116,91	6 232,45	381 522,11
10	Change windows + Improving roof	49 560,00	1 244,76	-	242 446,89	165,75	318,67	293 736,07
11	Change windows + Ventilation	38 444,90	1 057,21	-	243 216,57	161,97	264,87	283 145,52
12	Change windows + PV panels	78 853,80	1 197,39	41 129,09	247 321,49	170,58		368 672,35
13	Improving roof + Ventilation	12 212,90	227,27	-	275 029,70	12,16	583,54	288 065,57
14	Improving roof + PV panels	52 621,80	367,45	41 129,09	280 930,53	20,78	318,67	375 388,31
15	Ventilation + PV panels	41 506,70	179,90	41 129,09	279 904,30	16,99	264,87	363 001,85

16	Improving wall + Change windows + Improving roof	73 603,00	1 768,37	-	198 062,43	269,86	6 551,12	280 254,78
17	Improving wall + Change windows + Ventilation	62 487,90	1 580,82	-	198 575,55	266,07	6 497,32	269 407,67
18	Improving wall + Change windows + PV panels	102 896,80	1 721,00	41 129,09	203 706,70	274,69	6 232,45	355 960,73
19	Improving wall + Improving roof + Ventilation	36 255,90	750,87	-	229 105,90	116,27	6 815,99	273 044,94
20	Improving wall + Improving roof + PV panels	76 664,80	891,05	41 129,09	236 546,07	124,88	6 551,12	361 907,02
21	Improving wall + Ventilation + PV panels	65 549,70	703,51	41 129,09	235 006,72	121,10	6 497,32	349 007,44
22	Change windows + Improving roof + Ventilation	50 108,90	1 264,62	-	210 377,20	169,94	583,54	262 504,20
23	Change windows + Improving roof + PV panels	90 517,80	1 404,80	41 129,09	214 225,56	178,55	318,67	347 774,48
24	Change windows + Ventilation + PV panels	79 402,70	1 217,25	41 129,09	214 995,23	174,77	264,87	337 183,92
25	Improving roof + Ventilation + PV panels	53 170,70	387,31	41 129,09	246 808,37	24,97	583,54	342 103,98
26	Improving wall + Change windows + Improving roof + Ventilation	74 151,90	1 788,23	-	164 966,51	274,05	6 815,99	247 996,68
27	Improving wall + Change windows + Improving roof + PV panels	114 560,80	1 928,41	41 129,09	169 841,10	282,66	6 497,32	334 239,38
28	Change windows + Improving roof + Ventilation + PV panels	91 066,70	1 424,66	41 129,09	182 155,87	182,74	583,54	316 542,60
29	Improving wall + PV panels + Improving roof + Ventilation	77 213,70	910,91	41 129,09	200 884,57	129,07	6 815,99	327 083,34
30	Improving wall + Change windows + Ventilation + PV panels	103 445,70	1 740,86	41 129,09	170 354,22	278,88	6 497,32	323 446,07
31	All	115 109,70	1 948,27	41 129,09	136 745,18	286,85	6 815,99	302 035,08

Table 111 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 20 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-		-	453 593,76	-		453 593,76
1a	100mm EPS	12 021,50	261,80	-	404 334,71	52,05	3 116,23	419 786,30
1b	120mm EPS	14 425,80	314,16	-	401 598,10	62,46	3 739,47	420 140,00
1c	150mm EPS	18 032,25	392,71	-	398 861,48	78,08	4 674,34	422 038,86
1d	200mm EPS	24 043,00	523,61	-	395 440,72	104,11	6 232,45	426 343,88
2	Change windows PVC	37 896,00	1 037,35	-	367 390,42	157,78	-	406 481,55
3	Improving roof	11 664,00	207,41	-	412 202,48	7,97	318,67	424 400,53
4	Ventilation	548,90	19,86	-	410 834,17	4,19	264,87	411 671,99
5	PV panels	40 957,80	160,04	41 129,09	415 965,32	12,80	-	498 225,05

6	Improving wall + Change windows	61 939,00	1 560,96	-	309 237,38	261,88	6 232,45	379 231,68
7	Improving wall + Improving roof	35 707,00	731,01	-	353 023,20	112,08	6 551,12	396 124,42
8	Improving wall + Ventilation	24 591,90	543,47	-	350 970,74	108,30	6 497,32	382 711,73
9	Improving wall + PV panels	65 000,80	683,65	41 129,09	357 812,27	116,91	6 232,45	470 975,18
10	Change windows + Improving roof	49 560,00	1 244,76	-	323 262,52	165,75	318,67	374 551,71
11	Change windows + Ventilation	38 444,90	1 057,21	-	324 288,75	161,97	264,87	364 217,70
12	Change windows + PV panels	78 853,80	1 197,39	41 129,09	329 761,98	170,58		451 112,85
13	Improving roof + Ventilation	12 212,90	227,27	-	366 706,27	12,16	583,54	379 742,14
14	Improving roof + PV panels	52 621,80	367,45	41 129,09	374 574,04	20,78	318,67	469 031,82
15	Ventilation + PV panels	41 506,70	179,90	41 129,09	373 205,73	16,99	264,87	456 303,28
16	Improving wall + Change windows + Improving roof	73 603,00	1 768,37	-	264 083,25	269,86	6 551,12	346 275,60
17	Improving wall + Change windows + Ventilation	62 487,90	1 580,82	-	264 767,40	266,07	6 497,32	335 599,52
18	Improving wall + Change windows + PV panels	102 896,80	1 721,00	41 129,09	271 608,94	274,69	6 232,45	423 862,97
19	Improving wall + Improving roof + Ventilation	36 255,90	750,87	-	305 474,53	116,27	6 815,99	349 413,57
20	Improving wall + Improving roof + PV panels	76 664,80	891,05	41 129,09	315 394,76	124,88	6 551,12	440 755,71
21	Improving wall + Ventilation + PV panels	65 549,70	703,51	41 129,09	313 342,30	121,10	6 497,32	427 343,02
22	Change windows + Improving roof + Ventilation	50 108,90	1 264,62	-	280 502,93	169,94	583,54	332 629,93
23	Change windows + Improving roof + PV panels	90 517,80	1 404,80	41 129,09	285 634,08	178,55	318,67	419 183,00
24	Change windows + Ventilation + PV panels	79 402,70	1 217,25	41 129,09	286 660,31	174,77	264,87	408 849,00
25	Improving roof + Ventilation + PV panels	53 170,70	387,31	41 129,09	329 077,83	24,97	583,54	424 373,43
26	Improving wall + Change windows + Improving roof + Ventilation	74 151,90	1 788,23	-	219 955,35	274,05	6 815,99	302 985,52
27	Improving wall + Change windows + Improving roof + PV panels	114 560,80	1 928,41	41 129,09	226 454,80	282,66	6 497,32	390 853,09
28	Change windows + Improving roof + Ventilation + PV panels	91 066,70	1 424,66	41 129,09	242 874,49	182,74	583,54	377 261,22
29	Improving wall + PV panels + Improving roof + Ventilation	77 213,70	910,91	41 129,09	267 846,09	129,07	6 815,99	394 044,86
30	Improving wall + Change windows + Ventilation + PV panels	103 445,70	1 740,86	41 129,09	227 138,96	278,88	6 497,32	380 230,81
31	All	115 109,70	1 948,27	41 129,09	182 326,90	286,85	6 815,99	347 616,81

Table 112 - GWP of renovation Scenarios at Blåsutgatan 8 (Lifespan: 35 years)

Scenario	Renovation Measure	A1-A3	A4	B4	B6	C2	C3-4	Total (kg CO_2 eq)
0	Nothing	-		-	793 789,09	-		793 789,09
1a	100mm EPS	12 021,50	261,80	-	707 585,75	52,05	3 116,23	723 037,33
1b	120mm EPS	14 425,80	314,16	-	702 796,67	62,46	3 739,47	721 338,57
1c	150mm EPS	18 032,25	392,71	-	698 007,60	78,08	4 674,34	721 184,97
1d	200mm EPS	24 043,00	523,61	-	692 021,25	104,11	6 232,45	722 924,42
2	Change windows PVC	37 896,00	1 037,35	-	642 933,24	157,78	-	682 024,37
3	Improving roof	11 664,00	207,41	-	721 354,33	7,97	318,67	733 552,39
4	Ventilation	548,90	19,86	-	718 959,80	4,19	264,87	719 797,62
5	PV panels	40 957,80	160,04	41 129,09	727 939,31	12,80	-	810 199,05
6	Improving wall + Change windows	61 939,00	1 560,96	-	541 165,41	261,88	6 232,45	611 159,71
7	Improving wall + Improving roof	35 707,00	731,01	-	617 790,60	112,08	6 551,12	660 891,82
8	Improving wall + Ventilation	24 591,90	543,47	-	614 198,79	108,30	6 497,32	645 939,78
9	Improving wall + PV panels	65 000,80	683,65	41 129,09	626 171,48	116,91	6 232,45	739 334,38
10	Change windows + Improving roof	49 560,00	1 244,76	-	565 709,42	165,75	318,67	616 998,60
11	Change windows + Ventilation	38 444,90	1 057,21	-	567 505,32	161,97	264,87	607 434,27
12	Change windows + PV panels	78 853,80	1 197,39	41 129,09	577 083,47	170,58		698 434,33
13	Improving roof + Ventilation	12 212,90	227,27	-	641 735,97	12,16	583,54	654 771,84
14	Improving roof + PV panels	52 621,80	367,45	41 129,09	655 504,56	20,78	318,67	749 962,35
15	Ventilation + PV panels	41 506,70	179,90	41 129,09	653 110,02	16,99	264,87	736 207,58
16	Improving wall + Change windows + Improving roof	73 603,00	1 768,37	-	462 145,68	269,86	6 551,12	544 338,03
17	Improving wall + Change windows + Ventilation	62 487,90	1 580,82	-	463 342,95	266,07	6 497,32	534 175,07
18	Improving wall + Change windows + PV panels	102 896,80	1 721,00	41 129,09	475 315,64	274,69	6 232,45	627 569,67
19	Improving wall + Improving roof + Ventilation	36 255,90	750,87	-	534 580,43	116,27	6 815,99	578 519,47
20	Improving wall + Improving roof + PV panels	76 664,80	891,05	41 129,09	551 940,83	124,88	6 551,12	677 301,78
21	Improving wall + Ventilation + PV panels	65 549,70	703,51	41 129,09	548 349,02	121,10	6 497,32	662 349,74

22	Change windows + Improving roof + Ventilation	50 108,90	1 264,62	-	490 880,13	169,94	583,54	543 007,13
23	Change windows + Improving roof + PV panels	90 517,80	1 404,80	41 129,09	499 859,64	178,55	318,67	633 408,56
24	Change windows + Ventilation + PV panels	79 402,70	1 217,25	41 129,09	501 655,55	174,77	264,87	623 844,23
25	Improving roof + Ventilation + PV panels	53 170,70	387,31	41 129,09	575 886,20	24,97	583,54	671 181,80
26	Improving wall + Change windows + Improving roof + Ventilation	74 151,90	1 788,23	-	384 921,86	274,05	6 815,99	467 952,03
27	Improving wall + Change windows + Improving roof + PV panels	114 560,80	1 928,41	41 129,09	396 295,91	282,66	6 497,32	560 694,19
28	Change windows + Improving roof + Ventilation + PV panels	91 066,70	1 424,66	41 129,09	425 030,35	182,74	583,54	559 417,09
29	Improving wall + PV panels + Improving roof + Ventilation	77 213,70	910,91	41 129,09	468 730,66	129,07	6 815,99	594 929,43
30	Improving wall + Change windows + Ventilation + PV panels	103 445,70	1 740,86	41 129,09	397 493,18	278,88	6 497,32	550 585,03
31	All	115 109,70	1 948,27	41 129,09	319 072,08	286,85	6 815,99	484 361,99

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
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