Linnæus University
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Degree Project

Life Cycle Analysis and Life Cycle Cost Assessment of a Single-family house Energy Renovation

Case study Växjö, Sweden

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Abstract

Humans are increasingly influencing the climate and the temperature of the Earth by burning fossil fuels, destroying forests, and raising livestock. This adds massive amounts of greenhouse gases (GHG) to those already present in the atmosphere, amplifying the greenhouse effect and contributing to global warming. The building sector accounts for a significant amount of greenhouse gas emissions. Decarbonizing the building industry can result in significant emission reductions in the future years. Sweden's energy and climate goals have been updated, and some of them include reducing GHG emissions in the building sector, increasing energy efficiency, and making electricity production 100 percent renewable. In Sweden, energy renovations in single-family houses (SFHs) have the potential to reduce GHG emissions and improve energy efficiency, but the rate of energy renovations remains low because of financial, social, and behavioral barriers. This thesis aims to use LCA and LCC methodologies to assess energy renovations on SFH in Växjö by combining various combinations of energy efficiency measures (EEMs) to reduce energy use. The energy performance and eight different renovation scenarios using different EEMs have been evaluated for the selected single-family building. To evaluate building renovation measures, we developed a method based on life cycle assessment (LCA) and life cycle cost (LCC) that incorporates building information modeling (BIM). Five different renovation measures were combined in eight scenarios in this research, including different thicknesses of thermal insulation for walls and roofs, triple-glazed windows, and doors with different U-values, air-source heat pumps, mechanical ventilation with heat recovery, and solar photovoltaic. The present cost values of renovation measures over 50 years for LCC calculation were calculated. The global warming potential (GWP) of each renovation measure was estimated over 50 years using One-click LCA. According to the findings of this thesis project, scenarios 1 and 8 had the lowest and highest reductions in primary energy number, respectively. Scenarios 5, 6, 7, and 8 are the most cost-effective in comparison to other scenarios. All scenarios resulted in a reduction in GWP impact from an LCA perspective in which scenario 7 resulted in the highest reduction in GWP impact.

Keywords: LCA, LCC, EEMs, insulation, windows, mechanical ventilation, ASHP, PV, GWP, building renovation, BIM energy simulation, single-family house

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<u>Contributions:</u>

Mohammed Abou Ghadir:
1 Introduction, 1.2 Research questions, 2.1 Swedish building regulations, 2.3 Examining the concept of renovations in the literature, 3.1 Description of the case house, 3.3.1 Wall insulation, 3.3.2 Roof insulation, 3.3.3 Changing windows, 3.3.6 PV system, 3.7.1.1 Wall insulation, 3.7.1.2 Roof insulation, 3.7.1.3 Changing windows, 3.7.1.6 PV system 3.7.2 Scenarios, 4.2 Building energy simulation, 4.3 Life cycle inventory, 4.4 Environmental Impact Assessment, 4.5 LCC analysis, 4.6 Primary energy and LCA, 4.7 Primary energy and LCC, 4.9 Sensitivity analysis, 4.9.1 Discount rate and LCC, 4.9.2 Lifespan and LCC, 5 Discussion (first half), 6 Conclusion (second half)

Zahra Aghaei:
Abstract, 1.1 The aim of the study, 1.3 Limitations, 2.1 Swedish building regulations, 2.2 Renovation Strategies (2.2, 2.2.1, 2.2.2, 2.2.3, 2.2.4, 2.2.5), 2. Literature review, 2.4 The State of the Art of LCA and LCC methodology in Building renovation, 3 Methodology, 3.2 Energy Modeling, 3.3.4 Ventilation System, 3.3.5 Heating System, 3.4 Life cycle assessment, 3.5 Life cycle cost analysis, 3.6 Simulation, and calculation tools (3.6, 3.6.1, 3.6.2, 3.6.3), 3.7.1.4 Ventilation System, 3.7.1.5 Heating System, 4.4 Environmental Impact Assessment, 4.5 LCC analysis, 4.7 LCA and LCC, 5 Discussion, 6 Conclusion (First half), 7 Future Work

Abbreviations

GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LCIA	Life-cycle impact assessment
ASHP	Air source heat pump
FEBY	Forum for energy-efficient construction
BBR	Boverket Building regulations
EPD	Environmental Product Declaration
GHG	Greenhouse gases
PV	Photovoltaic
EEMs	Energy efficiency measures
BIM	Building information modeling
ISO	International Organization for Standardization
EU	European Union
SFHs	Single family houses
EPS	Expanded polystyrene
IAQ	Indoor air quality
CO2	Carbon dioxide
ETI	External thermal insulation
ITI	Internal thermal insulation
HR	Heat recovery
EER	Energy-efficient retrofitting
CED	Cumulative energy demand
NPC	Net present cost
SEK	Swedish Krona

Notions

U-value	Thermal transmittance (W/m²/K)
A_{temp}	Living area of the building for temperature-controlled spaces
VFT	Total heat lose
COP	Coefficient of Performance
Q	Heat
W	Work
PV	Present value
t	Time in unit of year
Ft	Future cash amount that occurs in year t
d	Discount rate
I	Investment costs
Rep	Replacement costs
E	Operational energy costs
EOL	End-of-life costs

1. Table of Contents

1. Introduction

The adoption of the Paris Agreement marks a worldwide action plan to mitigate catastrophic climate change impacts by keeping the increase in temperature below 2 °C in comparison with pre-industrial times and preferably limiting it to 1.5 °C to stop global warming. (Nations, 2022). To achieve such a target the EU has updated its climate targets in 2020 to reduce the emission levels by at least 55% in comparison to 1990 by 2030. Moreover, all member parties of the Paris agreement should also update their national climate plan to decrease their GHG emissions in the upcoming decades ("Climate change: EU to cut CO2 emissions by 55% by 2030", 2021).

The service and housing sectors combined in 2019 consumed about 41% of the final energy use in the EU ("Energy statistics - an overview", 2022d; "The energy mode", 2022c). The building sector also accounts for 36% of GHG emissions in the Union, therefore, decarbonizing this sector can deliver immense emission reductions in the upcoming years if energy-saving technologies, governmental regulation, and behavioral changes are applied (UN News, 2007).
Sweden has updated its energy and climate goals for 2030 and beyond to achieve the agreed-on targets within the Paris agreement. Some of Sweden´s agreed on climate goals and targets are first to reduce GHG emissions in the building sector by 63% by 2030 compared to 1990, energy supply compared to 2005 should be 50% more efficient by 2030, and electricity production must be 100% renewable by 2040 and finally, Sweden must have net-zero emissions by 2045.("Sweden's energy and climate goals", 2022f)

Industry, transport, and the housing and service sector are Sweden´s main energy-consuming sectors. In 2019 all of these sectors were responsible for total energy consumption of 396 TWh whereas the housing and service sector accounts for 144 TWh of the total energy consumption ("The energy mode", 2022c). At the end of 2018, the Swedish housing stock was estimated to have approximately 5 million dwellings. Almost 2.1 million (42%) of the Swedish housing stock is single-family houses (Boverket, 2022a; Statistiska Centralbyrån, 2022a). Nearly 931 000 (45 percent) of one- or two dwelling buildings were built between 1961 and 1990 (Statistiska Centralbyrån, 2022b). The number of dwellings per type of building and year of construction is depicted in Figure 1 (Statistiska Centralbyrån, 2022b). During the million-house program, rational construction in big projects was regarded as necessary to produce affordable housing with good standards. Buildings within the program have low energy performance because there was no request for energy efficiency in the building sector during the construction phase of the million-house program. Timber was the most common material for the structure and the facades for SFHs. About half of the SFHs were built in groups with identical houses, where, 70% of the SFHs are detached, while fewer than 30% are row or chain houses (Boverket, 2022b; Taylor & Francis, 2022).

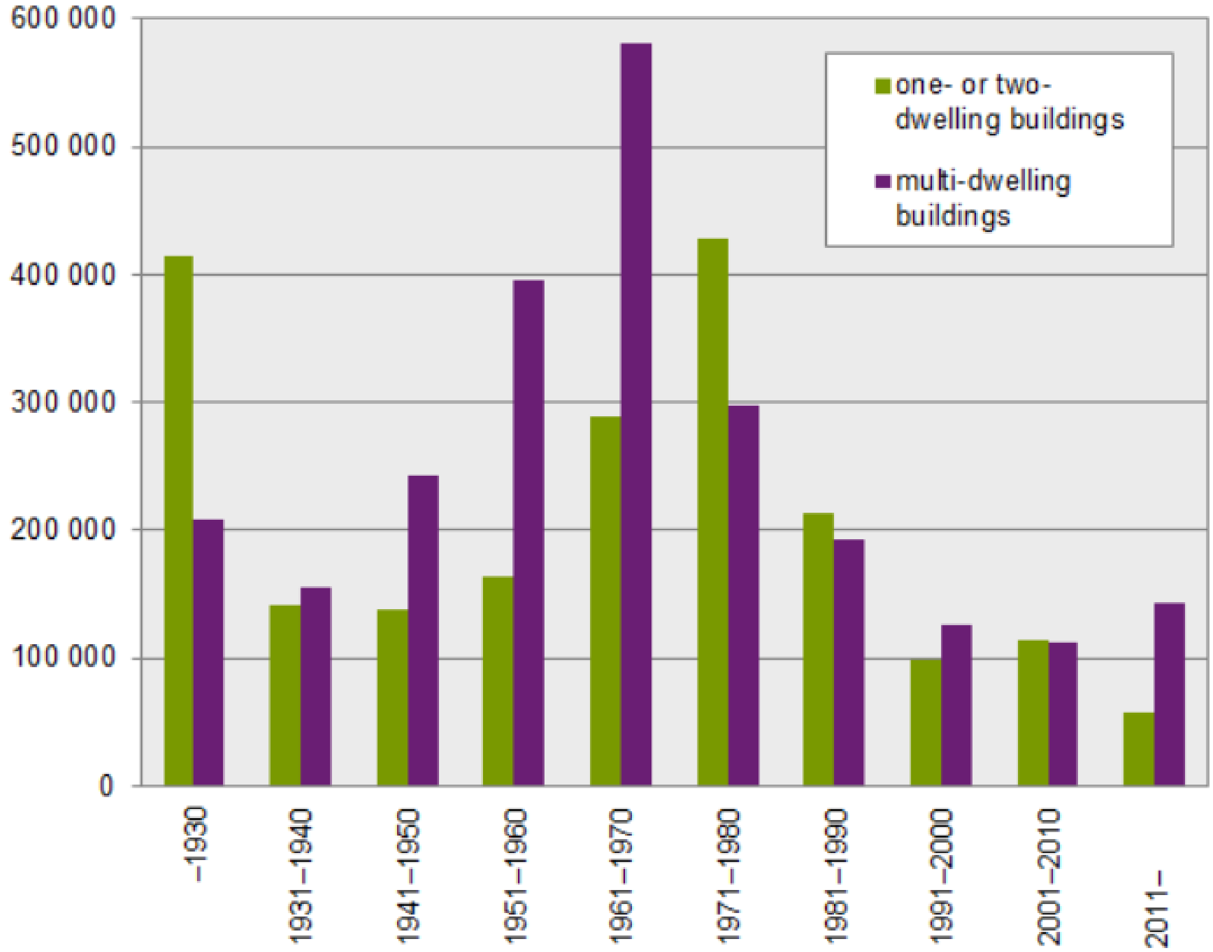

Figure 1. Number of dwellings by type of building and period of construction

According to the Swedish energy agency, the average final energy use for SFHs between 1960-1980 was approximately 61-70% higher than the final energy use of newly built SFHs after 2011 ("Energistatistik för småhus", 2022b). Renovating an SFH from the million-house program is an excellent opportunity to apply energy efficiency measures and reduce final energy use. Applications of energy-efficient measures could include changing old windows with better energy-performing ones, improving insulation on the envelope of the building, introducing a heat-exchanger in the ventilation system, changing the heating system, and finally adding renewable energy sources (涵).

The renovations rate of the old building stock in Sweden is low where the percentage of the renovated areas for buildings between 1960-1980 doesn't exceed 18% where the majority of those renovations are not connected to energy efficiency due to several factors (financial, social and behavioral) that hinder the implementation of EEMs in building renovations (Meijer). Financial factors for example homeowners being unable to finance the renovations due to the high total price

for renovation and its long payback period, behavioral factors such as the lack of owner´s awareness of how EEMs can affect the building energy use, and finally social factors such as the lack of reliable information about what renovations should be made that might help homeowners while taking the decision (Lina La Fleur; "Recommended Read - Financial Barriers to Climate & Comfort Renovations, Interreg VB North Sea Region Programme", 2022e).
There is a need for cost-effective integrated renovation solutions based on the needs and financial abilities of homeowners. This thesis aims to provide an assessment of 8 different renovation scenarios, including combinations of different EEMs. Those scenarios will be assessed for their energy efficiency and cost-effectivity.

1.1 The Aim of this study

This thesis aims to evaluate the energy performance of the building before and after different renovation scenarios, as well as the financial and environmental impact of the renovation measures. The research combined five different renovation measures in eight scenarios, including different insulation thicknesses for walls and roofs, triple-glazed windows and doors with different U-values, air-source heat pumps, mechanical ventilation with heat recovery, and solar photovoltaics. Economic feasibility has been conducted by analyzing life cycle costs including investment, replacement, end-of-life, and operation energy saving cost. Also, an LCA assessment of all scenarios has been performed by evaluating their global warming potential (GWP).

1.2 Research questions

This study is intended to investigate the following two main research questions:

1. How are different renovation scenarios implemented to improve the energy efficiency performance of the dwelling?

2. How can LCA and LCC be used to provide homeowners with better information regarding different renovation scenarios that can be applied to the dwelling?

1.3 Limitation

The case study is limited to one single-family house located in Sweden, and the results are based on the geographical location of Växjö and have not been examined for other climate zones. However, certain general conclusions could be drawn from this degree project.

Examined parameters for energy-efficient strategies are limited to insulation, windows, doors, ventilation system, solar photovoltaic, and air source heat pumps. The authors acknowledge the limitation and propose the need for further research by considering a wide range of other energy efficiency strategies and robust parameterizations for simulations.

The BIM energy software treats both windows and doors as a single unit. So, the doors are considered windows in the simulation. Student licenses of One-Click LCA software do not include LCC licenses, and only the database for computing LCC is comprised. Thus, we only used the software to perform LCAs and continued to do LCC analysis in Excel. In LCC calculation only life cycle cost considering PV (Present value) has been calculated for all scenarios and the pay pack period including IRR and NPV have not been calculated.

2 Literature Review

There is a detailed literature review in this chapter covering information and studies focused on renovation, life cycle assessment, and life cycle cost analysis of renovated buildings. This chapter is divided into four parts: I) a description of building regulations in Sweden, II) an overview of renovation strategies, III) an evaluation of the concepts of renovation used in the selected recent studies, and IV) how different selected studies have used LCA and LCC to provide information regarding different renovation scenarios to be applied to the dwelling.

2.1 Swedish building regulations

In Sweden, there is the national board of housing building and planning or the (BBR) that consist of mandatory provisions that must be fulfilled and considered while building or renovating a building. BBR is often updated and the latest BBR is BBR29. The latest version of the BBR recommends the U-values of the building elements to fulfill the mandatory total U-value and primary energy number before building or renovating. The requirements for single-family houses in Sweden between 90-130 m^2 are a total U-value of the building envelope of 0.3 W/m²K and a maximal primary energy number of 95.(Boverket)

Forum for energy-efficient construction (FEBY) is a voluntary low-energy building criterion developed by the Swedish Centre for Zero Energy Buildings. The FEBY standard is divided into three grading levels: bronze, silver, and gold. The FEBY regulation contains specified components and specifications for windows, doors, and airtightness. According to the FEBY gold, the U-value of the windows and doors ought to be 0.8 (W/m2 K) and this requirement refers to the building's average U-value, not the single window. And, airtightness of a maximum of 0.3 l/(s·m2) at 50 pa pressure difference is required. (feby, 2019)

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Table *1* shows the primary energy according to BBR 29 regulation. Table *2* shows the U-values for building envelope according to BBR 29 and FEBY gold regulations.

Table 1. Primary energy according to BBR 29

Building Regulations	BBR 29
Primary energy [kWh/m². year]	95

Table 2. U-value for different building elements according to BBR 29, FEBY gold

Building Regulations	Windows	Doors	Roof	Walls
BBR 29	1.2	1.2	0.13	0.18
FEBY gold	0.8	0.8	0.8	0.1

2.2 Renovation strategies

To fulfill the building regulations such as Forum for energy-efficient construction (FEBY) and the swedish national board of housing building and planning (BBR), it is dramatically important to conduct renovation measures. Common energy renovation contains adding insulation on walls, exchanging the windows renovations, improving the heating system, installing a ventilating and air conditioning system, and controlling the building's operational schedules (Ma, Cooper, Daly, & Ledo, 2012). In addition, the implementation of solar energy systems, lighting improvements such as lamp replacement, and the use of lighting control systems are further energy actions that can be considered(Kolokotsa, Diakaki, Grigoroudis, Stavrakakis, & Kalaitzakis, 2009). The following are five renovation measures that have been conducted in this study.

2.2.1 Insulation

Implementing insulation to the building components of existing buildings is one technique to reduce energy use. Thermal insulation could be installed on the exterior (external thermal insulation, ETI) or interior side (internal thermal insulation, ITI) of the building envelope during the energy-efficient retrofitting (EER) process (Kolaitis et al., 2013). Depending on whether the insulation is applied to the interior or exterior of the wall, the moisture content of the existing wall assembly varies (Pär Johansson, 2011). The ETI design is most widely used in EER measures deployed in apartment and office buildings because it provides several major benefits, including moisture condensation prevention, straightforward tackling of thermal bridges, and use of the building's thermal mass. ETI, on the other hand, has higher installation costs, especially when installed on higher floors, and it can be damaged by weather, accidents, or vandalism (Kolaitis et al., 2013).

Insulation not only improves a building's energy efficiency but also improves its indoor environmental quality (Anastaselos, Oxizidis, & Papadopoulos, 2017). Expanded polystyrene (EPS) is used most frequently for building insulation purposes (Almusaed & Almssad, 2016). EPS boards are made of polystyrene and are produced by “expanding” the polystyrene polymer by combining a blowing agent (pentane) and heat (Biswas, Shrestha, Bhandari, & Desjarlais, 2016). EPS is produced from non-renewable raw materials, which makes it one of its limitations (Pargana, Pinheiro, Silvestre, & Brito, 2014). One of the advantages of the EPS is that it proved to be more cost-effective (Ede et al., 2014).

2.2.2 Windows

Windows are key building components that provide vision, air ventilation, passive solar gain, daylighting, and the ability to exit the building in emergencies. Windows have significantly high U-values compared to the other components of buildings (Aburas et al., 2019).

In summer, solar radiation entering the building through the windows significantly exceeds the required cooling load of the buildings. In winter, the heat losses through the windows similarly contribute to the significant increase of the required heating load of the building. Thus, it is vital to reduce these unintended losses or gains of heat by proposing optimal designs for windows with low thermal transmission (Bitaab, Hosseini Abardeh, & Movahhed, 2020).

2.2.3 Ventilation system

The ventilation system is essential because, without it, the air in the house would become stale, damp, and generally unpleasant. The heating and ventilation system frequently influences indoor air quality (IAQ) in apartment buildings (Palm & Reindl, 2016). Ventilation systems in old buildings are often technologically obsolete; thus, using integrated renovation packages, including measures to improve indoor air quality (IAQ), is inevitable (Michal Pomianowski, Yovko Ivanov Antonov, & Per Heiselberg, 2019). The appropriate ventilation system helps control a large portion of the thermal comfort, interior air quality, and heat losses. These characteristics can be improved by being able to alter the ventilation airflow mechanically. As a result, a mechanical ventilation system with heat recovery is preferable (Hastings & Wall, 2007). Renovation of existing ventilation systems is a natural part of the renovation process, and in cold climatic regions, exhaust air heat recovery (HR) is needed to meet the EU's energy-saving requirements (Dodoo, Gustavsson, & Sathre, 2011).

2.2.4 Solar photovoltaic (PV) systems

Photovoltaics (PV) is the direct conversion of light into electricity. Photovoltaic systems use solar cells to convert sunlight into power. On-grid, off-grid (stand-alone), and hybrid systems are the three primary types of solar systems utilized in household applications (Masoud Farhoodnea, Azah. Mohamed, Hussain. Shareef, & Hadi. Zayandehroodi, 2013), (EL-Shimy, 2009), (Ayompe, Duffy, McCormack, & Conlon, 2011).

In an on-grid PV system, the solar system's electrical output power is directly connected to the grid and the residence. The PV system and grid electricity are used to power the residence's loads. Depending on the solar radiation and the electric energy given by the PV system, the load can take all the required energy from the PV system or be split between the PV and the electric grid. PV systems with modest needs and large amounts of generated power can be fed into the grid via an electric meter (Fetyan & Hady, 2021)

2.2.5 Air Source Heat Pump

Heat pumps are energy recovery systems that utilize electricity to transfer higher temperature heat from the external ground or air to the heating and hot water of a building ("Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC …", 2009; Carroll, Chesser, & Lyons, 2020). The most popular type of heat pump in Europe is an air source heat pump (ASHP) ("European Heat Pump Market and Statistics Report", 2014; Carroll et al., 2020). ASHPs have a substantially small land footprint in comparison with other heat pumps. As home heating becomes more electrified, ASHPs are expected to play a prominent role, mainly through renovation plans for older homes in urban areas (Carroll et al., 2020).

Air-to-air heat pumps acquire their energy from the outside air. Heat is distributed by wall radiators or underfloor pipes in air systems using a hydronic system. Heat energy is distributed throughout the building via ducts by air-to-air heat pumps (Carroll et al., 2020).

Heat pump efficiency is calculated by comparing the amount of heat energy delivered to the amount of energy consumed by the heat pump. The Coefficient of Performance (COP) is the ratio of a heat pump's heating or cooling capacity in kilowatts to the heat pump's power consumption in kilowatts, W (Carroll et al., 2020). Equation 1 also shows the calculation of COP.

Equation 1

$$CoP = \frac{Q}{W}$$

2.3 Examining the concept of renovations in the literature

This chapter contains a literature review of prior studies regarding energy renovation for single-family and multi-family buildings. Different research papers were analyzed to better understand how energy renovations are done and what building regulations are to be met.
Ekström et al (Ekström & Blomsterberg, 2016) discuss the theoretical energy savings potential of renovating houses built between 1964-1975. In his study, four houses were selected as case houses and simulated with standard renovation measures. The research demonstrated that it is possible to reduce final energy use by approximately 65-75 %. Results also indicated that single-family houses would not likely be able to attain passive house standards after renovation due to some house characteristics such as shape, foundation, and composition of the building envelope which force a limiting factor on the energy renovation.
Rose et al (Rose, Kragh, & Nielsen, 2022) also researched passive house renovation of a block of flats in Denmark. This research aimed to apply the German passive house standards and then test how much the renovation measures will reduce the energy use and CO_2 emissions. The renovation included different measures such as insulating the façade from the outside, replacing all windows, insulating the roofs, installing decentralized mechanical ventilation systems with efficient heat recovery, and a photovoltaic system on the roof. The research also gave a detailed description of indoor climate before and after renovation and energy use measurements. The results of the research showed that the goal of meeting the passive house requirements was not met yet a significant reduction in energy use can be reached with this type of building. Moreover, the building fulfilled less strict requirements of the passive house renovation certification EnerPHit. Finally, results showed that the heat consumption was reduced by more than 50% and the indoor climate was increased from 21.7 C to 23.3 C.

2.4 The State of the Art of LCA and LCC methodology in Building renovation

Ekström et al (Ekström, Bernardo, & Blomsterberg, 2018) asses in their paper the cost-effectiveness of renovating a single-family house to passive house standards while comparing to other renovation standards done which are the BBR standards and minimum building standards. Two reference buildings that need major renovations are represented in their research and an LCC was performed through an NPV study. The results show that passive house renovations can be the most cost-effective, but it depends on the type of heat generation in the house. The research concludes that the most cost-effective individual act was installing an exhaust air heat pump and the least cost-effective personal act was installing new windows.

La Fleur et al. (La Fleur, Rohdin, & Moshfegh, 2019) also studied the cost-effectiveness of energy renovation buildings. The selected case study was a multi-family building in Linköping, Sweden, constructed in 1961. The study used the LCC method with an optimization tool OPERA-MILP (Optimal Energy Retrofit Advisory-Mixed Integer Linear Programming) software for reducing the life cycle cost during a selected life cycle of a building. And the LCC was calculated and optimized for 40 years. The results revealed that the studied dwelling required extensive renovations, and the building envelope, including windows, required maintenance or replacement. Yet it was not cost-effective from the LCC perspective to invest in ambitious EEMs to decrease space heating demand. The lowest LCC was recognized when only modern windows with a longer technical lifetime than the original window type were installed. Low energy prices were identified as a barrier to the cost-effectiveness of energy renovation. Under the specified framework conditions and assumptions in their study, the results demonstrated that improving the thermal performance of the building envelope or implementing heat recovery ventilation methods to lower the space heating demand in the building is not cost-optimal. It was found that a balanced mechanical ventilation system with heat recovery was cost-optimal when an energy-saving target of 40% was introduced.

In these two reviewed articles (one for single-family and one for multi-family buildings), new windows have been recognized as the lowest LCC in comparison with other implemented measures. Moreover, the most cost-effective measure for the single-family structure case study was recognized as installing an exhaust air heat pump. However, the multi-family structure was equipped with an exhaust air ventilation system itself and installing the mechanical ventilation system with heat recovery was the most cost-effective measure.

Colli et al., (Colli, Bataille, Antczak, & Buyle-Bodin, 2018) studied the life cycle assessment of a French single-family house renovation. According to the LCA study, the hotspots were: A1-A3 Modules (product stage), B4 Module~~,~~ (Replacement included in the use stage), and B6 Module (Energy consumption included in the use stage). Moreover, the environmental impact of the A1-A3 module is primarily due to the following construction products: EPS is used for ground insulation, ceramic tile flooring, PVC window frames, outdoor pathway material, and roofing tiles, and B4 is contributed by window frames, front and inside doors, and boiler replacements. It resulted that the main contributor to the B6 module's associated impacts was natural gas used for heating and hot water supply. It was also found that the assessment of uncertainties reveals that the A1-A3 modules and the B4 module produce the most reliable results. Results also revealed that the most contributing modules are A1-A3, B6 and B4. In addition, in terms of the construction product's climate change indicator, two-thirds of this impact category is mainly a contribution by three construction materials: ground insulating EPS, ground and wall ceramic tiles, and PVC window frames.

Ramírez-Villegas et al. (Ricardo Ramírez-Villegas, Ola Eriksson, & Thomas Olofsson, 2019) analyzed four rehabilitation scenarios for a building located in Borlänge, Sweden. The study aimed to investigate how four various renovation scenarios affect the life cycle environmental impact concerning materials and operational energy use and recognize the different life cycle stages that contribute to the total environmental impact of these renovation scenarios. The four scenarios included: I) deep energy renovation scenario, II) building envelope scenario, III) heat recovery ventilation scenario with reduced indoor temperature, and IV) heat recovery ventilation scenario without reduced indoor temperature. The results showed that, from the life cycle perspective, the operating energy use and the building and installation operations were recognized as having the largest environmental impact in all scenarios. Due to the cold temperature and poor sun irradiation during the heating season, renovation efforts greatly impacted energy utilization. It was also found that the building materials and the construction processes gave a dramatic amount of environmental impact.

Ramírez-Villegas et al. (Ramírez-Villegas, Eriksson, & Olofsson, 2020) also analyzed eight rehabilitation scenarios for the same building located in Borlänge, Sweden, utilizing six different Northern European power mixes. The goal of the research was to assess the life cycle environmental impacts of using fossil fuels and nuclear power in various renovation strategies for multi-family buildings in a Nordic climate and also to identify the energy carriers for building space heating and domestic hot water use and how changes in the electricity production mix affect the environmental impacts. This study covered all life cycle steps from cradle to grave, and the functional unit was considered the entire case study building in use for 50 years. Combinations of photovoltaics, geothermal heat pumps, heat recovery ventilation, and building envelope improvements were among the renovation scenarios. PV modules produced a small amount of electricity in the scenario where PV was employed as a renovation alternative. Despite Sweden's efforts to subsidize PV, many housing companies claim that large-scale energy production taxes make this form of investment unappealing, despite widespread desire. Due to the relatively short lifetime of PV panels both its environmental payback and the lifetime of the building, installing such a system is counterproductive. Moreover, according to the study, PV systems in northern latitudes cannot compensate for the environmental impacts of their generation due to their low output.

Potrč Obrecht et al. (Potrč Obrecht, Röck, Hoxha, & Passer, 2020) studied a literature review on BIM (building information modeling) and LCA (life cycle assessment) integration. , and the implemented BIM-LCA workflows were thoroughly examined. This study revealed that because of the ability of BIM software to retain essential information for building environmental assessments, BIM software is becoming more widely used, and it should not be disregarded. It also revealed that the major BIM and LCA integration issues are (1) developing a synchronized LCA methodology that enables a clear identification of the inputs required, (2) developing information databases that ontologically and semantically conform to the BIM environment and also correspond to the desired design phase of the project, and (3) creating a flawless and automated exchange of information between BIM and LCA tools, regardless of whether they are embedded or not. The results suggest that Potrč Obrecht et al. study (Potrč Obrecht et al., 2020) shows that BIM software can benefit LCA case studies. This provides a reason for the use of BIM software in our degree project.

Moschetti et al., (Moschetti & Brattebø, 2017) conducted a combined life cycle environmental and economic assessment in building energy renovation. The case study for this project was on a single-family house in Norway that has recently undergone a serious energy upgrade. Seven scenarios involving various EEMs were investigated, and for each scenario, certain environmental and economic indicators were computed. The results demonstrated that an increase in net present cost (NPC) was usually accompanied by a reduction in both global warming potential (GWP) and cumulative energy demand (CED). It was also found that the higher the house life span after the renovation, the lower the total annual GWP and CED. Moreover, results showed that the environmental and economic variables computed had a close to negative linear relationship. However, in terms of environmental impact, the best scenarios' CED and GWP values were 50 percent and 32 percent lower, respectively, than the worst scenarios' values, although their NPC was roughly 6% higher. This paper was in the decision-making process for a meaningful combination of environmental and economic assessments in building energy refurbishment projects to choose the most sustainable option.

To conclude, the state of the art of LCA and LCC methodology in building renovation started with reviewing seven articles related to LCA and LCC of renovation houses. The two reviewed articles related to using the LCC method have the same results in which new windows have been recognized as the lowest LCC in comparison with other implemented measures. Two reviewed articles related to LCA methodology had the common result from the life cycle perspective in which the operating energy use, building materials, construction processes, and installation operations were recognized as having a large environmental impact. A review of articles dealing with energy consumption and BIM-LCA case studies has led to the conclusion that BIM energy software is a useful tool for LCA cases. The state of the art of LCA and LCC methodology in building renovation was finalized with a review article evaluating both LCA and LCC methodology in renovation projects. The results showed a close to negative linear relationship between environmental and economic variables.

3 Methodology

The method of our project has been described in this methodology section, with subsections for each of the steps that have been taken in conducting this degree project. Figure 2 demonstrates the framework of the proposed methodology in this thesis project.

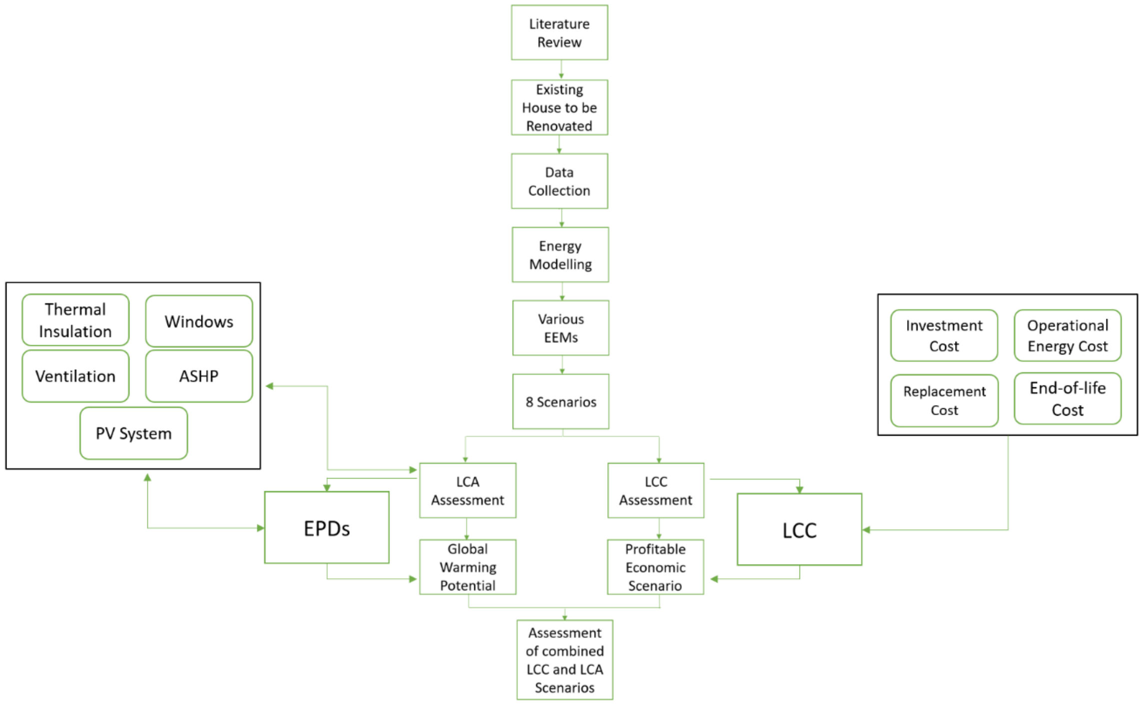

Figure 2. Methodological structure for combined LCA and LCC assessments in building energy renovation

A mixed-method approach has been followed, combining quantitative and qualitative research. This method focused on numerical calculations based on simulations applied to representative reference houses and literature reviews. In the first place, to obtain an overview of the current knowledge, a literature review (section 2) based on the research question and relevant identified keywords have been conducted, which organizes and summarizes data related to the technical evaluation of building renovation. Then the concept of renovations in the recent studies has been evaluated to acquire more knowledge regarding potential energy efficiency measures in the renovation of single-family houses. It was followed by investigating more studies to determine how LCA, LCC, and combined LCA and LCC methodologies have been applied and concluded in building renovation projects.

Then, the data collection has been carried out to obtain the required information. Data about the building's technical aspects were collected via e-mails and phone calls to the public building administration of Växjö municipality. These steps have been done for monitoring the renovation process, as well as an examination of the existing house.

The case study house is a one-story single-family house located in Växjö, Kronoberg. It was built in 1975, with a double pitched roof and without a basement. As part of our assessment of the house and its need for renovation, we proposed 5 energy efficiency measures (EEMs) to be applied to the building, including thermal insulation, windows and doors replacement, mechanical ventilation with heat recovery, and air-source heat pump, and solar PV.

Various items were randomly merged in different variations, resulting in 8 different scenarios. Scenarios 1, 3, 5, and 7 included adding insulation for walls, roofs, and windows, and doors replacement to fulfill only envelope requirements regarding BBR 29 regulation. Scenarios 2, 4, 6, and 8 included adding insulation for walls, roof, and windows and door replacement to fulfill only envelope requirements regarding FEBY gold regulation. In scenarios 1 and 2 only insulation and windows and doors replacement has been done according to BBR 29 and FEBY gold regulation, respectively. Scenarios 3 and 4 included mechanical ventilation with heat recovery. Scenarios 5 and 6 included ASHP, and solar PV. Scenarios 7 and 8 included ASHP, solar PV, and mechanical ventilation with heat recovery.

Then, Building Information Modeling (BIM) Energy analysis software has been used, which is an easy-to-use, fully dynamic energy simulation software that allows for quick and accurate building energy simulation energy. So, computer energy simulations have been done to assess both the feasibility of different renovation scenarios and existing house.

After the energy simulation of the selected house with the eight different scenarios, One-Click LCA software has been used to evaluate the life cycle assessment of the different scenarios. Using the One-Click LCA software, we chose the EPDs based on the measurements and technical data we used in various scenarios. Furthermore, we used One-Click LCA software to calculate the global warming potential (GWP) of each scenario based on the energy simulation results. Then LCC analysis has been done by Microsoft Excel considering all amounts that have been used in different renovation scenarios including investment, replacement, end-of-life, and operation energy cost. So, the present cost value, and LCC have been calculated. Next, the sensitivity analysis of LCC has been done. LCA and LCC results have been evaluated and compared to primary energy results. Finally, combined LCA and LCC evaluations were performed to determine the optimal scenario in terms of both economic and environmental considerations. A combined LCA-LCC assessment of renovation scenarios has been also conducted, in which both LCA and LCC results were displayed in graphs.

For the development of the study, we used several software. The energy simulation was done through BIM energy software. Based on construction drawings and technical details, we have modeled the house using BIM energy software. The LCA was done through One-Click LCA, and the software has its databases, including a list of EPDs, average statistics for construction materials, and average statistics for construction materials from all manufacturers in the world. Although the LCC analysis was calculated by Excel Microsoft, the database for the LCC analysis was created using One-Click LCA software.

3.1 Description of the case house

The selected reference house as a case study for this thesis is located in Växjö, Kronoberg Region, Sweden. The selected structure represents a typical house, built in the period between 1960 to 1980. The house is a one-story single-family house built in 1975, with a double pitched roof and without a basement. The house is old, and has not undergone any renovation, therefore, represents a great potential to improve the energy performance. The site plan of the case house is shown in Figure 3.

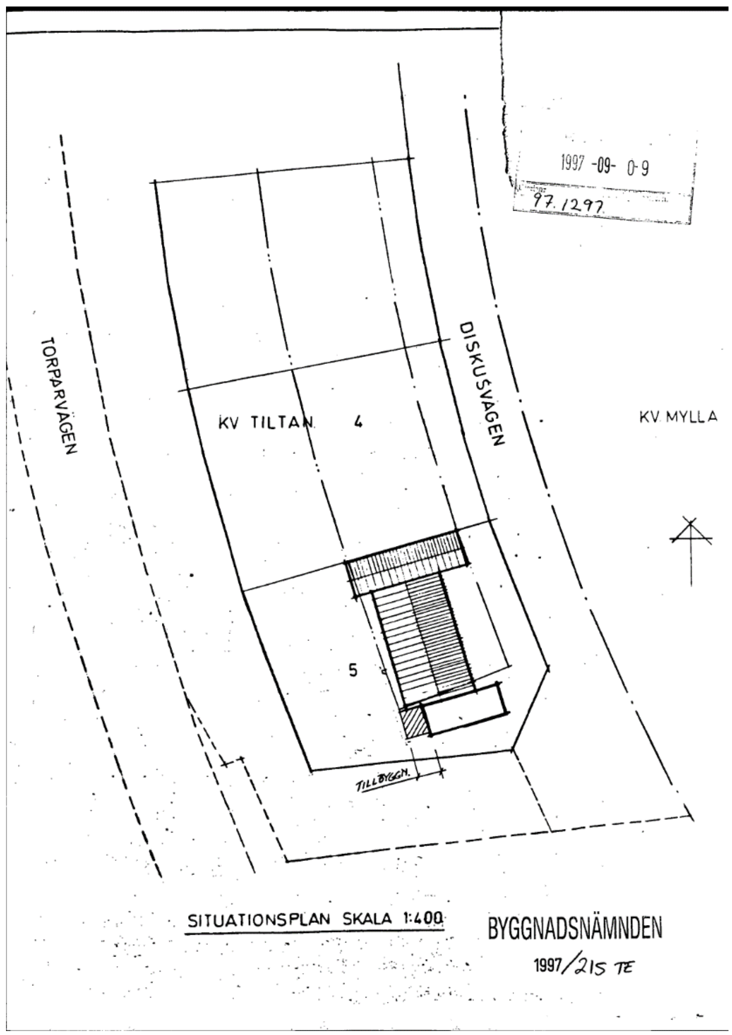

Figure 3. Site plan for the Case house

The single-family dwelling has a T shape composed of two blocks with outside dimensions of 8 x 9.78 m and 4.17 x 13.2 m. The total heated surface is 130 m^2 with a height of 2.4m, without taking into consideration the garage area which is considered in this study a non-heated area. The general information about the case house is shown in Table 3.

Table 3. General information about the case house.

Heated floor area	130 m²
Envelope area	382.5 m²
Glazing area	31 m²
Roof area	130 m²
Ventilation system	Exhaust ventilation
Heating source	District heating

The house can be considered a 5-room house with a kitchen (according to the Swedish standard), and it has a living area, an eating area, a kitchen, a bathroom, a laundry, and three bedrooms. The floor plan is shown in Figure 4.

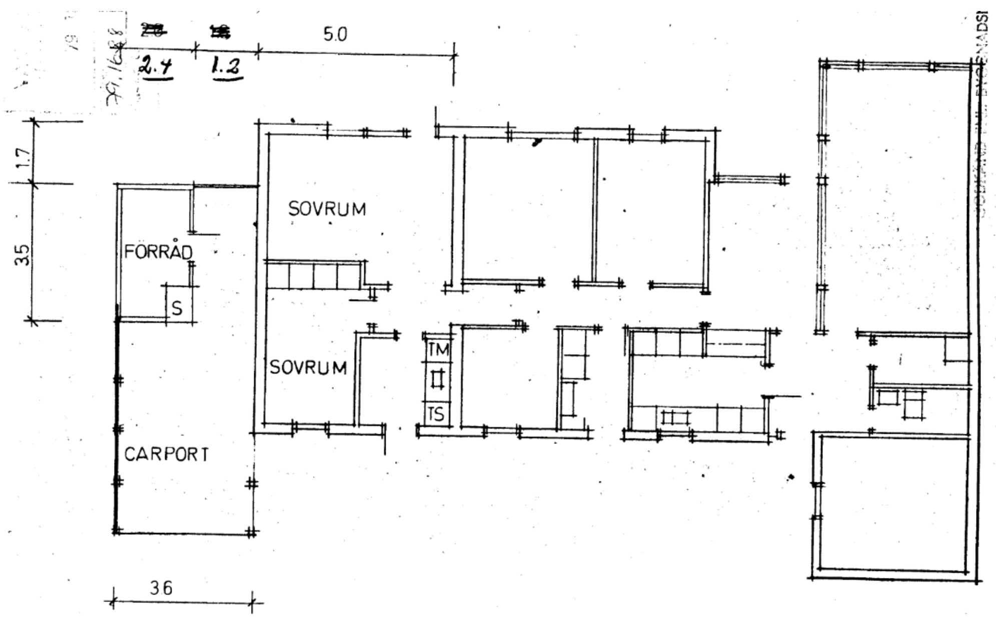

Figure 4. Floor plan of the case house

The building façade finishing is a mix between tiles and wood panels, but it will be assumed to have only facade brick on a wood bar system wall with insulation. The construction of the exterior wall is shown in Figure 5 below. It is composed of facade brick, a layer of asphalt,100 mm mineral wool with lambda 36 between wooden studs 45 x 95mm, c/c 600, and gypsum board from the outside layer to the inside layer. The U-value for the exterior wall is 0.26 W/m²K which is the U-value given by the energy simulation software data which is almost the same as the given exterior wall U-value.

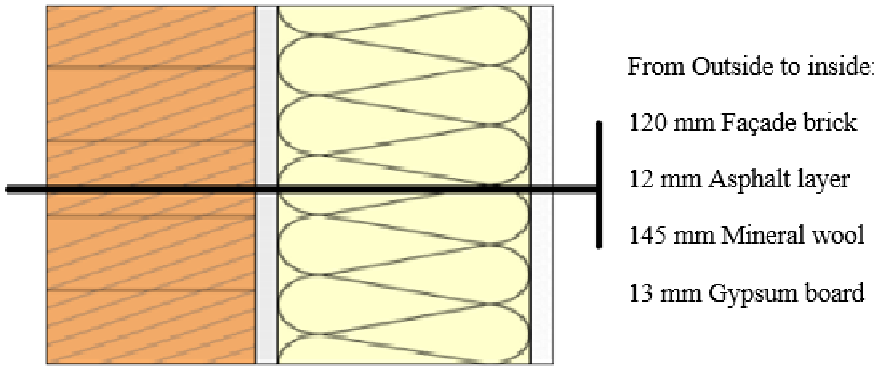

Figure 5. Construction of the exterior wall

The roof on both blocks is pitched but with different slopes respectively 17° and 45°. The construction of the roof for the reference house is shown in Figure 6 below. It is composed of the outdoor roof tiles, 100 mm mineral wool with lambda 36 between wooden studs 45mm, c/c 600, and gypsum board from the outside layer to the inside layer. The U-value for the roof is 0.24 W/m²K which is the U-value calculated by the energy simulation software data which is almost the same as the given roof U-value.

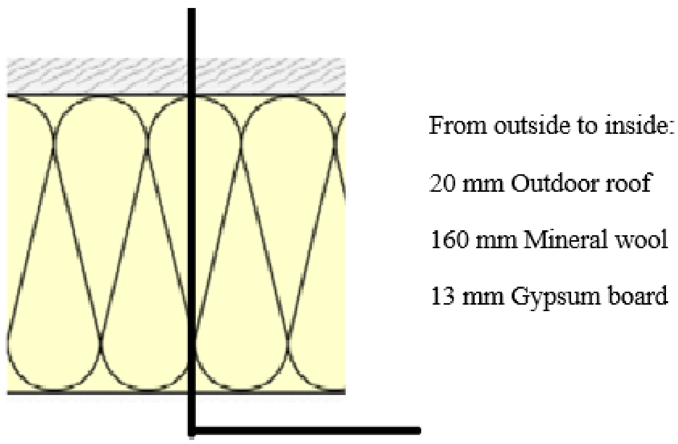

Figure 6.Construction of the roof

The existing windows are double glazed with a 2.7 W/m²K U-value as was given by the energy simulation software data. The windows are assumed to have air gaps between the panes and are not tightly sealed due to the pure condition which may let the heat be taken directly by the inner panes by air convection. There was no specific information about the U-values of the windows, so the U-value of a double-glazed window was adopted in the energy simulations as mentioned before.

The existing ventilation system used in the case house is mechanical exhaust air ventilation. The average ventilation flow used in the energy simulation is set to 0.35 l/s.m² as requested by the BBR standards. (Boverket)
The main source of space heating and domestic hot water for the case study house is district heating.

3.2 Energy Modeling

The next step was to analyze the acquired data of the selected house to determine which area requires the greatest attention. As part of this process, the Building Information Modeling (BIM) Energy analysis software has been used, which is an easy-to-use, fully dynamic energy simulation software that allows for quick and accurate calculations when optimizing a building's energy use and discovering potential savings.

In this project, the selected house was first modeled based on the construction drawings and technical details in the documentation made available by the Växjö municipality. The construction drawing and technical details have been integrated into the BIM energy software program, allowing us to manage the 3D drawing of the house, and the collected data have been digitalized to illustrate the entire house life cycle. Then, the building's thermal properties, and construction materials, which have been obtained from Växjö municipality, have been filled manually in the software after determining the building's location, orientation, and weather data. To complete the simulation, it was necessary to define the existing systems for the dwellings, such as the heating, cooling, and ventilation system. Figure 7 demonstrates the 3D model of the selected house.

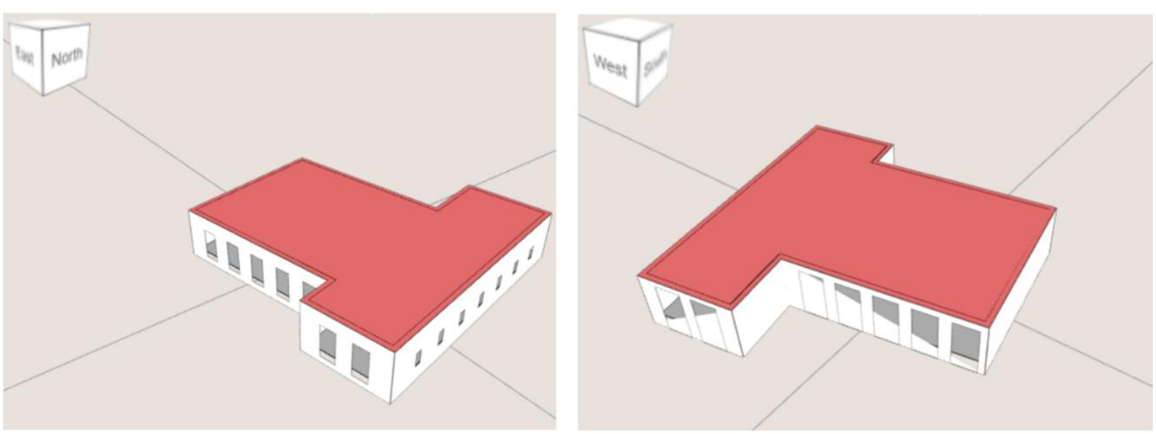

Figure 7.3D model of the house (simulated in the BIM energy software)

The feasibility of renovation scenarios has been then verified using BIM energy simulation software. So, energy efficiency measures (EEMs) have been examined in BIM energy software for different scenarios concerning three main categories, I) the renovation of the building envelope to meet the BBR or FEBY regulation for only envelope requirements, II) the development of the technical building systems which means either adding the mechanical ventilation with heat exchanger or keeping the existing mechanical ventilation, and III) the combination of both ASHP and solar PV to supply heat demand of the house or the implementation of district heating alone. In the following section, we have discussed EEMs that have been used in BIM energy software for different scenarios.

3.3 Energy efficient strategies

3.3.1 Wall insulation

For the renovation of the external walls, two solutions were considered to satisfy either the BBR or FEBY´s minimum requirement. The first and cheapest solution is to keep the existing construction and add new insulation material after the façade brick. But by doing such a solution the daylight factor will decrease so the daylight inside the house will reduce and some construction problems with the roof will occur, so such a solution was not considered. The other solution was to remove existing insulation and replace it with a thicker one which is enough to reach the desired U-value suggested by the BBR which is 0.18 W/m^2. K or FEBY which is 0.10 W/m^2. K so this solution was considered to be implemented. (Boverket)
Two insulation alternatives are set to be done, one alternative is insulating the exterior wall to meet BBR29's suggested U-value, and the second alternative is insulating the exterior wall to meet FEBY's suggested U-value.

3.3.2 Roof insulation

For renovating the roof, one solution was considered. Adding a new insulation material to the existing roof will allow us to reach the desired U-value suggested by the BBR which is 0.13 W/m^2. K or FEBY which is 0.10 W/m^2. K for the roof. (Boverket)
Two insulation alternatives are set to be done, one alternative is to insulate the existing roof to meet BBR29's suggested U-value, and the second alternative is insulating the existing roof to meet FEBY's suggested U-value.

3.3.3 Changing windows

In a building envelope, windows offer the least resistance to heat transfer, where heat is transferred through the window via conduction, convection, and radiation. (Engineer-Educators.com, 2020)

Due to the high U-value of the current windows and outside doors which is 2.7 W/m². K, it is suggested to replace the existing elements with new ones with a lower U-value to meet either the BBR which is 1,2 W/m².K or FEBY which is 0,8 suggested U-values.

Two alternatives are set to be done, the first alternative is changing current windows with better ones to meet BBR29's window U-value, and the second alternative is changing current windows with better windows to meet FEBY's suggested window U-value

3.3.4 Ventilation system

This project has been considering two types of ventilation systems, of which one will be installed in each scenario. The first alternative is the existing ventilation system which is exhaust air ventilation. The ventilation system is equipped with exhaust fans that draw air out of the building from areas where low-quality, moist, or polluted air may accumulate. In addition to exhaust air systems, the bathroom has extractor fans to prevent moisture build-up and accompanying mold issues, and the kitchen has extractor hoods to remove cooking fumes, odors, and deoxygenated air.

The second chosen ventilation system is the mechanical ventilation system with heat recovery to minimize ventilation losses. In this process of the ventilating house, the heat exchanger is applied in the kitchen and bathroom to provide a continuous supply of fresh filtered warm air, which is done by a concealed duct system inside. Air routed through a heat exchanger, then doctored outside. Fresh air from outside is drawn in and passed through the heat exchanger, which warms it and docks it to the living rooms and bedrooms and extracted from the bathroom, and kitchen.

3.3.5 Heating system

Aside from insulation and ventilation, sustainable energy is critical to making the house more energy efficient. Air-to-air source heat pumps (ASHP) are being considered for installation in the house to reduce the primary energy required for the heating system. In this project, the installed ASHP extracts heat from the outside air and transfers it to a coolant which is pushed through a compressor to heat the air to a higher temperature. It results in forming vapor which is transported to the indoor units.

3.3.6 Photovoltaic system

To reduce electricity and achieve a significant reduction in primary energy consumption for the building, and onsite renewable source of energy is proposed by installing PV cells on the roof of the dwelling. To provide more electricity and have maximum output power, the PV cells were installed and distributed on two roofs one facing south and the other facing west. The PV system doesn’t consider batteries, but a direct connection to the grid, is accounted.

3.4 Life Cycle Assessment

The LCA analysis of the building is done according to the European Standard EN 15978. One-Click LCA software and related datasets are also compliant with ISO 14040/14044 or EN 15804. Life cycle assessment (LCA) is a comprehensive and systematic approach to assessing the environmental impacts of a process or product over its entire life cycle (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Ciambrone, 2018?; Satish Joshi, 1999a; Satish Joshi, 1999b). In the 1990s, the International Organization for Standardization (ISO) adopted an environmental management standard as part of its 14,000-standard series, with the 14,040 series focusing on developing LCA methodologies ("ISO 14044: 2006. Environmental management—Life cycle assessment—Requirements and guidelines. International Organization for Standardization", 2006b). The ISO standard includes a four-stage framework for conducting LCA analyses. Goal and scope definition; inventory analysis; life-cycle impact assessment (LCIA); and interpretation ("Environmental management: life cycle assessment; Principles and Framework", 2006a). The goal and scope determine how much of the product life cycle will be assessed and to what end the evaluation will be used. The criteria for system comparison and specific times are provided in this stage. In our project, an LCA analysis of renovation scenarios was conducted to study their environmental impact in which only global warming potential (GWP) impact has been evaluated. The inventory analysis stage describes the material and energy flow throughout the product system, particularly their connection with the environment, consumed raw materials, and environmental emissions. Figure 8 demonstrates the LCA framework based on ISO 14040.

Life Cycle Assessment Framework

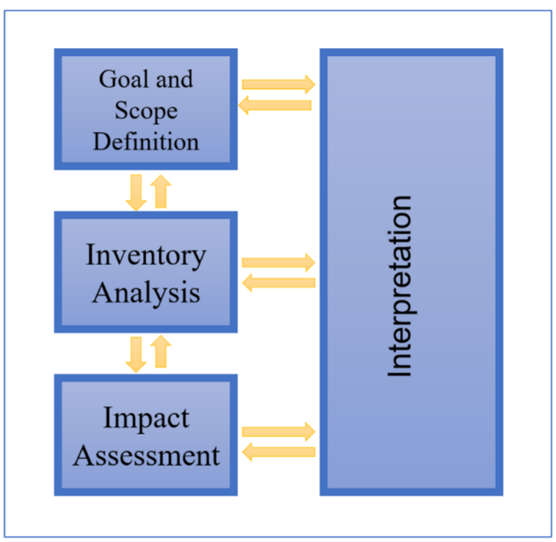

Figure 8.Life Cycle Analysis Assessment Framework

LCA methodology has been applied in the building industry since 1990 (Taborianski & Prado, 2004), (James A. Fava, 2006). In the case of buildings, stages are defined as product stage, construction, use and maintenance, and end of life. A building's entire life cycle energy includes both embodied energy (sequestered in building materials through processes of production, on-site construction, and demolition and disposal stages) and operating energy (expended in preserving the inside environment over processes of heating and cooling, lighting, and operating appliances) (Santero, Masanet, & Horvath, 2011), (Nicholas J Santero & Arpad Horvath, 2009).

In our project, for each of the scenarios, an LCA analysis (using Environmental Product Declarations (EPDs)) was performed, in which Global Warming Potential environmental impacts were calculated. To conduct the LCA, the calculation has been done by using a One-Click LCA. The LCA analysis section has covered all life cycle steps from cradle to grave, and the functional unit was considered the entire case study building in use for over 50 years. Moreover, the goal of our LCA part is to investigate how different renovation strategies affect the GWP. The system boundary of our LCA project includes A1 to C4 stages (from the raw material extraction stage (A1-A3) until disposal stage C4. Figure 9 shows the system boundary of this study.

Product Stage			Construction Process Stage		Use Stage							End-Of-Life Stage			
Raw Material Supply	Transport	Manufacturing	Transport	Installation into the building	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water use	Deconstruction	Transport	Waste Processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4

Figure 9.The system boundary of the proposed case study

3.5 Life Cycle Cost Analysis

As an economic equivalent of Life Cycle Assessment, Life Cycle Costing (LCC) was established in the 1980s (Guinée et al., 2011). In the context of construction and renovation, a life cycle cost (LCC) analysis is an assessment based on present and future costs for the construction, installation, maintenance, and operation of a building throughout its life cycle (Gluch & Baumann, 2004; S Fuller & Steve Petersen). Initial costs, fuel costs, replacement costs, operation and maintenance costs, finance charges, and residual values are all project-related costs that can be assessed using LCC.

To begin, each renovation scenario's LCC was estimated separately. The LCC calculation considers material costs, labor costs, post-maintenance costs, replacement costs, and operation costs (district heating and electricity costs). The calculations are done in Microsoft Excel to calculate the net present value of renovation scenarios in our project. In the LCC calculation, the present value (PV) formula was used to estimate future cash flows to present values. The present value calculation was used to calculate all costs that arise during the building's lifetime. In our case, the general LCC formula for structures was applied to total all expenditures from cradle to grave.

Furthermore, because both LCAs and LCCs are crucial for the decision-making process, both LCAs and LCCs have been combined to create the best possible energy renovation scenario for the selected house. The LCA and LCC results have been represented in one graph, which illustrates the interconnections. A combined LCA and LCC in this project aim to determine the best energy renovation scenario that accommodates both economic and environmental aspects.

3.6 Simulation and calculation tools

The project was conducted with the use of three different software: a simulation tool (BIM Energy software) to assess the energy efficiency of the existing building as well as eight different scenarios of renovation, One-Click LCA to assess the life cycle assessment, and finally Microsoft Excel to analyze the life cycle cost (LCC) of the scenarios. In this manner, in this section, three tools that have been used in this degree project have been presented.

3.6.1 Building Information Modeling software

Building Information Modeling (BIM) Energy analysis software is a cutting-edge web-based building energy simulation and calculation engine. The framework allows BIM components to use data collected by other systems to calculate intended energy performance and compare it to actual energy performance, which can determine whether the building meets energy efficiency requirements (Bim Energy, 2022).

The selected platform for BIM Energy is an energy calculation program from StruSoft. StruSoft software provides users with crucial insights and expertise to help them deal with difficult, assignment-critical building analyses and design challenges (Bim Energy, 2022).

The software allows us to model the house based on the construction drawings and technical details. So, using intuitive tools, building geometries could be easily modeled. The calculation results will be displayed during the modeling process, which is incredibly useful when attempting alternative approaches to determine the best ways to reduce energy consumption. Applying the construction drawing and technical details in the BIM energy software could provide the ability to manage the 3D drawing of the house, and the collected data in a digital format during the entire house life cycle. The software gives the ability to fill manually in the building's thermal properties, and construction materials and determines the building's location, orientation, and weather data. It is possible to adjust the temperature setpoints, the heating and cooling setpoints, and the flow schedules throughout the year. When the model is defined, the report shows all the data entries for the model and the building's entire energy footprint (Bim Energy, 2022)

3.6.2 One-Click LCA software

The One-Click LCA is a web-based software that combines intuitive features with the largest construction life cycle assessment database on the market so life-cycle assessments can be performed quickly and efficiently. The One-Click LCA tool was created by BioNova in Finland. The software has its databases, which include a list of EPDs and average statistics for building materials from manufacturers worldwide. The One-Click LCA material database also allows any EPD as long as it is third-party verified, which means that the database only contains specific materials and products from specific producers, rather than generic materials. An EPD document is a detailed description of a product's environmental impact. The One-Click LCA is unique in that it is compliant with over 50 rating systems, assessment methods, and standards worldwide, allowing for a wide range of impact categories to be assessed and compared depending on the user's needs (One Click LCA® software, 2022).

The One-Click LCA software calculates construction emissions based on material selection and quantities. This software also enables detailed inputs for estimating emissions related to transporting materials to the site, including distance and means of transportation for each material. To guarantee the most accurate emissions factor can be applied, a drop-down menu of over 30 options, including delivery type (van, truck, mixer, plane, train, ship), vessel capacity, and percent fill rate, can all be specified. The volume or weight of materials is used to estimate the number of vehicles, amount of fuel, and transportation duration. The software also includes operational energy inputs for grid electricity consumption, stationary unit fuel demands such as generators, district heating, and cooling consumption, and exported energy such as on-site generation. The emissions factor applied to grid electricity is geographically specific. Based on climate, exposure, use, and other circumstances, the material life span of each particular material can be modified to reflect the actual life span of materials (One Click LCA® software, 2022).

3.6.3 Microsoft Excel

Excel includes a spreadsheet format with contiguous cells that form a grid. Each cell can hold data as well as formulas (Divisi, Di Leonardo, Zaccagna, & Crisci, 2017). The data can be structured as numbers, dates, times, percentages, or texts. The use of spreadsheets in Excel simplifies data processing and management (Divisi et al., 2017).

3.7 Input data

3.7.1 Renovating strategies

3.7.1.1 Wall insulation

Expanded polystyrene (EPS) is most frequently used as insulation material for building envelopes since its light, practical, and can be handled and installed easily. Versatility, lifetime durability, and excellent thermal insulation are some advantages of using EPS as insulation material ("Benefits of EPS - EUMEPS Construction", 2022a). EPS is a more cost-effective insulating material for renovating residential buildings (anthony Ede), therefore the newly added insulation material is EPS with such characteristics: thermal conductivity of 0.038 W/, the density of 25 kg/m, and thermal capacity of 1400 Ws/kg, K.
Two wall insulation alternatives were considered, and the proposed new constructions are shown in the figures below. The first alternative is done to meet the BBR29's suggested U-value as shown in Figure 10 and the second alternative is to meet FEBY's suggested U-value as shown in Figure 11.

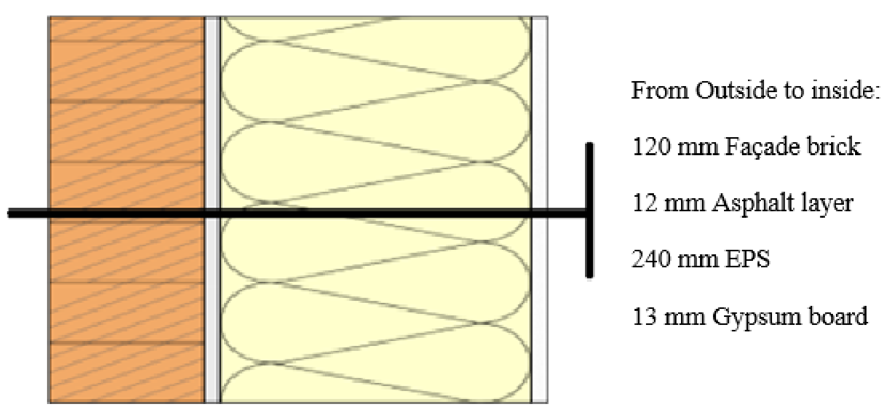

Figure 10.Construction of new wall meeting BBR29.

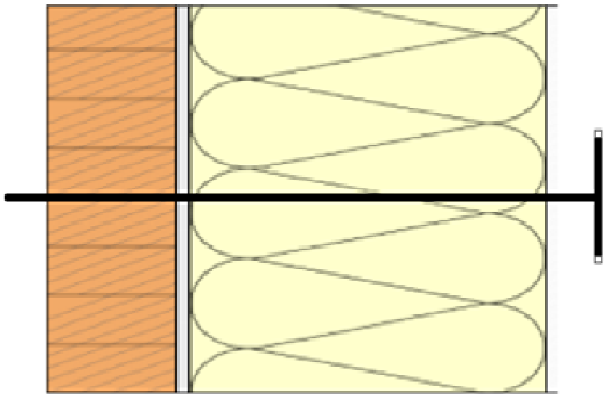

Figure 11.Construction of new wall meeting FEBY

Two different thicknesses of insulation material were considered to be installed on the exterior walls. The U-values and thicknesses are shown in Table 4 below.

Table 4. Properties of the external wall after adding insulation

Wall alternatives	Base envelope	BBR 29	FEBY gold
Wall U-value	0.26 W/m²K	0.15 W/m²K	0.11 W/m²K
Added EPS thickness	0	240 mm	330 mm

3.7.1.2 Roof insulation

Two alternatives were considered for the roof insulation. The first alternative is adding EPS insulation with a specific thickness as shown in Figure 12 to meet BBR29's suggested U-value for the roof, whereas the second alternative is adding a thicker EPS insulation compared to alternative 1 as shown in Figure 13 to meet FEBY's suggested U-value for the roof.

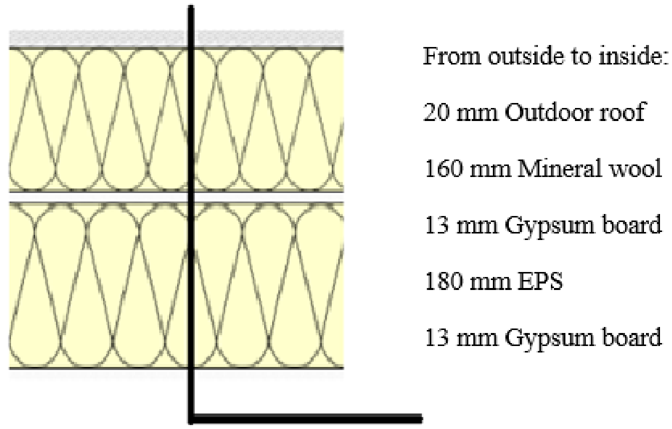

Figure 12.Construction of new roof meeting BBR

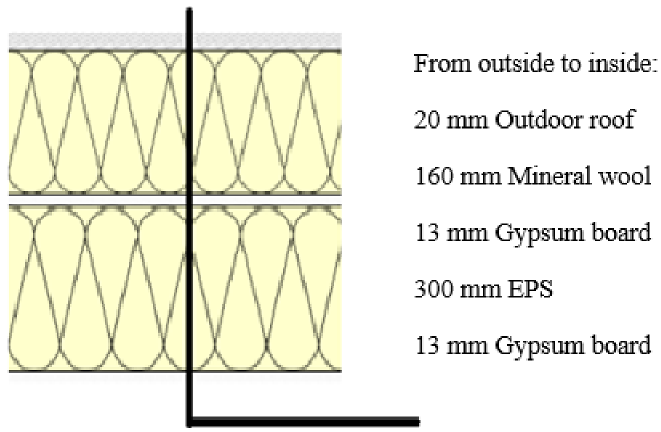

Figure 13.Construction of new roof meeting FEBY

Two different thicknesses of insulation material were considered to be added to the existing roof. The U-values and thicknesses are shown in Table 5 below.

Table 5. Properties of the roof after adding insulation

Roof alternatives	Base envelope	BBR 29	FEBY gold
Roof U-value	0.24 W/m²K	0.11 W/m²K	0.08 W/m²K
Added EPS thickness	0	180 mm	300 mm

3.7.1.3 Windows

For the first alternative and to meet the BBR29's suggested U-value, a new window was installed, and it is made by Svenska Fönster AB. The window has a wooden casement with outer aluminum cladding and insulating glass with 3 glass planes. The first chosen window has a U-value of 1.21 W/m². K with a daylight factor of 74%. ("getEpdFile (1)")

For the second alternative and to meet FEBY's suggested U-value, a new triple-glazed insulated window with a wooden frame was installed. The second chosen window is made by Gilje Tre and has a U-value of 0,82 W/m² with a daylight factor of 71%. (Legouvello)

3.7.1.4 Ventilation system

The first alternative ventilation system was the exhaust air ventilation and in the building energy simulations, the ventilation rate was set to the minimum value of 0.35 l/s/m². The fan efficiency was considered as 60%. The indoor temperature is set to 20°C. Since the total floor area of the selected house is 130 m^2, and the airflow is $0.35\, l/s.m^2$, the total flow according to this ventilation system is 45.5 l/s which has been computed in Equation 2.

Equation 2

$$0.35 l/s.m^2 \times 130 m^2 = 45.5 l/s$$

In the second chosen ventilation system (mechanical ventilation system with heat recovery), the minimum and maximum heat exchanger efficiency of 75% and 85% were determined, respectively. Heat exchangers and fan operations have been considered to work constantly. For the heat exchanger, the minimum and maximum outdoor temperatures were -20°C and 0°C, respectively. And the minimum and maximum outdoor temperature for the supply air was -20°C and 20°C, respectively.

3.7.1.5 Heating System

In this study, a 6 kW ASHP system has been provided. Temperature limits for evaporation, in this case, are set to be between -40 and +20 °C. In the energy simulation, the air-to-air heat pump has been set which aims only for space heating with a coefficient of performance (COP) of 3.45. The applied refrigerant type is R410A which works properly for absorbing and releasing heat.

3.7.1.6 Photovoltaic system

The PV system consists of 17 single-glass monocrystalline PV panels manufactured by Risen Energy with 46 m^2. To have maximum output from the PV system, the PV panels should be distributed on two roofs, one facing south and the other facing west. The tilt of PV panels distributed on the south roof is 45 degrees, while that on the west roof is 17 degrees. In Table 6 below all information about the installed PV system is mentioned.

Table 6.PV system description ("Microsoft Word - Risen Energy single glass 210 Series EPD report.docx")

Panel efficiency	21 %
Power of panel	600
Number of panels	17
Area	46.4 m^2
Panels installed on the south-oriented roof	10
Panels installed on the west oriented roof	7
Inverter capacity	8 kW
Number of inverters	1
System capacity	10 kW

3.7.2 Scenarios

Different EEMs were combined randomly in different variations which resulted in 8 different scenarios. Table *7* below describes what combination of EEMs each scenario includes.

Table 7. Combination of different EEMs in different scenarios

Scenarios / **EEMs**	**Base scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Base envelops	X	-	-	-	-	-	-	-	-
BBR standard insulation	-	X	-	X	-	X	-	X	-
FEBY standard insulation	-	-	X	-	X	-	X	-	X
Base windows	X	-	-	-	-	-	-	-	-
BBR standard windows	-	X	-	X	-	X	-	-	
FEBY standard windows	-	-	X	-	X		X	-	X
Mechanical ventilation	X	X	X	-	-	X	X	-	
Mechanical ventilation with heat exchanger	-	-	-	X	X	-	-	X	X
District heating	X	X	X	X	X	-	-	-	-
Air source heat pump	-	-	-	-	-	X	X	X	X
Solar panels	-	-	-	-	-	X	X	X	X

4 Results

4.1 Building energy simulation

Building energy simulation was carried out by BIM energy software and the output results are shown in Table 6 below. As mentioned before, the accepted U-value for a building between 90-130 m2 by BBR 29 is 0.3 W/m²K and the accepted primary energy number is 95 (KWh/m2/year). (Boverket)

As shown in Table 8 below all scenarios meet the accepted U-value suggested by BBR29.

It is also visible that scenarios 3 till 8 met the accepted primary energy value suggested by the BBR2 while scenarios 1 and 2 were close to achieving it but failed.

In Table 8 below other output, parameters were mentioned.

Table 8.Output data for all scenarios

Scenarios Output data	**Base scenario**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
U-value (W/m²K)	0.5	0.3	0.27	0.3	0.27	0.3	0.27	0.3	0.27
Primary energy number (kWh/m2/year)	160	109	98	90	78	71	60	55	45
Primary energy number reduction (%)	0	32	39	44	51	55	62,5	66	71
Heat supply (kWh/year)	29192	19701	17656	14885	12837	2937	2745	2745	2745
Heat energy saving (kWh/year)	0	9491	11536	14307	16355	26255	26447	26447	26452
Electricity supply (kWh/year)	4066	4066	4066	4541	4541	508	64	-505	-966
Electricity energy saving (kWh/year)	0	0	0	-475	-475	3558	4002	4571	5032

4.2 Life cycle inventory

In this study, the material manufacturing process emissions for grid electricity and energy efficiency were adjusted to Sweden instead of the original country the material was produced, and the Swedish electricity mix was considered (One Click LCA Help Centre, 2022). All material used data is shown in Table 9 below. The datasets adopted in this study are product-specific environmental product declarations (EPD). All materials have transport distances already included in the software One-Click LCA is the production stage which is based on average data from the Nordic countries (60 km, trailer combination 40 ton, 100% fill rate), therefore only the transport distance from material manufacturer to the building site is assumed to be 100 km as an average distance.

Table 9. Material datasets

Resource	**Quantity**	**Unit**	**Service life**	**Country**
EPS insulation panels for external walls to meet BBR29	22	m^3	As building	Norway
EPS insulation panels for external walls to meet FEBY gold	30.3	m^3	As building	Norway
EPS insulation panels for the roof to meet BBR29	23.3	m^3	As building	Norway
EPS insulation panels for the roof to meet FEBY gold	32.4	m^3	As building	Norway
Triple glazed wooden frame window fixed to meet BBR29	31	m^2	40 years	Sweden
Triple glazed wooden frame window to meet FEBY gold	31	m^2	40 years	Norway
Air exchanger + heat recovery	1	pcs	25 years	Sweden
Air/Air heat pump	1	pcs	22 years	France
Solar panel photovoltaic system	46	m^2	20 years	Sweden

4.3 Environmental Impact Assessment

Embodied carbon benchmarks are calculated for a fixed 60-year assessment period for all building materials and do consider the material stage (A1-A3), replacement stage (B4-B5), and end of life stage (C1-C4). Figure 14 shows the embodied carbon benchmark for Sweden. (One Click LCA® software, 2021)

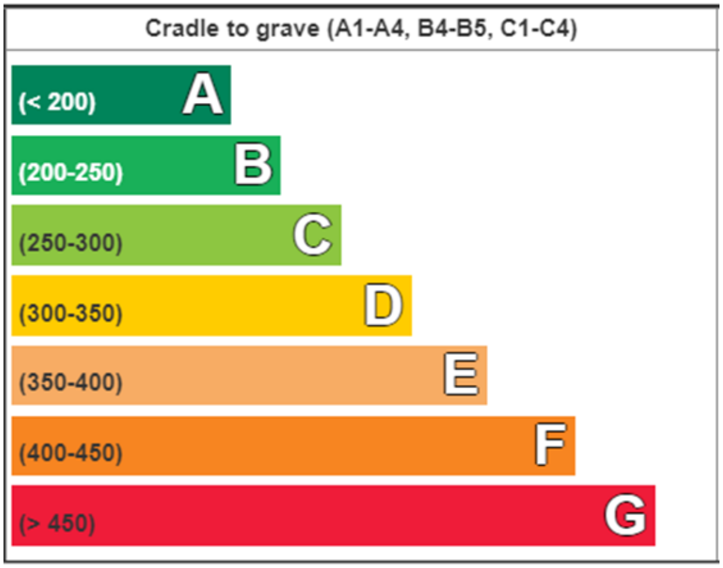

Figure 14.Embodied carbon benchmark for Sweden

As shown in Table 10 below scenarios 1,2,3 and 4 have embodied carbon of 54,86,60 and 91 kg CO_2e/m^2 respectively and all belong to class A which is less than 200 kg CO_2e/m^2 as shown in figure 14 above. Whereas scenarios 5 and 7 have embodied carbon of 228 and 234 CO_2e/m^2 respectively classifying them in category B While scenarios 6 and 8 have embodied carbon of 260 and 265 CO_2e/m^2 classifying them in category C. as shown in Figure 14 above.

Table 10.Embodied carbon amount for each scenario

Scenario number	Embodied Carbon (Kg CO_2e/m^2)
1	54
2	86
3	60
4	91
5	227
6	260
7	232
8	265

Figure 15 illustrates the Global Warming Potential (GWP) in kg CO_2 eq for the base scenario and all eight scenario's elements and life cycle stages. The GWP impact associated with the base scenario is calculated and expressed as positive values that represent how much GWP emission results from the base scenario from the energy (B6) stage. Each of the eight renovation scenarios is depicted as a negative value representing the reduction in GWP impacts, and the amounts of the reduction in GWP impacts are calculated from the base scenario. From Figure 15, it can be observed that the A1-A3 stage has the biggest GWP impact in scenarios 1, 2, 3, and 4. However, B1-B5 has the biggest GWP impacts in scenarios 5, 6, 7, and 8. The A4, the transportation phase, has the lowest GWP impact in all eight scenarios.

In scenarios 1, 2, 3, and 4, the End-of-Life stage (C1-C4) and maintenance and replacement (B1-B5) had a large GWP impact following the material stage (A1-A3). The material stage (A1-A3) is the second large GWP impact in scenarios 5, 6, 7, and 8. The End-of-life stage (C1-C4) is the third large GWP impact in these scenarios.

Figure 15 below also shows how much each scenario is reducing Global Warming Potential (GWP) after introducing EEMs to minimize energy in terms of district heating and electricity use. Figure 15 shows that scenarios 1,2,3 and 4 reduce GWP by 54,854, 66,674, 81,457, and 93294 kg CO_2 eq, respectively, after introducing EEMs and reducing the district heating amount. Whereas scenarios 5,6,7 and 8 reach a maximum amount of GWP reduction and that's a result of changing the heating supply from district heating to ASHP with the addition of a PV system for those 4 scenarios.

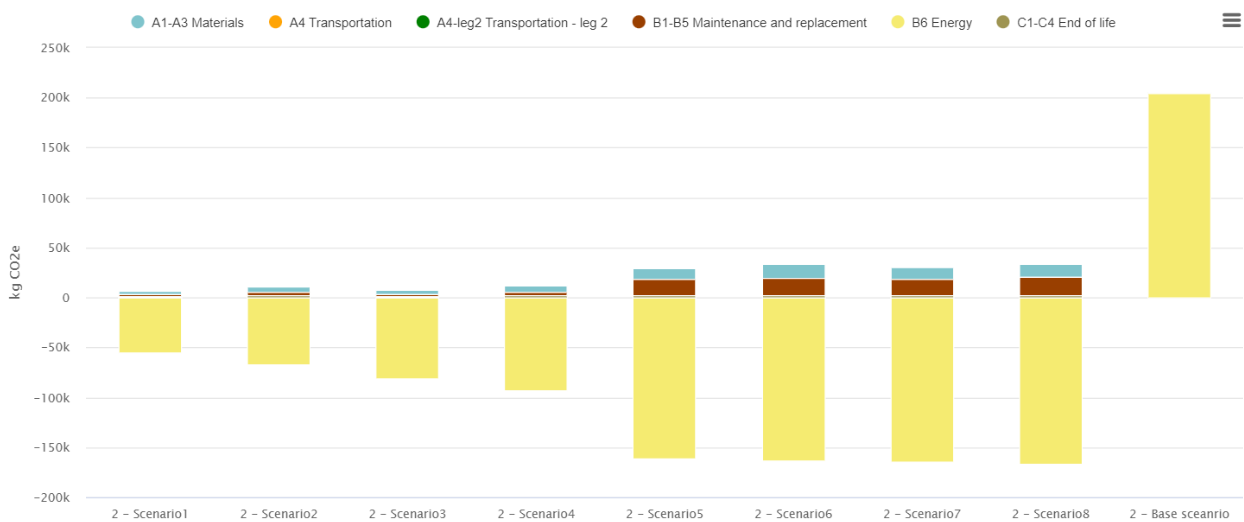

Figure 15.Life-cycle assessment, EN-15978 - Global warming, kg CO2e – Elements and Life cycle stages

Table 11.Life-cycle assessment, EN-15978 - Global warming, kg CO2e – Elements and Life cycle stages over a 50-year period

Scenarios	A1-A3 Materials	A4 Transportation	B1-B5 M & R	B6 Energy	C1-C4 End of life	A1-C4 Total
0	-	-	-	204887.3	-	204887.3
1	3851.661	7.29	1476.117	-54854.8	1735.23	-47784.5
2	6000.900	10.95	2717.54	-66674.2	2403.54	-54403.7
3	4076.661	9.73	1701.117	-81457.6	1735.639	-73934.4
4	6225.900	13.40	2942.54	-93294.3	2403.95	-81708.5
5	11296.99	31.24	16366.77	-160974	1759.332	-131519.6
6	13446.22	34.90	17608.19	-163235	2427.65	-129718
7	11521.99	33.68	16591.77	-164711	1759.741	-134803.8
8	13671.22	37.35	17833.19	-165936	2428.06	-131966.3

Table 11 also illustrates detailed numbers of the "Global Warming Potential" (GWP) impacts for each phase of the elements and life cycle for each scenario and also the base scenario's energy (B6) stage. Scenario 8, through the maintenance and replacement (B1-B5) stage, has the highest GWP impact of 17,833.19 kg CO_2 eq across all scenarios for life cycle stages. In contrast, with 7.29 kg CO_2 eq in the transportation (A4) stage, scenario 1 has the lowest GWP impact of all scenarios for life cycle stages. In scenarios 5 to 8, the GWP impact of stages A4 (from 31.24 to 37.35 kg of CO_2 eq) has increased slightly.

Table 11 also shows the total GWP reduction of renovation for each scenario, which is represented in negative values to illustrate the reduction of GWP impacts. Scenario 8 has the highest reduction in energy (B6) stage by 165,936 due to lower U-values for envelope and installation of the PV system, mechanical ventilation, and ASHP. The lowest GWP impact reduction could be found in scenario 1 because no renewable energy is installed, and only the envelope is regulated to comply with BBR 29.

Total GWP shows that the base scenario will result in 204,887.3 kg CO_2 eq for energy (B6). Furthermore, scenario 1 resulted in the least reduction of 47,784.5 kg CO_2 eq, while scenario 7 resulted in the highest reduction of 134803.8 kg CO_2 eq from A1-C4.

4.4 LCC Analysis

The LCC for each renovation scenario was calculated separately. The LCC calculations include investment cost for EEM applied, the replacement and maintenance cost of materials after a specific time, the end-of-life costs, and energy savings costs of electricity and district heating for each scenario in a timeframe of 50 years. All calculations were done in excel while considering the unit price per element from the One-Click LCA software database. Table 12 below shows the prices used in the calculation.

Table 12.Prices of renovation components

Product	Price/Unit	Unit
EPS insulation	1,157	SEK/m^3
Wood window	5,402	SEK/m^2
Wooden window	5,402	SEK/m^2
Ventilation system	6,000	SEK/unit
Solar PV system	10,000	SEK/Kw
Air/Air heat pump	24,000	SEK/unit
Labor cost	306	SEK/hr
District heating	0.92	SEK/kw
Electricity	1.77	SEK/kw
Discount rate	5	%
Period (t)	50	Years

The present value (PV) formula was used to assess the LCC:

Equation 3

$$PV = \frac{Ft}{(1+d)^t}$$

PV = Present value
t = Time in a unit of the year
Ft = Future cash amount that occurs in year t
d = Discount rate used for discounting future cash amounts to the present value

The operational energy cost for the whole period of 50 years is the sum of the present value (PV) for each year t as shown in Equation 4 below.

Equation 4

$$E = \sum_{t=1}^{50} PV$$

E= operational energy cost

The present value formula was applied to calculate all costs that appear through the building lifetime. The general LCC formula for buildings was used in our case to summarize all costs that occur from cradle-to-grave:

Equation 5

$$\mathrm{LCC} = \mathrm{I} + \mathrm{Rep} + \mathrm{EOL} - \mathrm{E}$$

I = Investment costs

Rep = Replacement costs

EOL = End-of-life costs

The total LCC calculation was done using Equation 3, Equation 4, and Equation 5 mentioned above. Table 13 below shows all the LCC costs in SEK for each scenario.

Table 13.LCC calculations for all 8 scenarios

Scenarios	**Investment cost**	**Operation saving cost**	**Replacement cost**	**End of life cost**	**Total cost**
1	219901	159406	0	6100	66595
2	240020	193752	0	6100	52367
3	225901	224944	6000	8100	15057
4	246020	259341	6000	8100	779
5	343901	555934	124000	11100	-94504
6	364020	573506	124000	11100	-74385
7	349901	591892	130000	13100	-98890
8	370020	606872	130000	13100	-93752

Table 13 illustrates life cycle cost analysis of renovation scenarios including investment, replacement, end-of-life, operation energy saving cost, and the total cost. It can be seen in figure

16 that in scenarios 5, 6, 7, and 8, the investment, replacement, and end-of-life costs are significantly higher than those in scenarios 1, 2, 3, and 4, due to the PV system installation, mechanical ventilation, and ASHP in some cases. These system installations result in a greater saving in energy operation costs in scenarios 5, 6, 7, and 8 than in scenarios 1, 2, 3, and 4.

According to Figure 16, the investment cost in scenario 8 is the greatest at 370,020 SEK. In contrast, scenario 1 has the lowest investment cost of 219,901 SEK. In scenarios 7 and 8, which require replacements of mechanical ventilation, ASHP, and PV systems, the replacement costs are greater than those in the other scenarios. Consequently, the end-of-life costs are higher in scenarios 7 and 8. Moreover, the end-of-life costs in scenarios 1 and 2 are the lowest. Aside from scenarios 1 and 2, which do not necessitate replacement, scenarios 3 and 4 have the lowest replacement costs of 6,000 SEK.

Over a 50-year period, the LCC analysis shows that scenarios 1, 2, 3, and 4 are not financially viable, but scenarios 5, 6, 7, and 8 are. The most profitable scenario in terms of operation energy savings is scenario 8, with 606,872 SEK, contributing to 93,752 SEK in total savings. Even though both scenarios 7 and 8 contained a PV system, an ASHP, and a mechanical ventilation system, the total cost savings of scenario 8 is significantly greater than scenario 7. This is because, in comparison to scenario 7, scenario 8 has higher insulation material and a lower u-value for windows.

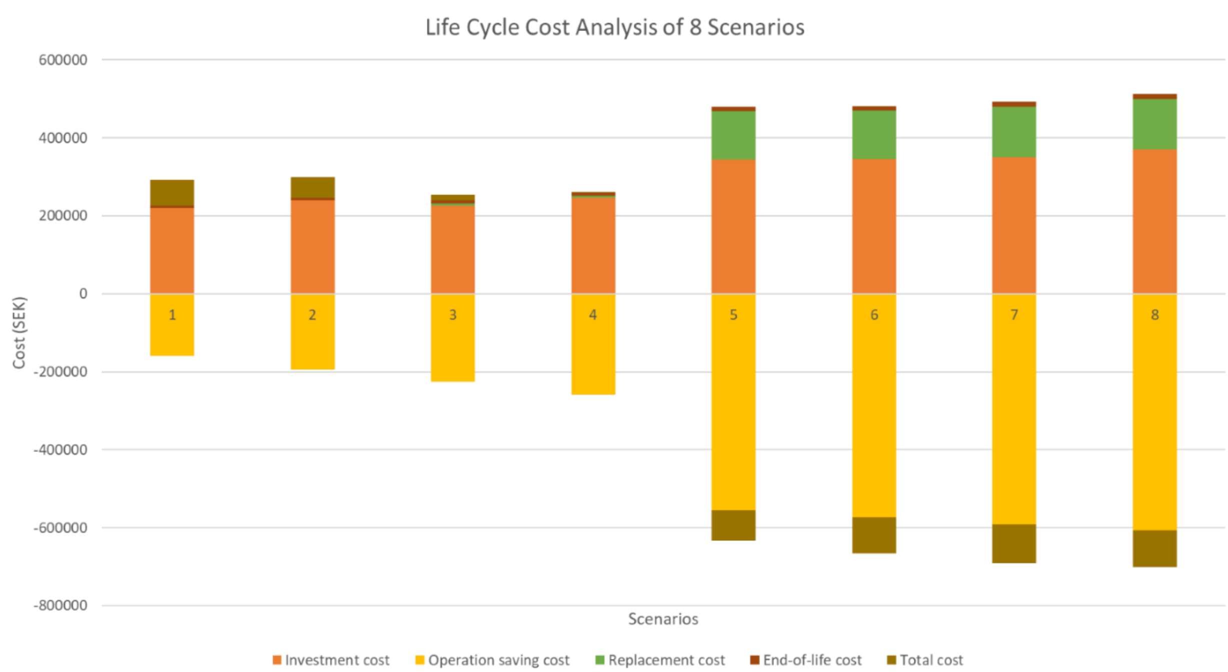

Figure 16.The life cycle cost analysis for each renovation scenario

4.5 Primary energy and LCA

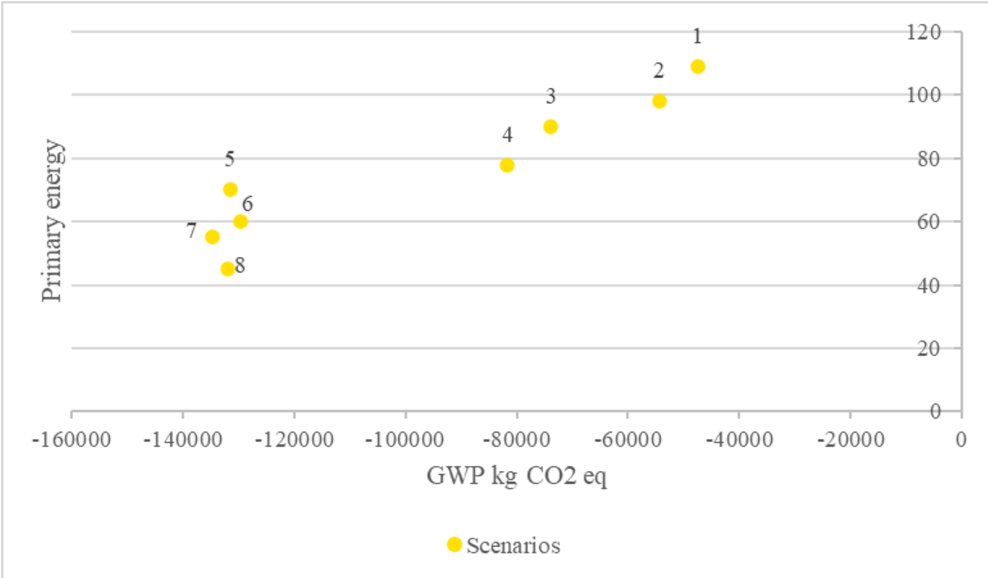

Figure 17.GWP reduction and primary energy of the whole renovation process in all 8 scenarios

As shown in Figure 17 above after adding insulation for walls and roof to meet the BBR´s suggested U-value in scenario 1 and to meet FEBY´s suggested U-value in scenario 2 both have a primary energy number above 95 which is the accepted primary energy number suggested by the BBR regulations and has the least amount of GWP (47784 and 54403 kg CO_2 eq) respectively for both scenarios 1 and 2 in comparison with the other 6 scenarios. After changing the ventilation system in scenarios 3 and 4 in addition to insulating walls and roof the primary energy number decreased to be below 95 while the GWP reduction for both scenarios 3 and 4 has slightly increased to (73934 and 81708 kg CO_2 eq) respectively in comparison to scenarios 1 and 2. Whereas after changing the heating system from district heating to ASHP and adding PV panels for scenarios 5,6,7 and 8 the primary energy number decreased to be below 70 and the GWP reduction for those 4 scenarios increased significantly to be 131519,129718,134803 and 131966 kg CO_2 eq respectively whereas scenario 7 had the highest reduction in GWP in comparison to other scenarios.

4.6 Primary energy and LCC

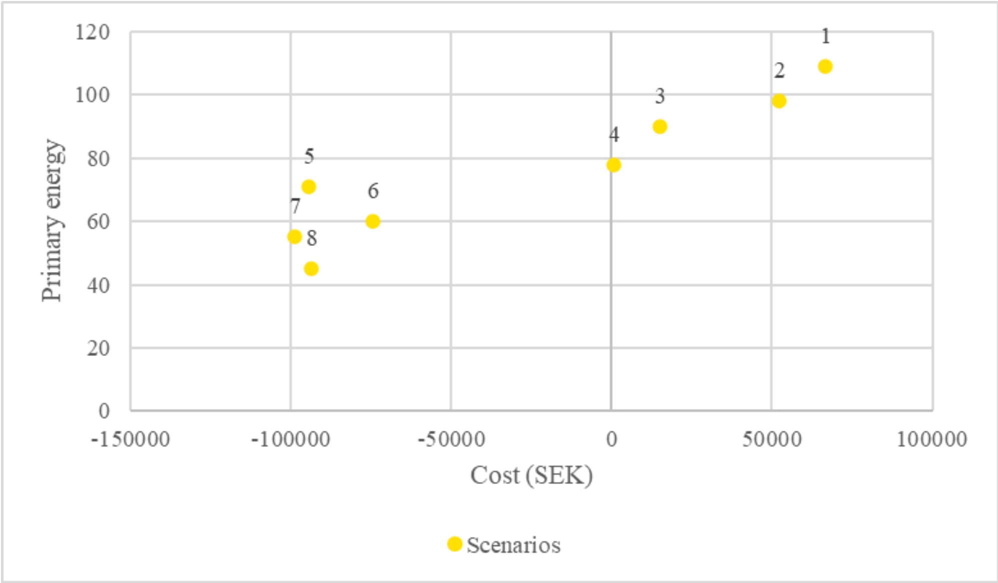

Figure 18.Primary energy and LCC for all 8 scenarios

As shown in Figure 18 above scenarios 1,2,3 and 4 have total costs above zero while scenarios 5,6,7 and 8 all resulted in a profit. Scenarios 1 and 2 both had a primary energy value above 95 which is the accepted primary energy number suggested by the BBR regulations and both scenarios resulted in total costs above zero with 66595 SEK for scenarios 1 and 52367 SEK for scenario 2. Scenarios 3 and 4 both resulted in a primary energy number less than 95 and both scenarios as scenarios 1 and 2 also resulted in a total cost above zero with 15057 SEK for scenario 3 and only 779 SEK for scenario 4 (almost zero). Scenarios 5,6,7 and 8 all had a primary energy number less than 70 and all made a profit with 94504,74385,98890 and 93752 SEK respectively as a saving cost.

4.7 LCA and LCC

Figure 19 illustrates the GWP reduction and LCCs of the eight renovation scenarios. Scenarios 1 to 4 resulted in positive values which represent that the renovation scenarios from 1, 2, 3, and 4 are not profitable. In contrast, scenarios 5, 6, 7, and 8 resulted in negative values representing profitable scenarios. Scenarios 1, 2, 3, and 4 did not result in profitable LCC, however, they resulted in a reduction in GWP impact.

Scenario 5 resulted in a 94,504 SEK profit in LCC analysis and a 131,519 kg CO_2 eq reduction of GWP. Scenarios 6, 7 and 8 also had a profitable LCC analysis and reduction of GWP impacts by 74,385, 98,890, 93,752 SEK and 129,718, 134,803, and 131,966 kg CO_2 eq respectively.

Scenarios 5, 6, 7, and 8 changed from district heating to ASHP, and PV panels contributed to much more GWP reduction and cost-saving than scenarios 1, 2, 3, and 4. Among scenarios 1, 2, 3, and 4, scenario 4 has the highest GWP reduction and lower LCC result by 81,708 kg CO_2 eq and 779 SEK, respectively, due to more insulation for walls and roofs and a lower U-value for doors and windows and also better mechanical ventilation system.

To conclude, scenario 7 was the most profitable in both LCC and LCA analysis. Scenario 1 has the lowest GWP reduction, as well as the least profitable LCC analysis.

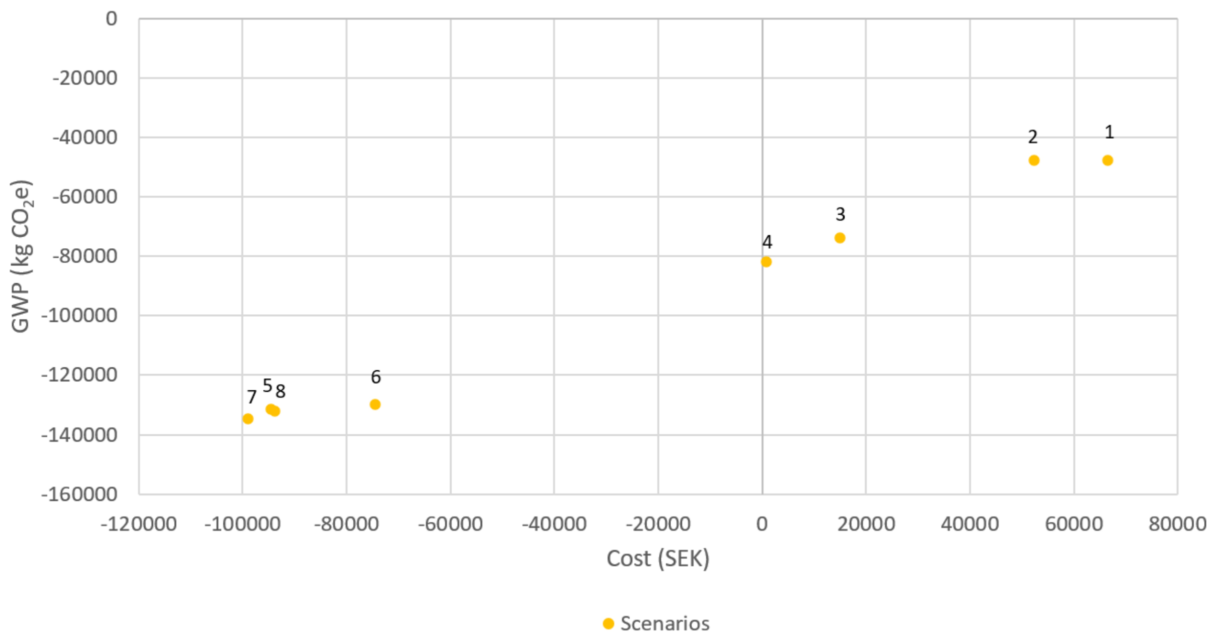

Figure 19.Life Cycle Assessment and Life Cycle Cost Assessment of 8 scenarios

4.8 Sensitivity analysis

4.8.1 Discount rate and LCC

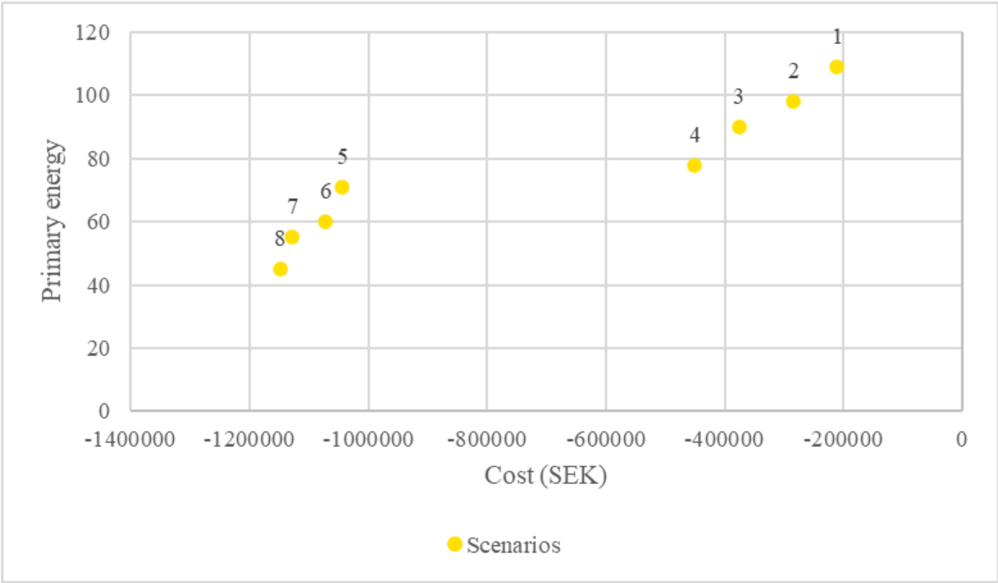

Figure 20.Primary energy and LCC for all 8 scenarios with a discount rate of 0%

As shown in Figure 20 above changing the discount rate from 5% in the base case to 0% resulted in a higher annual operating cost which means higher operating cost savings after 50 years life span. In comparison to the base case scenario, all scenarios, in this case, are profitable whereas in the base case scenarios 1,2,3, and 4 used to have total costs above zero. Scenarios 1,2,3 and 4 have a significant increase in profit in comparison to the base case with a profit of (210585, 284536, 376083, and 450712) SEK respectively. Scenario 8 has still the highest profit in comparison to all other scenarios with 1149004 SEK which is almost 12 times more than what profit it had in the base case. Scenarios 5,6 and 7 also had a significant increase in profit to be (1043611, 1071619, and 1128094) SEK respectively. Changing the discount rate from 5% to 0% will result in a less payback period in comparison to the base case.

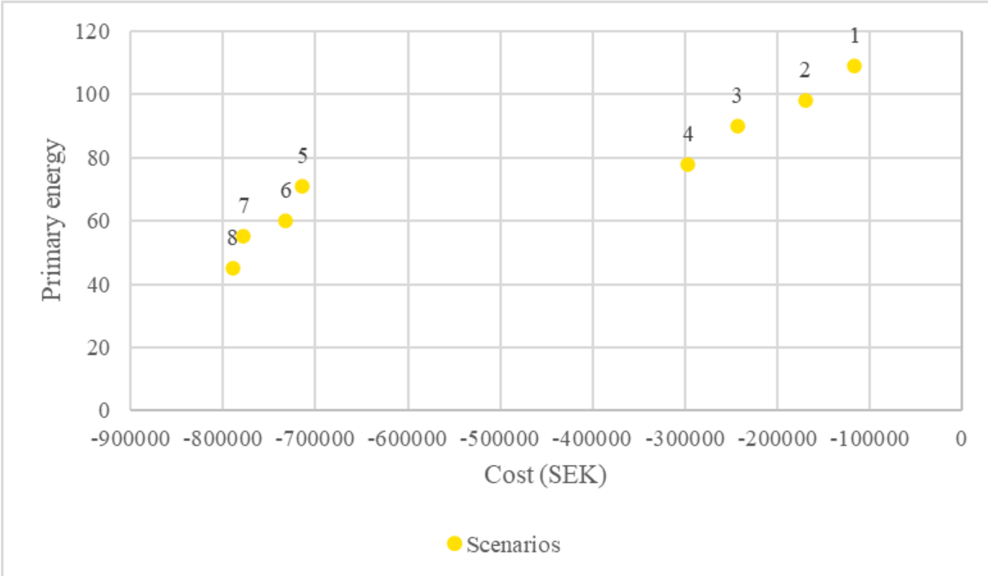

Figure 21.Primary energy and LCC for all 8 scenarios with a discount rate of 1%

As shown in Figure 21 above changing the discount rate from 5% in the base case to 1% resulted in a higher annual operating cost which means higher operating cost savings after 50 years life span. In comparison to the base case scenario, all scenarios, in this case, are profitable whereas in the base case scenarios 1,2,3, and 4 used to have total costs above zero. Scenarios 1,2,3 and 4 have a significant increase in profit in comparison to the base case with a profit of (116248,169873,242961,296694) SEK respectively. Scenario 8 has still the highest profit in comparison to all other scenarios with 789856 SEK which is almost 8 times more than what profit it had in the base case. Scenarios 5,6 and 7 also had a significant increase in profit to be (714609,732217 and 777811) SEK respectively. Changing the discount rate from 5% to 1% will result in a less payback period in comparison to the base case.

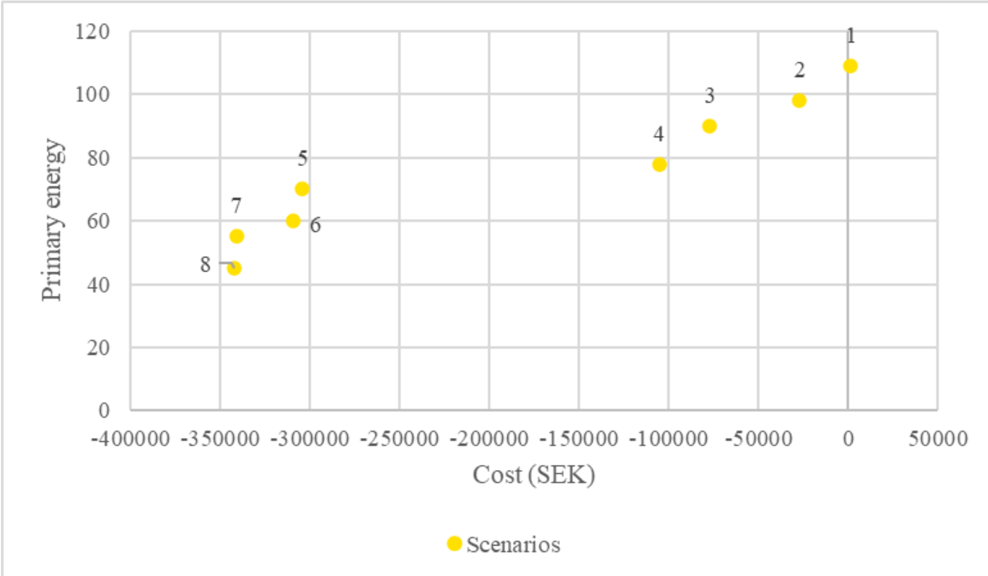

Figure 22.Primary energy and LCC for all 8 scenarios with a discount rate of 3%

As shown in Figure 22 above changing the discount rate from 5% in the base case to 3% resulted in a higher annual operating cost which means higher operating cost savings after 50 years life span. In comparison to the base case scenario, all scenarios, in this case, are profitable except scenario 1 which almost cost 0 SEK whereas in the base case scenarios 1,2,3, and 4 used to have total costs above zero. Scenarios 1 cost 1335 SEK while scenarios 2,3 and 4 have a significant increase in profit in comparison to the base case with a profit of (26953,77033,105393) SEK respectively. Scenario 8 has still the highest profit in comparison to all other scenarios with 342201 SEK which is almost 4 times more than what profit it had in the base case. Scenarios 5,6 and 7 also had a significant increase in profit to be (304528,309174 and 341207) SEK respectively. Changing the discount rate from 5% to 3% will result in a less payback period in comparison to the base case.

4.8.2 Life Span and LCC

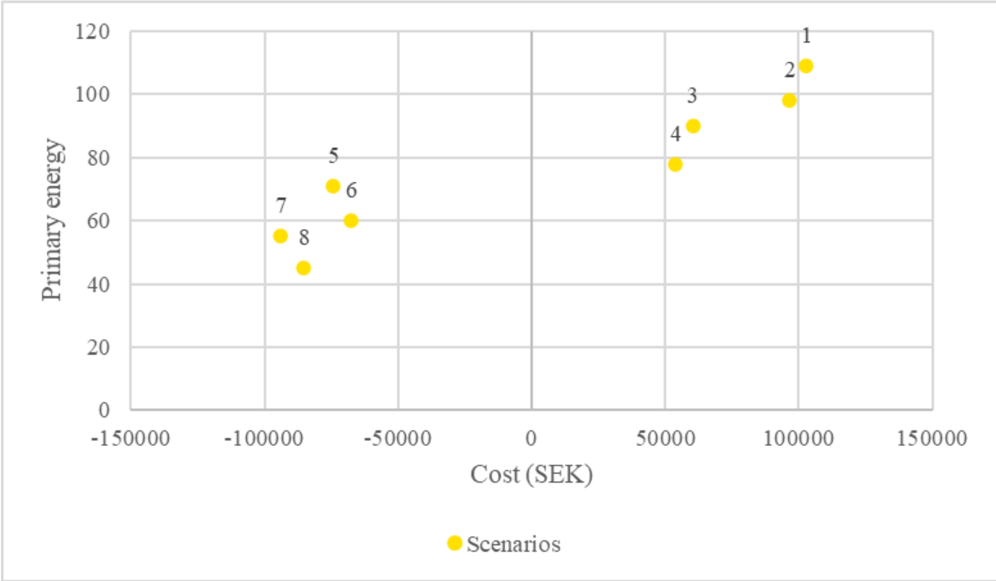

Figure 23.Primary energy and LCC for all 8 scenarios with a lifespan of 25 years

As shown in Figure 23 above changing the lifespan from 50 years in the base case to 25 years will result in less total operating cost savings in comparison to the base case and will also eliminate the replacement and maintenance cost since there is no need to replace the PV system, ASHP, and the ventilation system. After changing the lifespan to 25 years scenarios 1,2,3 and 4 still have a total cost above zero the same as the base case. Scenarios 1,2,3 and 4 had an increase in costs and now have a total cost of (102936,96539,60339,53903) SEK respectively. Scenario 7 now has the highest profit instead of scenario 8 in the base case in comparison to all the other scenarios with a profit of 93951 SEK. Scenarios 5,6 and 8 had a decrease in profit with (74191,67638, and 85397) SEK respectively. Changing the lifespan from 50 years to 25 years resulted in less profit in all scenarios.

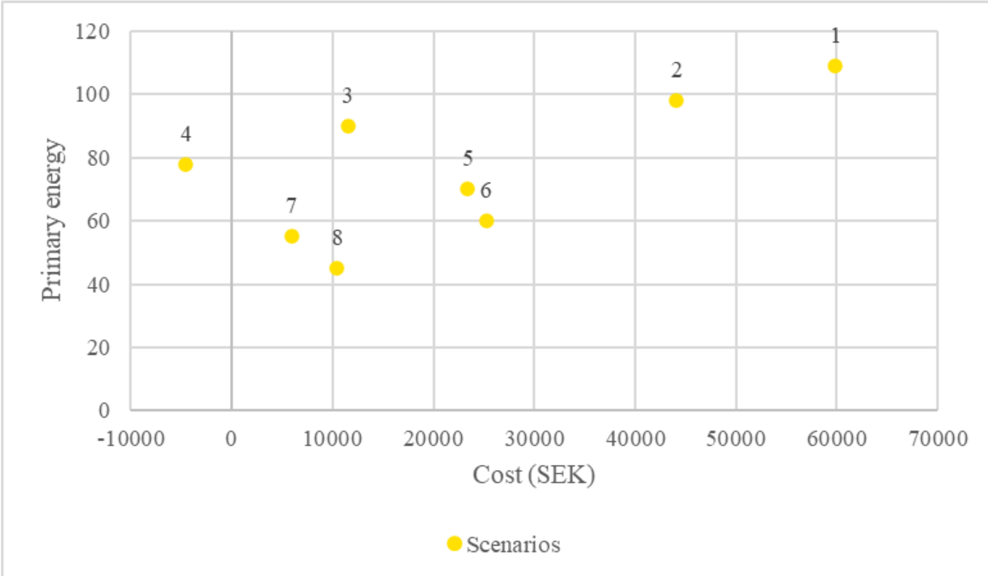

Figure 24.Primary energy and LCC for all 8 scenarios with a lifespan of 75 years

As shown in Figure 24 above changing the lifespan from 50 years in the base case to 75 years will result in an increase in the total operating cost savings in comparison to the base case and will also increase the replacement and maintenance cost since there is a need to replace the PV system, ASHP, and the ventilation system twice during the whole lifespan. After changing the lifespan to 75 years scenarios 1,2 and 3 had a decrease in total costs and now cost less with a total cost of (59814, 44125, 11488) SEK whereas scenario 4 had also decrease in total costs and now is profitable with a profit of 4522 Sek. Scenarios 5,6,7 and 8 had an increase in replacement costs and a slight increase in the total operating cost savings yet they have a total cost of (23418, 25218, 5930 and 10432) SEK respectively. Scenario 4 now has the highest profit in comparison to all the other scenarios. Changing the lifespan from 50 years to 75 years increased replacement costs in all scenarios and resulted in having 7 scenarios not being profitable and having total costs greater than zero.

5 Discussion

Insulating the walls, and roofs and changing the windows to meet either the BBR´s suggested U-value in scenarios 1,3,5 and 7 or FEBY´s suggested U-value in scenarios 2,4,6, and 8 accounts for the second most reduction in primary energy with almost 51 and 62 kWh/m2/year reduction. This item has the second least reduction in GWP with 47784.5 and 57475 kg CO_2 eq respectively and the least profit made in comparison to other EEMs. Changing the ventilation system from mechanical ventilation to mechanical ventilation with heat recovery in scenarios 3,4,7 and 8 resulted in the least reduction in primary energy with a 19 kWh/m2/year reduction. This EEM had the least reduction in GWP with 26150 kg CO_2 eq and resulted also in the second least profit made in comparison to other EEMs. Moreover, adding a PV system and ASHP instead of district heating in scenarios 5,6,7, and 8 resulted in the most reduction in primary energy with a 38 kWh/m2/year reduction. This EEM has the most reduction in GWP impact with 74507 kg CO_2 eq and has the most profit made in comparison to other EEMs. Scenarios 1 and 2 didn’t meet the BBR regulations by having a primary energy number above 95 which is the accepted primary energy number for single-family houses between 90 and 130 m^2. Whereas scenarios 3,4,5,6,7 and 8 all met the BBR regulations by having a primary energy number less than 95 whereas scenarios 7 and 8 had the greatest reduction of primary energy with 66 and 71 % of primary energy reduction from the base scenario. Results from the life cycle stages perspective showed that in all eight scenarios stages A1-A3, B1-B5, and B6 have a great GWP impact, and scenarios 1,2,3, and 4 are less cost-effective in comparison to scenarios 5,6,7 and 8 which resulted in a huge profit.

Our results are in line with what was discussed in the literature review by Ekström et al (Ekström & Blomsterberg, 2016) where he discussed in his paper the possibility of reaching a total reduction of between 65 and 75 % in primary energy which is achieved in our thesis where scenarios 7 and 8 reached a total reduction of 66 and 71 % respectively. Moreover, Rose et al (Rose et al., 2022) discussed in their paper the possibility of reaching a total of heat reduction more than 50 % which is compatible with the results we have from our thesis where we reached a total reduction of heat supply of more than 50% in scenarios 5,6,7 and 8 in comparison with the base scenario. Ekström et al (Ekström et al., 2018) discussed in their paper that renovating to the passive house standards can be the most cost-effective in comparison to other standards but it depends on the heating system used in the house. This conclusion is compatible with findings we had in our thesis where scenarios 2 and 4 were more cost-effective than scenarios 1 and 3 where the heating system was district heating, but when the heating system of the house was changed to ASHP scenarios 5 and 7 were more cost-effective than scenarios 6 and 8. Our LCA results are also in line with the literature review on LCA case studies from Ramírez-Villegas et al. (Ramírez-Villegas et al., 2020) and Colli et al., (Colli et al., 2018) which found that the operating energy use, building materials, construction processes, and installation operations contributed to having a large environmental impact.

The LCA for scenarios with PV systems, mechanical ventilation with heat recovery, and ASHP is higher than for scenarios without these elements. This is because scenarios without these systems had no impact on the GWP of manufacturing such products, while scenarios with these systems did, and the GWP of the product was computed from raw material to end-of-life. However, when it comes to evaluating the whole LCA and LCC of the renovation scenario, the PV system, ASHP, and mechanical ventilation system with heat recovery have a large influence on cost and GWP reduction. The reason is that using renewable-based resources makes the house much more energy-efficient. As a result, the more energy-efficient the house becomes, the higher the GWP reduction. Although the initial costs of PV panels, ASHPs, and mechanical ventilation with heat recovery are high, these systems have led to lower energy consumption and better LCC results over 50 years. Our results are in line with what has been discussed in the literature review by Moschetti et al., (Moschetti & Brattebø, 2017) in which a little bit of rising in NPC results in substantial reductions in GWP also a higher the house life span after the renovation, the lower the total annual GWP.

To reduce the risk assessment in data collection, the focus should be done on life cycle inventory analysis (LCIA) while doing the LCA. Moreover to increase the clarity in LCIA more transparent and comparable EPDs should be found and used (Petrović, Zhang, Eriksson, & Wallhagen, 2021). The LCC contains many uncertainties since it estimates and calculates future costs. To reduce risk assessment future predictions of discount rates, and energy rates can reduce these uncertainties. Along with discount rates also the total lifespan of the building plays a huge role in the LCC results. To reduce also risk assessment a sensitivity analysis is needed to lower the risk of misleading LCC calculations. A sensitivity analysis was done in this study to investigate how changing the discount rate and lifespan can affect the results significantly. (Petrović et al., 2021)

6 Conclusion

The climate target set in 2020 by the European Union requires a reduction in GHG emissions by at least 55% in comparison to 1990 by the year 2030. Energy renovation of the residential building stock and the application of renewable energy supply systems have been viewed as a means of meeting the EU targets. In Sweden, energy renovations in SFH show great potential for improved energy efficiency and reduced GHG emissions. However, the rate of such renovations remains low, due to various financial, social/behavioral barriers. The high total cost of energy renovations, the long payback period for investments in energy-efficient measures, and the lack of awareness on how the application of different EEMs affects the energy performance of the dwelling are among the most common barriers. Thus, it is necessary to evaluate various renovation scenarios to determine how to improve the energy efficiency performance of the dwelling while keeping costs low. This project analyzed 8 different renovation scenarios using 5 common energy efficiency measures such as thermal insulation, windows replacement, ventilation system, PV system, and ASHP system. Building energy simulations have been used to see how the energy efficiency measures have affected the building's energy performance in each renovation scenario. The results showed that the primary energy number has reduced in all 8 renovation scenarios. The scenarios with the lowest reduction in primary energy are scenarios 1 and 2 with 32% and 39% reduction respectively, in which only the windows and doors have been replaced and insulation has been added to the walls and roof. In contrast, scenarios 7 and 8 have the highest reduction in primary energy by 66% and 71%, respectively. This is because not only insulation and windows and doors have been added, but also a better ventilation system, PV system, and ASHP system have been added. The greatest reductions in primary energy were achieved by PV and ASHP systems, and the second greatest reductions in primary energy were achieved by insulation and windows replacement. Ventilation was the least effective EEM at reducing primary energy.

Adding insulations for walls and roofs and replacing windows to meet either the BBR´s or FEBY´s suggested U-value resulted in the second most reduction in GWP and least LCC profit while changing the ventilation system resulted in the least reduction of GWP and second most LCC profit and finally changing the heating system from district heating to ASHP and adding a PV system resulted in the most reduction in GWP and the most LCC profit. Scenarios 1 and 2 resulted in the least reduction in GWP but when the ventilation system was changed in addition to the wall and roof insulation and windows replacement done in scenarios 1 and 2, scenarios 3 and 4 had the second most reduction in GWP while scenarios 5,6,7 and 8 resulted in the most reduction in GWP after changing the heating system to ASHP and adding a PV system in addition to the other EEMS done in scenarios 1,2,3 and 4. Scenarios 1,2,3 and 4 have the least profit of all scenarios and resulted in LCC costs above zero, while scenarios 5,6,7, and 8 resulted in a good amount of profit whereas scenario 7 resulted in the most amount of profit in comparison to all other scenarios.

To conclude, scenarios 5,6,7, and 8 that changed the heating system from district heating to ASHP and added a PV system resulted in the most reduction in GWP and are the most cost-effective in comparison to other scenarios that didn't have those EEMs. Moreover, scenarios 1,3,5 and 7 which insulated the walls, and roof and replaced the windows to meet the BBR´s suggested U-value are more cost-effective in comparison to scenarios 2,4.6 and 8 that are meeting FEBY´s suggested U-value due to the high price of investment cost since to meet FEBY´s suggested U-values more insulation should be added for walls and roof.

Although our study was limited to a specific geographical zone with limited parameters for energy-efficient strategies, it can set the basis for similar studies in the field. It can help homeowners to analyze the environmental and financial impacts of doing renovations and then increase the willingness to renovate their houses.

7 Future Work

In future work, the research would be improved by conducting a survey and interviewing building companies in the sector to provide a broader understanding of the current market for installation costs and materials.

Changes or added energy-efficient measures are recommended for future work. For example, comparing ground source heat pumps (GSHP) versus air-source heat pumps (ASHP) in a scenario to examine both environmental and economic considerations. In addition, it would be beneficial to compare the environmental and economic impacts of alternative insulation materials to the current ones.

There is still the potential for further investigation of LCA and LCC and the discovery of other interconnections. A study could be conducted to investigate how secondary materials and installations could be reused or recycled after a building's lifespan and how they could be applied to new construction. Consequently, it may be interesting to study how these might be applied to new construction after a building has reached its end of life.

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9 Appendix

Appendix 1: Figures containing data concerning the general description of the building elements on the original state of the SFH.

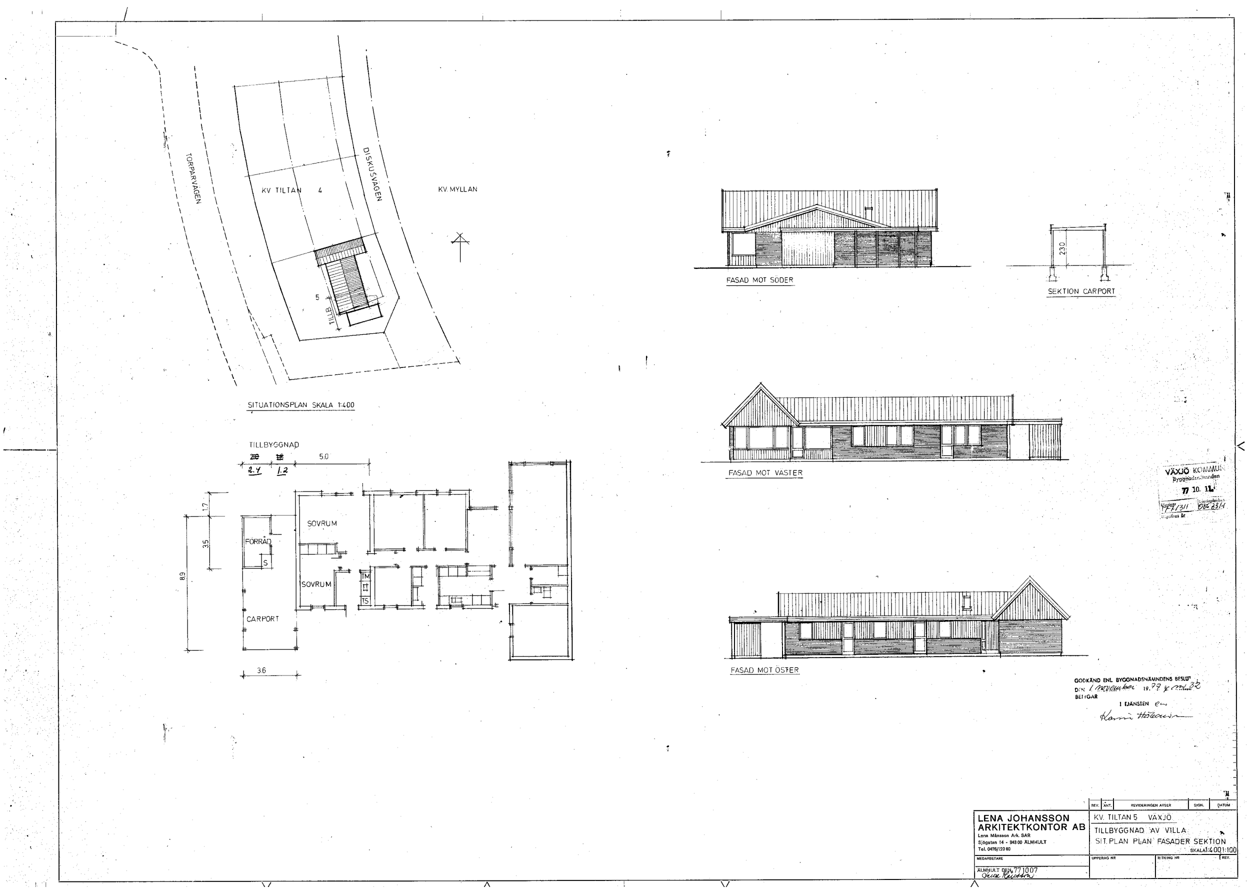
Appendix 2: Figures containing data concerning energy simulation

Appendix 3: Figures containing LCA calculation.

Appendix 4: Figures containing LCC calculation

Appendix 1

Figures of the SFH



Building components data of the SFH

Building components

Air-tight interior floors are used

Name	Type	Rotation (° clockwise from north)	Area (m²)	U-value (W/m²K)	Lowest Level (m)	Highest Level (m)
Outer walls	Exterior wall	165.99	7.82	0.26	0.4	2.7
Outer walls	Exterior wall	76.00	6.82	0.26	0.4	2.7
Outer walls	Exterior wall	346.00	28.60	0.26	0.4	2.7
Outer walls	Exterior wall	256.01	3.41	0.26	0.4	2.7
Outer walls	Exterior wall	165.99	4.14	0.26	0.4	2.7
Outer walls	Exterior wall	256.00	7.55	0.26	0.4	2.7
Outer walls	Exterior wall	166.00	18.40	0.26	0.4	2.7
Outer walls	Exterior wall	76.00	15.10	0.26	0.4	2.7
Medium insulated light building, slab on grade	Slab on grade 1-6 m	0.00	81.06	0.46	0.4	0.4
Roof	Roof	0.00	129.84	0.24	2.3	2.3
Medium insulated light building, slab on grade	Slab on grade 0-1 m	0.00	48.78	0.46	0.4	0.4
Inner walls	Interior wall	0.00	129.84	0.5	0.0	0.0
Double glazed window with constant solar shading	Window/Door	76.00	2.84	2.7	0.3	2.0
Double glazed window with constant solar shading	Window/Door	346.00	1.76	2.7	0.8	1.5
Double glazed window with constant solar shading	Window/Door	256.01	6.25	2.7	-0.1	2.4
Double glazed window with constant solar shading	Window/Door	256.00	13.84	2.7	-0.0	2.3
Double glazed window with constant solar shading	Window/Door	76.00	6.29	2.7	0.4	1.9

Appendix 2

Building components for scenarios 1, 3, 5, and 7

Building components

Air-tight interior floors are used

Name	Type	Rotation (° clockwise from north)	Area (m²)	U-value (W/m²K)	Lowest Level (m)	Highest Level (m)
BBR standard insulation for exterior wall	Exterior wall	165.99	7.82	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	75.99	6.82	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	346.00	28.60	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	256.00	3.41	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	165.99	4.14	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	256.00	7.55	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	166.00	18.40	0.15	0.4	2.7
BBR standard insulation for exterior wall	Exterior wall	76.00	15.10	0.15	0.4	2.7
Medium insulated light building, slab on grade	Slab on grade 1-6 m	0.00	81.06	0.46	0.4	0.4
BBR standard insulation for roof	Roof	0.00	129.84	0.11	2.3	2.3
Medium insulated light building, slab on grade	Slab on grade 0-1 m	0.00	48.78	0.46	0.4	0.4
Inner walls	Interior wall	0.00	129.84	0.5	0.0	0.0
Triple glazed window argon-filled with selective coating, constant solar shading BBR	Window/Door	75.99	2.84	1.1	0.3	2.0
Triple glazed window argon-filled with selective coating, constant solar shading BBR	Window/Door	346.00	1.76	1.1	0.8	1.5
Triple glazed window argon-filled with selective coating, constant solar shading BBR	Window/Door	256.00	6.25	1.1	-0.1	2.4
Triple glazed window argon-filled with selective coating, constant solar shading BBR	Window/Door	256.00	13.84	1.1	-0.0	2.3
Triple glazed window argon-filled with selective coating, constant solar shading BBR	Window/Door	76.00	6.29	1.1	0.4	1.9

Building components for scenarios 2, 4, 6, and 8

Building components

Air-tight interior floors are used

Name	Type	Rotation (° clockwise from north)	Area (m^2)	U-value (W/m^2K)	Lowest Level (m)	Highest Level (m)
FEBY standard insulation for exterior wall	Exterior wall	165.99	7.82	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	76.00	6.82	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	346.00	28.60	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	256.00	3.41	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	165.99	4.14	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	256.00	7.55	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	166.00	18.40	0.11	0.4	2.7
FEBY standard insulation for exterior wall	Exterior wall	76.00	15.10	0.11	0.4	2.7
Medium insulated light building, slab on grade	Slab on grade 1-6 m	0.00	81.06	0.46	0.4	0.4
FEBY standard insulation for roof	Roof	0.00	129.84	0.09	2.3	2.3
Medium insulated light building, slab on grade	Slab on grade 0-1 m	0.00	48.78	0.46	0.4	0.4
Inner walls	Interior wall	0.00	129.84	0.5	0.0	0.0
Triple glazed window argon-filled with selective coating, constant solar shading FEBY	Window/Door	76.00	2.84	0.82	0.3	2.0
Triple glazed window argon-filled with selective coating, constant solar shading FEBY	Window/Door	346.00	1.76	0.82	0.8	1.5
Triple glazed window argon-filled with selective coating, constant solar shading FEBY	Window/Door	256.00	6.25	0.82	-0.1	2.4
Triple glazed window argon-filled with selective coating, constant solar shading FEBY	Window/Door	256.00	13.84	0.82	-0.0	2.3
Triple glazed window argon-filled with selective coating, constant solar shading FEBY	Window/Door	76.00	6.29	0.82	0.4	1.9

Energy simulation results of 8 scenarios

Scenario	Heat supply [kWh/m2 /year]	Heat energy saving [kWh/m2/year]	Peak power heat [kW]	Electricity supply incl. process energy [kWh/m2/year]	Electricity energy saving [kWh/m2/year]	Peak power electricity [kW]	Energy performance [kWh/m2]
Base scenario	224.74	0	8.49	31.32	0	0.46	226.27
Scenario1	151.82	72.92	5.62	31.32	0	0.46	153.35
Scenario2	135.73	89.01	5.08	31.32	0	0.46	137.26
Scenario3	114.09	110.64	4.43	34.97	-3.66	0.52	119.28
Scenario4	98.62	126.12	3.89	34.97	-3.66	0.52	103.81
Scenario5	22.64	202.1	2.24	74.04	-42.72	1.93	66.90
Scenario6	21.00	203.74	1.70	69.49	-38.17	1.91	60.70
Scenario7	21.14	203.6	1.05	66.05	-34.73	1.92	57.40
Scenario8	21.10	203.64	0.57	61.04	-29.72	1.83	52.35

Key values for the selected SFH

Key values		
Heated floor area	129.84	m²
Envelope area	382.51	m²
Infiltration at 50 Pa	191.25	l/s
Infiltration at 50 Pa	0.50	l/s,m²
Internal air pressure average	-6.36	Pa
Peak power electricity	0.46	kW
Peak power heating	8.49	kW
Average U-value	0.51	W/m²,K
Average ventilation flow	0.35	l/s,m²
Heat loss form factor	2.95	
Total energy use	29 379.0	kWh/year
Energy performance	226.3	kWh/m²/year

Appendix 3

Environmental Product Declaration of air-to-air source heat pump used in One-Click LCA

Résultats d'indicateurs environnementaux												
	Total cycle de vie [modules A - B - C]	Étape de production [module A1 - A3]	Étape du processus de construction [module A4 - A5]	Étape d'utilisation [module B]								Étape de fin de vie [module C]
				Total Étape d'utilisation [module B]	B1- Utilisation	B2- Maintenance	B3- Réparation	B4- Remplacement	B5- Réhabilitation	B6- Utilisation de l'énergie	B6- Utilisation de l'eau	
Indicateurs décrivant les impacts environnementaux												
Potentiel de réchauffement climatique (GWP) (kg CO2 eq)	1.89E+03	9.59E+02	1.99E+01	8.98E+02	8.49E+02	4.96E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.57E+01
Potentiel de destruction de la couche d'ozone stratosphérique (ODP) (kg CFC 11 eq)	1.32E-03	1.26E-03	4.28E-08	6.29E-05	0.00E+00	6.29E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.84E-07
Potentiel d'acidification du sol et de l'eau (AP) (kg SO2 eq)	5.95E+00	5.53E+00	9.35E-02	2.83E-01	0.00E+00	2.83E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.66E-02
Potentiel d'eutrophisation (EP) (kg PO4 3- eq)	5.29E+00	4.52E+00	4.48E-02	2.51E-01	0.00E+00	2.51E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.79E-01
Potentiel de formation d'oxydants photochimiques de l'ozone troposphérique (POCP) (kg C2H4 eq)	6.91E-01	6.03E-01	1.23E-02	3.28E-02	0.00E+00	3.28E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.31E-02
Potentiel de dégradation abiotique des ressources pour les éléments (ADP_éléments) (kg Sb eq)	4.01E-01	3.82E-01	1.53E-06	1.91E-02	0.00E+00	1.91E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.99E-06
Potentiel de dégradation abiotique des combustibles fossiles (ADP_combustibles fossiles) (MJ)	1.20E+04	1.11E+04	2.72E+02	5.71E+02	0.00E+00	5.71E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.55E+01
Pollution de l'air (m3)	2.77E+05	2.09E+05	1.97E+03	4.37E+04	3.21E+04	1.16E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.16E+04
Pollution de l'eau (m3)	3.46E+04	3.17E+04	6.20E+01	1.65E+03	0.00E+00	1.65E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.23E+03

Environmental Product Declaration regarding Solar PV used in One-Click LCA

Solar panel photovoltaic system, 3 000 Wp (Gaia Solar)

Show empty rows

General information	
Country	Sweden
Manufacturer	Gaia Solar
Material type	Energy production systems from renewable energy
Datapoint background information	
EPD program	One Click LCA
Year	2014
Product Category Rules (PCR)	-
Standard	ISO14040
Data source	One Click LCA
Verification	Internally verified
Upstream database	ecoinvent
Technical characteristics	
Mass per unit	23.4 kg/m^2
Available units	m^2, kg, ton
Environmental profile	
Global warming potential (A1-A3) before local compensation	6.07 kg CO_2e / kg 142.14 kg CO_2e / m^2 — This feature is available under license Business Download EPD
Q Metadata	+/- 34.64 % variation in dataset
Others	
Notes about PCR	Only with EN15804
Properties	Internally verified

Environmental Product Declaration regarding ventilation system with heat recovery used in One-Click LCA

Air exchanger+heat recovery, 444 liters / s

Add to input | Add to compare

General information	
Country	Sweden
Material type	HVAC components and equipment
Warning	Datapoint may be expired
Datapoint background information	
Technical characteristics	
Mass per unit	52.7 kg/unit
Available units	unit, kg, ton
Environmental profile	
Global warming potential (A1-A3) before local compensation	4.27 kg CO_2e / kg
Biogenic CO_2 storage	2.96 kg CO_2e / unit
Performance in group	HVAC components and equipment
Performance ranking	CO_2 CML: **40 / 103** See full ranking
Q Metadata	+/- 34.64 % variation in dataset
Default scenarios and assumptions	
Transportation distance	70
Transportation method	Large delivery truck, 9 ton capacity, 100% fill rate: 0.0928 kg CO_2e / tonkm
Wastage on site	1.0 %
Default service life	25
Product-specific service life	25.0
Others	

Environmental Product Declaration of windows in scenarios 2, 4, 6, and 8 used in One-Click LCA

Miljøpåvirkning	Gilje Innadslående eXtra vindu uten aluminiumsbekledning								
Parameter	**Unit**	**A1-A3**	**A4 Oslo**	**A4 Stavanger**					
GWP	kg CO_2-eqv	9,96E+01	2,21E+00	4,13E-01					
ODP	kg CFC11-eqv	1,00E-05	4,16E-07	7,77E-08					
POCP	kg C_2H_4-eqv	4,27E-02	3,53E-04	6,84E-05					
AP	kg SO_2-eqv	7,94E-01	6,23E-03	1,34E-03					
EP	kg PO_4^{3-}-eqv	1,80E-01	1,34E-03	2,94E-04					
ADPM	kg Sb-eqv	6,54E-04	6,75E-06	1,25E-06					
ADPE	MJ	1,41E+03	3,34E+01	6,24E+00					

Miljøpåvirkning	Gilje Innadslående eXtra vindu med aluminiumsbekledning								
Parameter	**Unit**	**A1-A3**	**A4 Oslo**	**A4 Stavanger**					
GWP	kg CO_2-eqv	1,35E+02	2,28E+00	4,27E-01					
ODP	kg CFC11-eqv	1,15E-05	4,29E-07	8,02E-08					
POCP	kg C_2H_4-eqv	5,55E-02	3,65E-04	7,07E-05					
AP	kg SO_2-eqv	9,90E-01	6,44E-03	1,38E-03					
EP	kg PO_4^{3-}-eqv	2,31E-01	1,38E-03	3,04E-04					
ADPM	kg Sb-eqv	7,04E-04	6,98E-06	1,29E-06					
ADPE	MJ	1,78E+03	3,45E+01	6,44E+00					

GWP Globalt oppvarmingspotensial; ODP Potensial for nedbryting av stratosfærisk ozon; POCP Potensial for fotokjemisk oksidantdanning; AP Forsurningspotensial for kilder på land og vann; EP Overgjødslingspotensial; ADPM Abiotisk uttømmingspotensial for ikke-fossile ressurser; ADPE Abiotisk uttømmingspotensial for fossile ressurser

Environmental Product Declaration of windows in scenarios 2, 4, 6, and 8 used in One-Click LCA

RESULTS (A1 - A3) PER 1 M² WINDOW

PRODUCT ↓ (INDICATOR / UNIT PER M²)	GWP (kg CO_2e)	ODP (kg CFC11e)	POCP (kg C_2H_4e)	AP (kg SO_2e)	EP (kg PO_4^{3-}-e)	ADPE (kg Sb e)	ADPF (MJ)
Wood sidehung window 3-glass	76.7	5.2E-06	0.08	0.56	0.10	0.013	350.9
Wood/aluminum sidehung window 3-glass	90.1	6.8E-6	0.08	0.63	0.13	0.013	503.2
Wood fully reversable window 3-glass	93.4	6.4E-6	0.1	0.71	0.12	0.022	351.0
Wood/aluminum fully reversable window 3-glass	106.9	8.1E-6	0.1	0.78	0.15	0.023	503.3
Wood fixed window 3-glass	62.1	3.9E-6	0.06	0.39	0.08	0.001	353.4
Wood/aluminum fixed window 3-glass	66.7	4.4E-6	0.06	0.42	0.09	0.001	412.0
Wood/aluminum inward window 3-glass	84.6	6.9E-6	0.08	0.57	0.13	0.007	583.6
Wood/aluminum inward window 2+1-glass	90.8	8.0E-06	0.08	0.60	0.15	0.007	656.6
Wood/aluminum inward Kipp-dreh window 3-glass	89.3	7.2E-6	0.08	0.61	0.14	0.009	586.0
Wood/aluminum inward Kipp-dreh window 2+1-glass	95.5	8.4E-6	0.08	0.65	0.15	0.010	658.7

Environmental Product Declaration of insulation material used in One-Click LCA

Environmental impact									
Parameter	**Unit**	**A1-A3**	**A4**	**C1**	**C2**	**C3**	**C4**	**D**	
GWP	kg CO_2-eqv	1.75E+00	1.12E-01	0.00E+00	3.19E-02	1.81E+00	3.53E-05	-8.94E-03	
ODP	kg CFC11-eqv	5.84E-08	2.54E-08	0.00E+00	7.62E-09	1.25E-09	1.58E-11	-5.68E-10	
POCP	kg C_2H_4-eqv	1.27E-02	3.84E-04	0.00E+00	5.26E-05	2.68E-04	3.08E-07	-1.96E-05	
AP	kg SO_2-eqv	5.68E-03	3.93E-04	0.00E+00	7.23E-05	2.19E-04	2.77E-07	-3.43E-05	
EP	kg PO_4^{3-}-eqv	9.68E-04	2.26E-06	0.00E+00	6.58E-07	1.67E-06	1.95E-07	-3.64E-07	
ADPM	kg Sb-eqv	4.00E-06	3.36E-07	0.00E+00	9.48E-08	7.47E-08	5.83E-10	-2.14E-07	
ADPE	MJ	5.15E+01	1.58E+00	0.00E+00	4.75E-01	1.38E-01	1.07E-03	-1.19E-01	

Appendix 4

Operational cost savings for first 20 years for a discount rate of 5% in a 50-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10
(1/(1+d)^t)	1	0.952380952	0.907029478	0.863837599	0.822702475	0.783526166	0.746215397	0.71068133	0.676839362	0.644608916	0.613913254
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8315.92381	-7919.927438	-7542.788036	-7183.607653	-6841.531098	-6515.743903	-6205.470384	-5909.971794	-5628.544566	-5360.518634
scneario 2	-10613.12	-10107.73333	-9626.412698	-9168.012094	-8731.440089	-8315.657228	-7919.67355	-7542.546238	-7183.37737	-6841.311781	-6515.535029
scenario 3	-12321.69	-11734.94286	-11176.13605	-10643.9391	-10137.08486	-9654.36653	-9194.634791	-8756.795039	-8339.804799	-7942.671237	-7564.448797
sceanrio 4	-14205.85	-13529.38095	-12885.12472	-12271.54735	-11687.18795	-11130.65519	-10600.62399	-10095.83237	-9615.078451	-9157.217572	-8721.159593
scneario 5	-30452.26	-29002.15238	-27621.09751	-26305.80715	-25053.14967	-23860.14254	-22723.94527	-21641.85264	-20611.28823	-19629.79831	-18695.04601
sceanrio 6	-31414.78	-29918.8381	-28494.13152	-27137.26811	-25845.01725	-24614.30214	-23442.19252	-22325.89764	-21262.75965	-20250.24729	-19285.9498
sceanrio 7	-32421.91	-30878.00952	-29407.62812	-28007.26487	-26673.58559	-25403.41485	-24193.72843	-23041.64612	-21944.42488	-20899.45227	-19904.24025
sceanrio 8	-33242.48	-31659.50476	-30151.9093	-28716.10409	-27348.67056	-26046.35292	-24806.0504	-23624.8099	-22499.81896	-21428.39901	-20407.99905

Years (t)	11	12	13	14	15	16	17	18	19	20
(1/(1+d)^t)	0.584679289	0.556837418	0.530321351	0.505067953	0.481017098	0.458111522	0.436296688	0.415520655	0.395733957	0.376889483
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-5105.255842	-4862.148421	-4630.617544	-4410.111947	-4200.106616	-4000.101539	-3809.620513	-3628.210013	-3455.438107	-3290.893435
scneario 2	-6205.271457	-5909.78234	-5628.364133	-5360.346793	-5105.092184	-4861.992556	-4630.469101	-4409.970573	-4199.971974	-3999.973308
scenario 3	-7204.23695	-6861.178047	-6534.455283	-6223.290746	-5926.943567	-5644.708159	-5375.912533	-5119.916698	-4876.111141	-4643.915372
sceanrio 4	-8305.866279	-7910.348837	-7533.665559	-7174.91958	-6833.256743	-6507.863565	-6197.9653	-5902.824095	-5621.737233	-5354.03546
scneario 5	-17804.80573	-16956.95784	-16149.48365	-15380.46062	-14648.05774	-13950.53118	-13286.22017	-12653.54302	-12050.99335	-11477.13652
sceanrio 6	-18367.57124	-17492.92499	-16659.92856	-15866.59863	-15111.04631	-14391.47268	-13706.16446	-13053.48996	-12431.8952	-11839.90019
sceanrio 7	-18956.41929	-18053.73266	-17194.0311	-16375.26772	-15595.49306	-14852.85054	-14145.57194	-13471.97328	-12830.45074	-12219.47689
sceanrio 8	-19436.18957	-18510.65674	-17629.19689	-16789.71133	-15990.20126	-15228.76311	-14503.58391	-13812.93706	-13155.17815	-12528.7411

Operational cost savings for the second 20 years for a discount rate of 5% in a 50-year lifespan

21	22	23	24	25	26	27	28	29	30
0.358942365	0.341849871	0.325571306	0.31006791	0.295302772	0.281240735	0.267848319	0.255093637	0.242946321	0.231377449
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-3134.184224	-2984.937356	-2842.797482	-2707.426174	-2578.501118	-2455.71535	-2338.776524	-2227.406213	-2121.339251	-2020.323096
-3809.498389	-3628.093704	-3455.327337	-3290.78794	-3134.083752	-2984.841669	-2842.706351	-2707.339382	-2578.418459	-2455.636628
-4422.776545	-4212.168138	-4011.588703	-3820.560669	-3638.629209	-3465.361151	-3300.343954	-3143.184718	-2993.509255	-2850.961195
-5099.081391	-4856.267991	-4625.017134	-4404.778223	-4195.026879	-3995.263695	-3805.013042	-3623.821945	-3451.258995	-3286.913329
-10930.60621	-10410.10116	-9914.382053	-9442.268622	-8992.636782	-8564.415983	-8156.586651	-7768.177763	-7398.264536	-7045.966225
-11276.09542	-10739.13849	-10227.75095	-9740.715187	-9276.871606	-8835.115816	-8414.396015	-8013.71049	-7632.105229	-7268.671646
-11637.59704	-11083.42575	-10555.64358	-10052.99388	-9574.279887	-9118.361797	-8684.154092	-8270.622945	-7876.783757	-7501.698816
-11932.13438	-11363.9375	-10822.79762	-10307.42631	-9816.596482	-9349.139507	-8903.942387	-8479.945131	-8076.13822	-7691.560209

31	32	33	34	35	36	37	38	39	40
0.220359475	0.209866167	0.19987254	0.1903548	0.181290285	0.172657415	0.164435633	0.156605365	0.149147966	0.142045682
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-1924.117234	-1832.492604	-1745.231051	-1662.124811	-1582.97601	-1507.5962	-1435.805905	-1367.434195	-1302.318281	-1240.303125
-2338.70555	-2227.33481	-2121.271247	-2020.258331	-1924.055553	-1832.43386	-1745.175105	-1662.071529	-1582.925265	-1507.547872
-2715.201138	-2585.905846	-2462.767472	-2345.492831	-2233.802696	-2127.431139	-2026.124894	-1929.642757	-1837.755006	-1750.242863
-3130.393647	-2981.327283	-2839.359317	-2704.15173	-2575.3826	-2452.745334	-2335.947937	-2224.712321	-2118.773639	-2017.879656
-6710.444023	-6390.89907	-6086.570543	-5796.73385	-5520.698905	-5257.808481	-5007.436649	-4768.987284	-4541.892652	-4325.612049
-6922.544425	-6592.899453	-6278.95186	-5979.954152	-5695.19443	-5423.994696	-5165.709234	-4919.72308	-4685.450552	-4462.333859
-7144.475063	-6804.261965	-6480.24949	-6171.666181	-5877.777316	-5597.883158	-5331.317293	-5077.445041	-4835.661944	-4605.392327
-7325.295438	-6976.471845	-6644.2589	-6327.865619	-6026.538685	-5739.560652	-5466.24824	-5205.950705	-4958.048291	-4721.950753

Operational cost savings for the last 10 years for a discount rate of 5% in a 50-year lifespan

41	42	43	44	45	46	47	48	49	50
0.135281602	0.128839621	0.122704401	0.116861334	0.111296509	0.105996675	0.100949214	0.096142109	0.091563913	0.087203727
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-1181.241071	-1124.991497	-1071.420473	-1020.40045	-971.8099528	-925.5332884	-881.4602747	-839.4859759	-799.5104532	-761.4385269
-1435.759878	-1367.39036	-1302.276533	-1240.263365	-1181.203205	-1124.955433	-1071.386127	-1020.36774	-971.7787997	-925.5036188
-1666.897965	-1587.521871	-1511.925592	-1439.929135	-1371.361081	-1306.058172	-1243.864926	-1184.633263	-1128.222155	-1074.497291
-1921.790148	-1830.276332	-1743.120316	-1660.114587	-1581.061511	-1505.772868	-1434.069398	-1365.780379	-1300.743218	-1238.803065
-4119.630523	-3923.457641	-3736.626325	-3558.691738	-3389.230227	-3227.838311	-3074.131725	-2927.7445	-2788.328095	-2655.550567
-4249.841771	-4047.468353	-3854.731765	-3671.173109	-3496.355342	-3329.862231	-3171.297363	-3020.283203	-2876.460193	-2739.485898
-4386.087931	-4177.226601	-3978.311048	-3788.867665	-3608.445395	-3436.614662	-3272.966345	-3117.110805	-2968.676957	-2827.311388
-4497.095955	-4282.948529	-4078.998599	-3884.76057	-3699.771972	-3523.592354	-3355.802242	-3196.002135	-3043.811557	-2898.86815

Operational cost savings for first 20 years for a discount rate of 0% in a 50-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10
(1/(1+d)^t)	1	1	1	1	1	1	1	1	1	1	1
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72
scneario 2	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12
scenario 3	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69
sceanrio 4	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85
scneario 5	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26
sceanrio 6	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78
sceanrio 7	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91
sceanrio 8	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48

Years (t)	11	12	13	14	15	16	17	18	19	20
(1/(1+d)^t)	1	1	1	1	1	1	1	1	1	1
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72
scneario 2	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12
scenario 3	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69
sceanrio 4	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85
scneario 5	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26
sceanrio 6	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78
sceanrio 7	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91
sceanrio 8	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48

Operational cost savings for the second 20 years for a discount rate of 0% in a 50-year lifespan

21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72
-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12
-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69
-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85
-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26
-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78
-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91
-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48

Operational cost savings for the last 10 years for a discount rate of 0% in a 50-year lifespan

41	42	43	44	45	46	47	48	49	50
1	1	1	1	1	1	1	1	1	1
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72	-8731.72
-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12	-10613.12
-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69	-12321.69
-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85	-14205.85
-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26	-30452.26
-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78	-31414.78
-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91	-32421.91
-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48	-33242.48

Operational cost savings for first 20 years for a discount rate of 1% in a 50-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
(1/(1+d)^t)	1	0.99009901	0.980296049	0.970590148	0.960980344	0.951465688	0.942045235	0.932718055	0.923483222	0.914339824	0.905286955	0.896323718	0.887449225	0.878662599	0.86996297	0.861349475	0.852821262	0.844377487	0.836017314	0.827739915	0.81954447
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8645.267327	-8559.670621	-8474.921406	-8391.011294	-8307.931974	-8225.675222	-8144.232893	-8063.596923	-7983.75933	-7904.712208	-7826.447731	-7748.958149	-7672.235791	-7596.273061	-7521.062436	-7446.596472	-7372.867794	-7299.869103	-7227.593171	-7156.032843
scneario 2	-10613.12	-10508.0396	-10403.99961	-10300.98971	-10198.99971	-10098.01952	-9998.039127	-9899.048641	-9801.038258	-9703.998275	-9607.919085	-9512.791173	-9418.605122	-9325.351606	-9233.021392	-9141.605338	-9051.094394	-8961.479598	-8872.752078	-8784.903047	-8697.923809
scenario 3	-12321.69	-12199.69307	-12078.90403	-11959.31092	-11840.9019	-11723.66525	-11607.58935	-11492.66273	-11378.87399	-11266.21187	-11154.66522	-11044.22299	-10934.87424	-10826.60816	-10719.41402	-10613.28121	-10508.19922	-10404.15764	-10301.14618	-10199.15463	-10098.1729
sceanrio 4	-14205.85	-14065.19802	-13925.93863	-13788.05805	-13651.54263	-13516.37884	-13382.55331	-13250.05278	-13118.86414	-12988.97439	-12860.37069	-12733.04028	-12606.97058	-12482.14909	-12358.56345	-12236.20144	-12115.05093	-11995.09993	-11876.33656	-11758.74907	-11642.32581
scneario 5	-30452.26	-30150.75248	-29852.23017	-29556.66354	-29264.02331	-28974.2805	-28687.40644	-28403.37271	-28122.1512	-27843.71406	-27568.03372	-27295.08289	-27024.83454	-26757.26193	-26492.33854	-26230.03816	-25970.33481	-25713.20278	-25458.61662	-25206.55111	-24956.98129
sceanrio 6	-31414.78	-31103.74257	-30795.78473	-30490.87597	-30188.98611	-29890.08525	-29594.14382	-29301.13249	-29011.02227	-28723.78442	-28439.39052	-28157.81239	-27879.02217	-27602.99225	-27329.6953	-27059.10425	-26791.19233	-26525.933	-26263.3	-26003.26733	-25745.80924
sceanrio 7	-32421.91	-32100.90099	-31783.07029	-31468.38642	-31156.81824	-30848.33489	-30542.90583	-30240.50083	-29941.08993	-29644.64349	-29351.13217	-29060.5269	-28772.79891	-28487.91971	-28205.8611	-27926.59515	-27650.09421	-27376.3309	-27105.27812	-26836.90903	-26571.19706
sceanrio 8	-33242.48	-32913.34653	-32587.47182	-32264.82358	-31945.36988	-31629.07909	-31315.91989	-31005.86128	-30698.87255	-30394.92332	-30093.98349	-29796.02325	-29501.01312	-29208.92388	-28919.72662	-28633.39269	-28349.89375	-28069.20174	-27791.28885	-27516.12757	-27243.69066

Operational cost savings for the second 20 years for a discount rate of 1% in a 50-year lifespan

20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
0.81954447	0.811430169	0.803396207	0.795441789	0.787566127	0.779768443	0.772047963	0.764403924	0.756835568	0.749342147	0.741922918	0.734577146	0.727304105	0.720103075	0.712973341	0.705914199	0.69892495	0.692004901	0.685153367	0.67836967	0.671653139
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-7156.032843	-7085.181032	-7015.030725	-6945.574975	-6876.806906	-6808.719709	-6741.306643	-6674.561032	-6608.47627	-6543.045811	-6478.26318	-6414.12196	-6350.615802	-6287.738418	-6225.483582	-6163.845131	-6102.816961	-6042.393031	-5982.567357	-5923.334017	-5864.687146
-8697.923809	-8611.805752	-8526.540348	-8442.119156	-8358.533818	-8275.776058	-8193.837681	-8112.710575	-8032.386708	-7952.858127	-7874.116957	-7796.155403	-7718.965746	-7642.540342	-7566.871626	-7491.952105	-7417.774361	-7344.331051	-7271.614902	-7199.618715	-7128.335361
-10098.1729	-9998.190995	-9899.199005	-9801.187133	-9704.145677	-9608.065026	-9512.93567	-9418.748188	-9325.493255	-9233.161639	-9141.744197	-9051.231878	-8961.615721	-8872.886852	-8785.036487	-8698.055928	-8611.936563	-8526.669864	-8442.24739	-8358.660782	-8275.901765
-11642.32581	-11527.05526	-11412.926	-11299.92673	-11188.04627	-11077.27354	-10967.59756	-10859.00749	-10751.49256	-10645.04214	-10539.64568	-10435.29275	-10331.97302	-10229.67626	-10128.39234	-10028.11123	-9928.822996	-9830.517817	-9733.185958	-9636.81778	-9541.403743
-24956.98129	-24709.88247	-24465.23017	-24223.00016	-23983.16848	-23745.71137	-23510.60531	-23277.82704	-23047.35351	-22819.16189	-22593.22959	-22369.53425	-22148.05371	-21928.76605	-21711.64956	-21496.68273	-21283.84429	-21073.11315	-20864.46847	-20657.88957	-20453.35601
-25745.80924	-25490.90023	-25238.51508	-24988.62879	-24741.21663	-24496.25409	-24253.71692	-24013.58111	-23775.82288	-23540.41869	-23307.34524	-23076.57944	-22848.09846	-22621.87966	-22397.90066	-22176.13926	-21956.57353	-21739.18171	-21523.94229	-21310.83395	-21099.83559
-26571.19706	-26308.1159	-26047.6395	-25789.74208	-25534.3981	-25281.58228	-25031.26958	-24783.43523	-24538.05468	-24295.10365	-24054.55807	-23816.39413	-23580.58824	-23347.11707	-23115.9575	-22887.08663	-22660.48181	-22436.12061	-22213.9808	-21994.0404	-21776.27762
-27243.69066	-26973.95115	-26706.88233	-26442.45775	-26180.65124	-25921.43687	-25664.78898	-25410.68216	-25159.09125	-24909.99133	-24663.35776	-24419.1661	-24177.39217	-23938.01205	-23701.00203	-23466.33865	-23233.99866	-23003.95907	-22776.1971	-22550.6902	-22327.41604

Operational cost savings for the last 10 years for a discount rate of 1% in a 50-year lifespan

41	42	43	44	45	46	47	48	49	50
0.665003108	0.658418919	0.651899919	0.645445465	0.639054916	0.632727639	0.626463009	0.620260405	0.614119213	0.608038825
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-5806.620936	-5749.12964	-5692.207564	-5635.849074	-5580.048588	-5524.800582	-5470.099586	-5415.940184	-5362.317014	-5309.224766
-7057.757783	-6987.878993	-6918.692073	-6850.190171	-6782.366506	-6715.214362	-6648.727091	-6582.89811	-6517.720901	-6453.189011
-8193.962143	-8112.833805	-8032.508718	-7952.978929	-7874.236563	-7796.273825	-7719.082995	-7642.65643	-7566.986565	-7492.065906
-9446.934399	-9353.400395	-9260.79247	-9169.101455	-9078.318273	-8988.433933	-8899.439538	-8811.326275	-8724.085421	-8637.708338
-20250.84754	-20050.3441	-19851.82584	-19655.27311	-19460.66544	-19267.98658	-19077.21443	-18888.33112	-18701.31794	-18516.15638
-20890.92633	-20684.08548	-20479.29255	-20276.52728	-20075.76958	-19876.99959	-19680.19761	-19485.34417	-19292.41997	-19101.40591
-21560.67091	-21347.19892	-21135.84052	-20926.57477	-20719.38096	-20514.23857	-20311.1273	-20110.02703	-19910.91785	-19713.78005
-22106.35251	-21887.47773	-21670.77003	-21456.20795	-21243.77025	-21033.43589	-20825.18405	-20618.99411	-20414.84565	-20212.71847

Operational cost savings for first 20 years for a discount rate of 3% in a 50-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
(1/(1+d)^t)	1	0.970873786	0.942595909	0.915141659	0.888487048	0.862608784	0.837484257	0.813091511	0.789409234	0.766416732	0.744093915	0.722421277	0.70137988	0.68095134	0.661117806	0.641861947	0.623166939	0.605016446	0.587394608	0.570286027	0.553675754
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8477.398058	-8230.483552	-7990.76073	-7758.020126	-7532.058375	-7312.678034	-7099.687411	-6892.900399	-6692.13631	-6497.219719	-6307.980309	-6124.252727	-5945.876434	-5772.695567	-5604.558803	-5441.319227	-5282.834201	-5128.965243	-4979.577906	-4834.541656
scenario 2	-10613.12	-10304	-10003.8835	-9712.508248	-9429.619658	-9154.970542	-8888.320914	-8629.437781	-8378.094933	-8134.07275	-7897.15801	-7667.143699	-7443.828834	-7227.018286	-7016.522607	-6812.157871	-6613.745506	-6421.112142	-6234.089458	-6052.514037	-5876.22722
scenario 3	-12321.69	-11962.80583	-11614.37459	-11276.09183	-10947.66197	-10628.79803	-10319.22139	-10018.66154	-9726.855868	-9443.549387	-9168.49455	-8901.45102	-8642.185456	-8390.471316	-8146.088657	-7908.823939	-7678.469843	-7454.825091	-7237.694263	-7026.887634	-6822.221004
sceanrio 4	-14205.85	-13792.08738	-13390.3761	-13000.36514	-12621.71373	-12254.091	-11897.17573	-11550.65605	-11214.22917	-10887.60114	-10570.48654	-10262.60829	-9963.697371	-9673.492593	-9391.740382	-9118.194545	-8852.616064	-8594.772877	-8344.439687	-8101.397754	-7865.434713
scneario 5	-30452.26	-29565.30097	-28704.1757	-27868.13175	-27056.43859	-26268.38698	-25503.28833	-24760.47411	-24039.29525	-23339.1216	-22659.34136	-21999.36054	-21358.60247	-20736.50725	-20132.53131	-19546.14691	-18976.84166	-18424.11811	-17887.49331	-17366.49836	-16860.67802
sceanrio 6	-31414.78	-30499.78641	-29611.44311	-28748.9739	-27911.62514	-27098.66519	-26309.38368	-25543.09095	-24799.11743	-24076.81303	-23375.54664	-22694.70547	-22033.69463	-21391.93654	-20768.87042	-20163.95187	-19576.6523	-19006.45854	-18452.87237	-17915.41007	-17393.60201
sceanrio 7	-32421.91	-31477.58252	-30560.75973	-29670.64052	-28806.4471	-27967.42437	-27152.8392	-26361.9798	-25594.15515	-24848.69432	-24124.94594	-23422.27761	-22740.07535	-22077.74306	-21434.702	-20810.39029	-20204.26242	-19615.78876	-19044.4551	-18489.76224	-17951.22547
sceanrio 8	-33242.48	-32274.25243	-31334.22566	-30421.57831	-29535.51292	-28675.25526	-27840.05365	-27029.1783	-26241.92068	-25477.5929	-24735.52708	-24015.07484	-23315.60664	-22636.5113	-21977.19544	-21337.08295	-20715.61451	-20112.2471	-19526.4535	-18957.72184	-18405.55519

Operational cost savings for the second 20 years for a discount rate of 3% in a 50-year lifespan

20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
0.553675754	0.537549276	0.521892501	0.506691748	0.491933736	0.477605569	0.463694727	0.450189056	0.437076753	0.424346362	0.41198676	0.399987145	0.388337034	0.377026247	0.3660449	0.355383398	0.345032425	0.334982937	0.325226152	0.315753546	0.306556841
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-4834.541656	-4693.729763	-4557.019188	-4424.290474	-4295.427644	-4170.318101	-4048.852525	-3930.924782	-3816.431827	-3705.273619	-3597.353028	-3492.575755	-3390.850248	-3292.087619	-3196.201572	-3103.108322	-3012.726527	-2924.97721	-2839.783699	-2757.071553	-2676.768498
-5876.22722	-5705.074971	-5538.907739	-5377.580329	-5220.951776	-5068.885219	-4921.247786	-4777.910472	-4638.748031	-4503.638865	-4372.464917	-4245.11157	-4121.467544	-4001.4248	-3884.878446	-3771.726647	-3661.870531	-3555.214108	-3451.664182	-3351.130274	-3253.524538
-6822.221004	-6623.515537	-6430.597609	-6243.29865	-6061.455	-5884.907767	-5713.502686	-5547.089987	-5385.524259	-5228.664329	-5076.373135	-4928.517607	-4784.96855	-4645.600534	-4510.291781	-4378.924059	-4251.382581	-4127.555904	-4007.335829	-3890.61731	-3777.298359
-7865.434713	-7636.344381	-7413.926584	-7197.986974	-6988.336868	-6784.793076	-6587.177744	-6395.318198	-6209.046794	-6028.200771	-5852.622108	-5682.157386	-5516.657656	-5355.978307	-5199.978939	-5048.523242	-4901.478875	-4758.717355	-4620.113937	-4485.547511	-4354.900497
-16860.67802	-16369.59031	-15892.80613	-15429.90886	-14980.49404	-14544.16897	-14120.5524	-13709.27418	-13309.97493	-12922.30575	-12545.92792	-12180.51254	-11825.74033	-11481.30129	-11146.89446	-10822.22763	-10507.01712	-10200.98749	-9903.871351	-9615.409079	-9335.34862
-17393.60201	-16886.99224	-16395.1381	-15917.6098	-15453.9901	-15003.87389	-14566.86785	-14142.59015	-13730.67004	-13330.74762	-12942.47341	-12565.50817	-12199.52249	-11844.1966	-11499.22	-11164.29126	-10839.11773	-10523.41527	-10216.90803	-9919.328182	-9630.41571
-17951.22547	-17428.37424	-16920.75169	-16427.91427	-15949.43133	-15484.88478	-15033.86872	-14595.98905	-14170.86315	-13758.11957	-13357.39764	-12968.34722	-12590.62837	-12223.91104	-11867.8748	-11522.20854	-11186.61023	-10860.78663	-10544.45304	-10237.33305	-9939.158301
-18405.55519	-17869.47105	-17349.00102	-16843.69031	-16353.09739	-15876.79358	-15414.3627	-14965.40068	-14529.51523	-14106.32546	-13695.46161	-13296.56467	-12909.28609	-12533.28747	-12168.24026	-11813.82549	-11469.73349	-11135.66358	-10811.32387	-10496.43094	-10190.70965

Operational cost savings for the last 10 years for a discount rate of 3% in a 50-year lifespan

41	42	43	44	45	46	47	48	49	50
0.297628001	0.288959224	0.280542936	0.272371782	0.264438624	0.256736528	0.249258765	0.241998801	0.234950292	0.22810708
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-2598.804367	-2523.111036	-2449.622365	-2378.27414	-2309.00402	-2241.751476	-2176.457743	-2113.06577	-2051.520165	-1991.767151
-3158.761687	-3066.75892	-2977.435844	-2890.714412	-2806.518847	-2724.775579	-2645.413184	-2568.362314	-2493.555645	-2420.927811
-3667.279961	-3560.465981	-3456.763088	-3356.080668	-3258.330746	-3163.427909	-3071.289232	-2981.834206	-2894.984666	-2810.664724
-4228.058734	-4104.911393	-3985.350867	-3869.272686	-3756.575423	-3647.160605	-3540.932626	-3437.798666	-3337.668608	-3240.454959
-9063.445262	-8799.46142	-8543.166427	-8294.336337	-8052.753725	-7818.2075	-7590.492718	-7369.410406	-7154.767385	-6946.376102
-9349.918165	-9077.590452	-8813.194613	-8556.499625	-8307.281189	-8065.321543	-7830.409265	-7602.339092	-7380.91174	-7165.933728
-9649.668254	-9368.609955	-9095.737821	-8830.813418	-8573.60526	-8323.888602	-8081.445245	-7846.063344	-7617.537228	-7395.667211
-9893.892862	-9605.721226	-9325.942938	-9054.313532	-8790.595662	-8534.558895	-8285.97951	-8044.640301	-7810.330389	-7582.845038

Operational cost savings for 25 years for a discount rate of 5% in a 25-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
(1/(1+d)^t)	1	0.952380952	0.907029478	0.863837599	0.822702475	0.783526166	0.746215397	0.71068133	0.676839362	0.644608916	0.613913254	0.584679289	0.556837418	0.530321351	0.505067953	0.481017098	0.458111522	0.436296688	0.415520655	0.395733957	0.376889483	0.358942365	0.341849871	0.325571306	0.31006791	0.295302772
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8315.92381	-7919.927438	-7542.788036	-7183.607653	-6841.531098	-6515.743903	-6205.470384	-5909.971794	-5628.544566	-5360.518634	-5105.255842	-4862.148421	-4630.617544	-4410.111947	-4200.106616	-4000.101539	-3809.620513	-3628.210013	-3455.438107	-3290.893435	-3134.184224	-2984.937356	-2842.797482	-2707.426174	-2578.501118
scenario 2	-10613.12	-10107.73333	-9626.412698	-9168.012094	-8731.440089	-8315.657228	-7919.67355	-7542.546238	-7183.37737	-6841.311781	-6515.535029	-6205.271457	-5909.78234	-5628.364133	-5360.346793	-5105.092184	-4861.992556	-4630.469101	-4409.970573	-4199.971974	-3999.973308	-3809.498389	-3628.093704	-3455.327337	-3290.78794	-3134.083752
scenario 3	-12321.69	-11734.94286	-11176.13605	-10643.9391	-10137.08486	-9654.36653	-9194.634791	-8756.795039	-8339.804799	-7942.671237	-7564.448797	-7204.23695	-6861.178047	-6534.455283	-6223.290746	-5926.943567	-5644.708159	-5375.912533	-5119.916698	-4876.111141	-4643.915372	-4422.776545	-4212.168138	-4011.588703	-3820.560669	-3638.629209
scenario 4	-14205.85	-13529.38095	-12885.12472	-12271.54735	-11687.18795	-11130.65519	-10600.62399	-10095.83237	-9615.078451	-9157.217572	-8721.159593	-8305.866279	-7910.348837	-7533.665559	-7174.91958	-6833.256743	-6507.863565	-6197.9653	-5902.824095	-5621.737233	-5354.03546	-5099.081391	-4856.267991	-4625.017134	-4404.778223	-4195.026879
scenario 5	-30452.26	-29002.15238	-27621.09751	-26305.80715	-25053.14967	-23860.14254	-22723.94527	-21641.85264	-20611.28823	-19629.79831	-18695.04601	-17804.80573	-16956.95784	-16149.48365	-15380.46062	-14648.05774	-13950.53118	-13286.22017	-12653.54302	-12050.99335	-11477.13652	-10930.60621	-10410.10116	-9914.382053	-9442.268622	-8992.636782
scenario 6	-31414.78	-29918.8381	-28494.13152	-27137.26811	-25845.01725	-24614.30214	-23442.19252	-22325.89764	-21262.75965	-20250.24729	-19285.9498	-18367.57124	-17492.92499	-16659.92856	-15866.59863	-15111.04631	-14391.47268	-13706.16446	-13053.48996	-12431.8952	-11839.90019	-11276.09542	-10739.13849	-10227.75095	-9740.715187	-9276.871606
scenario 7	-32421.91	-30878.00952	-29407.62812	-28007.26487	-26673.58559	-25403.41485	-24193.72843	-23041.64612	-21944.42488	-20899.45227	-19904.24025	-18956.41929	-18053.73266	-17194.0311	-16375.26772	-15595.49306	-14852.85054	-14145.57194	-13471.97328	-12830.45074	-12219.47689	-11637.59704	-11083.42575	-10555.64358	-10052.99388	-9574.279887
scenario 8	-33242.48	-31659.50476	-30151.9093	-28716.10409	-27348.67056	-26046.35292	-24806.0504	-23624.8099	-22499.81896	-21428.39901	-20407.99905	-19436.18957	-18510.65674	-17629.19689	-16789.71133	-15990.20126	-15228.76311	-14503.58391	-13812.93706	-13155.17815	-12528.7411	-11932.13438	-11363.9375	-10822.79762	-10307.42631	-9816.596482

Operational cost savings for first 25 years for a discount rate of 5% in a 75-year lifespan

Years (t)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
(1/(1+d)^t)	1	0.952380952	0.907029478	0.863837599	0.822702475	0.783526166	0.746215397	0.71068133	0.676839362	0.644608916	0.613913254	0.584679289	0.556837418	0.530321351	0.505067953	0.481017098	0.458111522	0.436296688	0.415520655	0.395733957	0.376889483	0.358942365	0.341849871	0.325571306	0.31006791	0.295302772
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
scenario 1	-8731.72	-8315.92381	-7919.927438	-7542.788036	-7183.607653	-6841.531098	-6515.743903	-6205.470384	-5909.971794	-5628.544566	-5360.518634	-5105.255842	-4862.148421	-4630.617544	-4410.111947	-4200.106616	-4000.101539	-3809.620513	-3628.210013	-3455.438107	-3290.893435	-3134.184224	-2984.937356	-2842.797482	-2707.426174	-2578.501118
scenario 2	-10613.12	-10107.73333	-9626.412698	-9168.012094	-8731.440089	-8315.657228	-7919.67355	-7542.546238	-7183.37737	-6841.311781	-6515.535029	-6205.271457	-5909.78234	-5628.364133	-5360.346793	-5105.092184	-4861.992556	-4630.469101	-4409.970573	-4199.971974	-3999.973308	-3809.498389	-3628.093704	-3455.327337	-3290.78794	-3134.083752
scenario 3	-12321.69	-11734.94286	-11176.13605	-10643.9391	-10137.08486	-9654.36653	-9194.634791	-8756.795039	-8339.804799	-7942.671237	-7564.448797	-7204.23695	-6861.178047	-6534.455283	-6223.290746	-5926.943567	-5644.708159	-5375.912533	-5119.916698	-4876.111141	-4643.915372	-4422.776545	-4212.168138	-4011.588703	-3820.560669	-3638.629209
scenario 4	-14205.85	-13529.38095	-12885.12472	-12271.54735	-11687.18795	-11130.65519	-10600.62399	-10095.83237	-9615.078451	-9157.217572	-8721.159593	-8305.866279	-7910.348837	-7533.665559	-7174.91958	-6833.256743	-6507.863565	-6197.9653	-5902.824095	-5621.737233	-5354.03546	-5099.081391	-4856.267991	-4625.017134	-4404.778223	-4195.026879
scenario 5	-30452.26	-29002.15238	-27621.09751	-26305.80715	-25053.14967	-23860.14254	-22723.94527	-21641.85264	-20611.28823	-19629.79831	-18695.04601	-17804.80573	-16956.95784	-16149.48365	-15380.46062	-14648.05774	-13950.53118	-13286.22017	-12653.54302	-12050.99335	-11477.13652	-10930.60621	-10410.10116	-9914.382053	-9442.268622	-8992.636782
scenario 6	-31414.78	-29918.8381	-28494.13152	-27137.26811	-25845.01725	-24614.30214	-23442.19252	-22325.89764	-21262.75965	-20250.24729	-19285.9498	-18367.57124	-17492.92499	-16659.92856	-15866.59863	-15111.04631	-14391.47268	-13706.16446	-13053.48996	-12431.8952	-11839.90019	-11276.09542	-10739.13849	-10227.75095	-9740.715187	-9276.871606
scenario 7	-32421.91	-30878.00952	-29407.62812	-28007.26487	-26673.58559	-25403.41485	-24193.72843	-23041.64612	-21944.42488	-20899.45227	-19904.24025	-18956.41929	-18053.73266	-17194.0311	-16375.26772	-15595.49306	-14852.85054	-14145.57194	-13471.97328	-12830.45074	-12219.47689	-11637.59704	-11083.42575	-10555.64358	-10052.99388	-9574.279887
scenario 8	-33242.48	-31659.50476	-30151.9093	-28716.10409	-27348.67056	-26046.35292	-24806.0504	-23624.8099	-22499.81896	-21428.39901	-20407.99905	-19436.18957	-18510.65674	-17629.19689	-16789.71133	-15990.20126	-15228.76311	-14503.58391	-13812.93706	-13155.17815	-12528.7411	-11932.13438	-11363.9375	-10822.79762	-10307.42631	-9816.596482

Operational cost savings for the second 25 years for a discount rate of 5% in a 75-year lifespan

26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
0.281240735	0.267848319	0.255093637	0.242946321	0.231377449	0.220359475	0.209866167	0.19987254	0.1903548	0.181290285	0.172657415	0.164435633	0.156605365	0.149147966	0.142045682	0.135281602	0.128839621	0.122704401	0.116861334	0.111296509	0.105996675	0.100949214	0.096142109	0.091563913	0.087203727
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-2455.71535	-2338.776524	-2227.406213	-2121.339251	-2020.323096	-1924.117234	-1832.492604	-1745.231051	-1662.124811	-1582.97601	-1507.5962	-1435.805905	-1367.434195	-1302.318281	-1240.303125	-1181.241071	-1124.991497	-1071.420473	-1020.40045	-971.8099528	-925.5332884	-881.4602747	-839.4859759	-799.5104532	-761.4385269
-2984.841669	-2842.706351	-2707.339382	-2578.418459	-2455.636628	-2338.70155	-2227.33481	-2121.271247	-2020.258331	-1924.055553	-1832.43386	-1745.175105	-1662.071529	-1582.925265	-1507.547872	-1435.759878	-1367.39036	-1302.276533	-1240.263365	-1181.203205	-1124.955433	-1071.386127	-1020.36774	-971.7787997	-925.5036188
-3465.361151	-3300.343954	-3143.184718	-2993.509255	-2850.961195	-2715.201138	-2585.905846	-2462.767472	-2345.492831	-2233.802696	-2127.431139	-2026.124894	-1929.642757	-1837.755006	-1750.242863	-1666.897965	-1587.521871	-1511.925592	-1439.929135	-1371.361081	-1306.058172	-1243.864926	-1184.633263	-1128.222155	-1074.497291
-3995.263695	-3805.013042	-3623.821945	-3451.258995	-3286.913329	-3130.393647	-2981.327283	-2839.359317	-2704.15173	-2575.3826	-2452.745334	-2335.947937	-2224.712321	-2118.773639	-2017.879656	-1921.790148	-1830.276332	-1743.120316	-1660.114587	-1581.061511	-1505.772868	-1434.069398	-1365.780379	-1300.743218	-1238.803065
-8564.415983	-8156.586651	-7768.177763	-7398.264536	-7045.966225	-6710.444023	-6390.89907	-6086.570543	-5796.73385	-5520.698905	-5257.808481	-5007.436649	-4768.987284	-4541.892652	-4325.612049	-4119.630523	-3923.457641	-3736.626325	-3558.691738	-3389.230227	-3227.838311	-3074.131725	-2927.7445	-2788.328095	-2655.550567
-8835.115816	-8414.396015	-8013.71049	-7632.105229	-7268.671646	-6922.544425	-6592.899453	-6278.95186	-5979.954152	-5695.19443	-5423.994696	-5165.709234	-4919.72308	-4685.450552	-4462.333859	-4249.841771	-4047.468353	-3854.731765	-3671.173109	-3496.355342	-3329.862231	-3171.297363	-3020.283203	-2876.460193	-2739.485898
-9118.361797	-8684.154092	-8270.622945	-7876.783757	-7501.698816	-7144.475063	-6804.261965	-6480.24949	-6171.666181	-5877.777316	-5597.883158	-5331.317293	-5077.445041	-4835.661944	-4605.392327	-4386.087931	-4177.226601	-3978.311048	-3788.867665	-3608.445395	-3436.614662	-3272.966345	-3117.110805	-2968.676957	-2827.311388
-9349.139507	-8903.942387	-8479.945131	-8076.13822	-7691.560209	-7325.295438	-6976.471845	-6644.2589	-6327.865619	-6026.538685	-5739.560652	-5466.24824	-5205.950705	-4958.048291	-4721.950753	-4497.095955	-4282.948529	-4078.998599	-3884.76057	-3699.771972	-3523.592354	-3355.802242	-3196.002135	-3043.811557	-2898.86815

Operational cost savings for the last 25 years for a discount rate of 5% in a 75-year lifespan

51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
0.083051169	0.079096351	0.075329858	0.071742722	0.068326402	0.065072764	0.061974061	0.059022915	0.0562123	0.053535524	0.050986213	0.048558298	0.046245998	0.044043808	0.041946484	0.039949032	0.038046697	0.03623495	0.034509476	0.032866168	0.031301112	0.029810583	0.028391031	0.027039077	0.025751502
operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost	operation cost
-690.6471899	-626.4373605	-568.1971523	-515.3715668	-467.4572034	-423.9974634	-384.5781981	-348.8237625	-316.3934353	-286.9781726	-260.2976623	-236.0976528	-214.1475309	-194.2381233	-176.1797037	-159.8001847	-144.9434782	-131.4680074	-119.2453582	-108.1590551	-98.10345132	-88.98272229	-80.70995219	-73.20630584	-66.4002774
-839.4590647	-761.4141176	-690.62505	-626.4172789	-568.1789378	-515.3550456	-467.4422182	-423.9838714	-384.5658698	-348.8125803	-316.3832928	-286.968973	-260.289318	-236.0900843	-214.140666	-194.2318966	-176.1740559	-159.795062	-144.9388318	-131.463793	-119.2415356	-108.1555879	-98.10030644	-88.97986979	-80.70736489
-974.6007171	-883.9915801	-801.8064219	-727.2620607	-659.6481276	-598.3202971	-542.6941471	-492.2395892	-446.4758178	-404.9667282	-367.3167603	-333.1671295	-302.1924077	-274.097422	-248.6144417	-225.5006274	-204.5357164	-185.5199242	-168.2720401	-152.6277008	-138.4378238	-125.5671871	-113.8931403	-103.3044356	-93.70016836
-1123.630898	-1019.166347	-924.4139204	-838.4706761	-760.51762	-689.8119002	-625.6797281	-567.5099575	-514.7482607	-466.8918465	-423.484668	-384.1130776	-348.4018844	-316.0107795	-286.6310925	-259.9828504	-235.8121092	-213.8885344	-194.0032058	-175.9666266	-159.6069175	-144.7681792	-131.309006	-119.1011393	-108.0282442
-2408.662646	-2184.728023	-1981.612719	-1797.381151	-1630.277688	-1478.709921	-1341.233489	-1216.538312	-1103.436111	-1000.84908	-907.7996189	-823.4010149	-746.8489931	-677.4140527	-614.4345149	-557.3102176	-505.496796	-458.5004952	-415.8734651	-377.2094921	-342.1401289	-310.3311827	-281.4795308	-255.310232	-231.5739066
-2484.794465	-2253.781828	-2044.246556	-1854.191888	-1681.806701	-1525.448255	-1383.626535	-1254.990054	-1138.312974	-1032.483423	-936.4929011	-849.4266676	-770.4550273	-698.8254216	-633.8552577	-574.9254038	-521.4742892	-472.9925525	-429.0181882	-389.1321435	-352.9543252	-320.1399775	-290.3763968	-263.3799518	-238.8933803
-2564.454773	-2326.036076	-2109.783288	-1913.635636	-1735.723933	-1574.352773	-1427.984375	-1295.223923	-1174.806279	-1065.583927	-966.5160334	-876.6585337	-795.1551326	-721.2291452	-654.1760954	-593.3570026	-538.1922926	-488.1562745	-442.7721311	-401.6073751	-364.269728	-330.4033814	-299.6856067	-271.8236796	-246.5520903
-2629.358866	-2384.906001	-2163.180046	-1962.068069	-1779.653577	-1614.198256	-1464.125402	-1328.0049	-1204.539592	-1092.552918	-990.9777033	-898.8459894	-815.279809	-739.4828199	-670.7327165	-608.374346	-551.8134658	-500.5110801	-453.9783039	-411.7717042	-373.4890741	-338.7656001	-307.2703856	-278.7032976	-252.7921067

LCC calculations for discount rate 0% and life span 50

sceanrios	investment	operation	replacment	EOL	Total
1	219901	-445317.72	0	6100	-219316.72
2	240020	-541269.12	0	6100	-295149.12
3	225901	-628406.19	6000	8100	-388405.19
4	246020	-724498.35	6000	8100	-464378.35
5	343901	-1553065.26	124000	11100	-1074064.26
6	364020	-1602153.78	124000	11100	-1103033.78
7	349901	-1653517.41	130000	13100	-1160516.41
8	370020	-1695366.48	130000	13100	-1182246.48

LCC calculations for discount rate 1% and life span 50

sceanrios	investment	operation	replacment	EOL	Total
1	219901	-350981.2434	0	6100	-124980.2434
2	240020	-426606.2189	0	6100	-180486.2189
3	225901	-495284.0994	6000	8100	-255283.0994
4	246020	-571020.0162	6000	8100	-310900.0162
5	343901	-1224062.622	124000	11100	-745061.622
6	364020	-1262752.189	124000	11100	-763632.1891
7	349901	-1303234.905	130000	13100	-810233.9049
8	370020	-1336218.633	130000	13100	-823098.6331

LCC calculations for discount rate 3% and life span 50

sceanrios	investment	operation	replacment	EOL	Total
1	219901	-233396.815	0	6100	-7395.814975
2	240020	-283686.193	0	6100	-37566.19298
3	225901	-329355.8659	6000	8100	-89354.86587
4	246020	-379719.018	6000	8100	-119599.018
5	343901	-813981.7233	124000	11100	-334980.7233
6	364020	-839709.6557	124000	11100	-340589.6557
7	349901	-866630.003	130000	13100	-373629.003
8	370020	-888563.6454	130000	13100	-375443.6454

LCC calculations for discount rate 5% and lifespan 25

sceanrios	investment	operation	replacment	EOL	Total
1	219901	-123064.3776	0	6100	102936.6224
2	240020	-149580.725	0	6100	96539.27505
3	225901	-173661.2158	0	8100	60339.78418
4	246020	-200216.4624	0	8100	53903.53759
5	343901	-429192.4644	0	11100	-74191.46435
6	364020	-442758.1679	0	11100	-67638.16787
7	349901	-456952.6023	0	13100	-93951.60227
8	370020	-468517.6704	0	13100	-85397.67036

LCC calculations for discount rate 5% and lifespan 75

sceanrios	investment	operation	replacment	EOL	Total
1	219901	-166186.4904	0	6100	59814.50957
2	240020	-201994.2423	0	6100	44125.7577
3	225901	-234512.6066	12000	8100	11488.3934
4	246020	-270372.8882	12000	8100	-4252.888173
5	343901	-579582.7414	248000	11100	23418.25855
6	364020	-597901.9066	248000	11100	25218.0934
7	349901	-617070.1117	260000	13100	5930.888266
8	370020	-632687.613	260000	13100	10432.38697