Life cycle assessment and structural analysis of renovation of Ulriksberg school building in Växjö

Authors: Amir Ahaki Lakeh & Milad Tahmasbi
Supervisor LNU: Ambrose Dodoo & Adel Younis
Examiner LNU: Björn Johannesson
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Linnaeus University, Faculty of Technology
Department of Building Technology
Abstract

Massive volumes of hazardous emissions have been produced by the construction sector for which some adequate steps are implemented, but the rising trend of emissions can still be seen. In this thesis, the goal is to identify and analyze renovation measures from primary energy use and environmental impacts perspective, according to Boverket’s mandatory provisions and general recommendations (BBR 2018), for an old school building. Also, as a part of the study goal, the building structure is analyzed under the updated Eurocode SS-EN 90-91-96 in order to see if the building meets structural stability requirements. Life cycle assessment of the building is limited to production and construction stages, and it is used as a tool to evaluate the environmental impacts according to standard SS-EN 15978:2011. Most of the relevant data are provided by VÖFAB, in cooperation with Växjö municipality, as well as the company WSP group.

The object of the thesis is an old three-story school building constructed in 1950 in Växjö, Sweden. The gross area of the building is 1,300 m² and for renovation scenarios, building envelope components are investigated by adding new insulation materials considering two life cycle stages. In the production phase, the lowest primary energy use was 137 kWh/m² for the scenario of using cellulose insulation material plus windows and exterior doors with a U-value of 1.1 [W/m²K]. The lowest environmental impacts were also obtained for this scenario, with 14 kg CO₂-eq/m² global warming potential (GWP), 0.06 kg SO₂-eq/m² acidification potential (AP), and 0.06 kg NOₓ-eq/m² eutrophication potential (EP). The results indicate that the share of the installation step in the primary energy use and environmental impacts during the construction phase is negligible, but the transportation role in this stage is significant. The highest global warming potential is for the scenario using cellulose insulation material plus windows and exterior doors with a U-value of 0.7 [W/m²K] with 4.4 kg CO₂-eq/m² in the construction stage. Ultimately, the material production stage accounts for the most share of primary energy use and environmental impacts.

This research provides several renovation measures investigated by life cycle assessment resulting in performing climate declarations. Regarding the sensitivity analysis, the electricity source has a considerable effect on reducing total primary energy consumption and environmental impacts during the production phase. It is also found that the scenario utilizing cellulose insulation material with windows with a U-value of 1.1 [W/m²K] shows the lowest total
primary energy use and environmental impacts. Through analyzing the building structure, all Eurocode criteria within the serviceability limit state (SLS) and ultimate limit state (ULS) are fulfilled, and the structure is still stable when new materials are added through renovation.

**Keywords:** Life cycle assessment, renovation measures, environmental impacts, primary energy use, insulation materials, structural analysis.
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We wish this thesis achievement would be useful and helpful for Växjö municipality as a reference for future renovations of school buildings and be followed to reach Sweden's goal of being a sustainable country.

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Amir Ahaki Lakeh

Milad Tahmasbi
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1 INTRODUCTION

1.1 Background and Problem Description

1.1.1 Background

1.1.1.1 Sustainable Development and Environmental Impact

These days, the concept known as “sustainability” in production and consumption is deemed as an ultimate objective. Notably, widespread consumption and manufacture of industrial items have significant adverse environmental consequences, which change the climate and deplete the ozone layer. Industrial products may now be consumed in large quantities since there has been a rapid growth in the technology of production processes. Previously, there was no concern about the negative environmental effects of manufacturing and developing products for which quality, function, design, cost, and safety were essential parameters. In contrast, there was no particular attention to the products’ environmental impacts during the whole life cycle. For products, different life cycle stages ranging from extracting raw material to the disposal phase, need to be considered to deal with the environmental impacts. Moreover, it is impossible to overcome environmental issues arising from the manufacture and product use without considering environmental consequences throughout the life cycle of products [1].

Many companies have recently realized the relevance of their products’ environmental implications and have begun to include environmental considerations in their design and development procedure of products. In other words, the identification of the product’s significant environmental concerns needs to be assessed for its entire life cycle. The significant difficulties encompass problematic actions, processes, and materials stemming from extracting raw material, transportation, production, distribution, use, and waste stages. As a result, technical tools for analyzing and assessing the impact of a product’s full life cycle are required [1]. According to research and studies, anthropogenic activities have a significant role in global warming caused by an increased level of greenhouse gas emissions in the atmosphere, which is observed to be the greatest in the last 800,000 years [2]. Climate change is considerably alarming, and according to the IPCC’s report (Intergovernmental Panel on Climate Change), global warming is accelerating at a rate that ecosystems cannot adjust to in time [3]. Regarding the Paris Agreement [4], a commitment has been established among the countries worldwide to reduce global warming to less than 2°C above pre-industrial levels and try to take strategies to keep
the rise to 1.5°C. In comparison to pre-industrial levels, there has been an increase in the average global temperature by around 1.1°C, and a growth rate of roughly 0.2°C rise each decade [3].

The World Green Building Council [5] has indicated that the construction sector produces approximately 39% of global greenhouse gases, of which 28% is related to heating and cooling supply and lighting, and 11% comes from the energy for materials production and construction across the building’s life cycle. Additionally, the analysis finds that reaching the Paris agreement’s climate goals requires a severe reduction of 30% in the construction sector’s energy per square meter until 2030, compared to 2015 [5]. The share of greenhouse gas emissions coming from building and construction operations in Sweden was about 11.1 million tons of CO₂ equivalents in 2015, contributing to over one-fifth of Sweden’s total greenhouse gas (GHG) emissions [6].

1.1.1.2 Previous Studies

Non-residential buildings include a wide range of structures, from basic retail outlets to more substantial complexes such as hospitals, and there are significant disparities within each category. For example, schools and education, offices, and bank building are included in the different groups. The estimation of climate effects from construction operations is nearly 2-3 million tons of CO₂/year for non-residential buildings in Sweden [7]. The average energy consumption in office buildings in Europe, excluding for electrical appliances, is about 232 kWh/m² year, with 69% for heating, 9% for cooling, 4% for domestic hot water, and 17% for lighting. Electricity is the preferred energy carrier in non-residential buildings; however, gas and oil are often used for heating [8]. Ascione et al. [9] researched retrofitting solutions for workplaces in 10 locations throughout Europe as part of office building renovation project and noted the possibility of significant purchased energy savings.

Martha et al. investigated the retrofit of an old existing school as a case study in Italy [10]. They assessed and monitored the energy consumption of different services and analyzed the occupancy of school zones. They used several measures, including external insulation of building envelopes (roof, exterior wall, ground floor, windows) and renovation of the heating system completely, ventilation system, and installation of a photovoltaic (PV) plant on the roof to reduce space heating energy and overall energy use. They concluded that using improved insulation materials in building envelope components and installing photovoltaic (PV) can help increase energy and economic saving. Another study is assessing energy performance and renovation measures for public school buildings in Rome, Italy [11]. In this study,
de Santoli et al. dealt with the interventions of renovation strategies and thermal envelopes of the existing school buildings to determine how much energy consumption can decrease, how much money can be saved by these measures, and the amount of CO$_2$ emission reduction. The consequence of this research was finding a proper type and quality of renovation packages and its payback time to consider a solution amid establishing a required standard for public schools in Italy. Durán et al. [12] evaluated the energy requirements of the heating system for a school building in Modena, Italy in which the heating system underwent a refurbishment. In this study, the building envelope was modeled by simulation software TRNSYS and energy requirements, and the building’s heating system was investigated for both the developed model and the dynamic one. By dealing with energy-saving obtained by alternative options, boilers and radiators, and new heat pumps, the effect of energy-saving strategies and thermal comfort in the building was sensitive to be reported.

Asdrubali et al. [13] assessed the energy consumption and carbon footprint of several renovation scenarios for a school building in Italy. They used the life cycle assessment approach to determine the building’s environmental effect over 50 years. Their results indicate that a cost-optimal scenario with an annual total specific building energy consumption of roughly 70 kWh/m$^2$ had a carbon payback period of around 3.2 years. Opher et al. [14] used the OneClick life cycle assessment program to perform a life cycle assessment to determine the embodied emissions involved with renovating an existing building. The findings indicated that the installation of renewable energy sources and the raised concrete floor accounted for 31% and 26% of the embodied CO$_2$-eq, respectively. Ylmén et al. [15] studied the embodied and operational carbon emissions from heating, ventilation, and air conditioning (HVAC) systems in a Swedish office building. They predicted that 38 kg CO$_2$-eq/m$^2$ was released during the manufacturing phase and 100 kg CO$_2$-eq/m$^2$ was emitted during the operating phase. Embodied energy related to three different heating, ventilation, and air conditioning (HVAC) systems in an Australian office building was investigated by Chen [16]. These heating, ventilation, and air conditioning (HVAC) installations included a variable air volume (VAV) system, a chilled beam system, and an underfloor air distribution system. Total embodied carbon emissions were calculated to be 21 kg CO$_2$-eq/m$^2$, 43 kg CO$_2$-eq/m$^2$, and 9 kg CO$_2$-eq/m$^2$, respectively. Moschetti et al., [17] studied several design alternatives for a zero-energy office building in Norway, intending to achieve a zero-emission building. The results indicated that it was difficult to achieve a complete zero life cycle emissions balance with materials based on renewable resources and photovoltaic panels. Therefore, materials’ embodied emissions should be prioritized. Pal et al. [18] suggested a life cycle assessment optimization technique for determining the
most carbon-efficient solutions in terms of both operational and embodied CO₂ emissions. The results revealed that the carbon optimum solution which is based on larger photovoltaic panels and thinner insulation for the building envelope represented 39% of the life cycle embodied carbon emissions. In contrast, the cost-optimal solution represented 28% of the life cycle embodied carbon emissions.

Sierra-Pérez et al. [19] assessed the suitability of each renovation choice in terms of the post-renovation energy performance of a commercial building in Spain using an integrated life cycle and thermal dynamic simulation. Their methodology included an assessment of the use of a renewable insulating material, namely a cork solution, in a low-energy building. The findings indicated that renovating a low-energy structure leads to an increase in the building's embodied effects, mostly due to the substantial quantity of insulating material used. Additionally, cork adoption did not meet the criteria for competing with commonly used non-renewable insulating materials since it did not result in improved environmental performance in buildings.

1.1.1.3 Renovation Importance

People’s contentment with the indoor climate determines their comfort in the buildings, so to provide a comfortable indoor climate; one has to supply energy for the building [20]. In buildings located in cold areas, much of the energy consumption is utilized to maintain the internal temperature comfortable. In the cold region, the space heating requirement often accounts for 60% to 80% of the overall energy demand of cold areas [21]. It is well recognized that the energy should be consumed effectively; however, roughly 75% of the existing building in Europe have ineffective energy use compared to current building requirements and the basic need for raising the efficiency of building stock is a significant task [22]. Notably, promoting decarbonization of the existing building stock can be obtained by substantial renovation, which enhances the energy performance according to the European Energy Performance of Buildings Directive (EPBD) [23].

In Sweden, there are also similar problems to the European countries about handling old buildings stock in terms of climate change effects reduction. However, Sweden’s national goals are to attain net-zero greenhouse gas emissions by 2050 and a 50% reduced energy consumption in the construction industry by 2050 in comparison with 1995 [24]. According to the IPCC report [25] (Intergovernmental Panel on Climate Change), CO₂ emissions coming from building energy consumption may be decreased by 29% without cost. To mitigate the negative effects of climate change, emission reduction is required for the environment and living organisms. Sweden consumes 80 TWh of energy for heating and hot water use in residential and
non/residential buildings [26]. In addition, this demand plays a considerable role in the rise of greenhouse gas emissions. According to reports, Sweden’s current building stock grows by around 1% per year. IPCC [25] indicated that 27% of total CO₂ emission is from the existing building stock, while a newly constructed house emits 0.86 tons of carbon dioxide each year. On the other hand, an old building generates an average of 1.60 tons of CO₂ yearly. As the building industry is a large source of greenhouse gas (GHG) emissions, emission reductions via energy-efficient techniques are essential [27]. Nowadays, the trend toward implementing stringent energy objectives in building design and using energy efficiency criteria are placed at the center of attention [28].

Existing building renovation is preferable to destruction since it reduces energy consumption and negative environmental effects [29]. Additionally, retrofitting has a greater potential for reducing greenhouse gas (GHG) emissions than demolition and new construction, which both raise the CO₂ emission [30]. Therefore, upgrading the current building stock through a renovation can help carbon reduction and reduce potential waste generated during demolition [31]. Because residents in colder climates spend the majority of their time indoors, it is essential to assure their thermal comfort. Therefore, any renovation measures must take into account inhabitants’ welfare concerns [32]. In the United Kingdom, the English Heritage Group works to preserve and restore old buildings as well as to optimize the environmental performance of the building refurbishment. They have reported that residents complain about low thermal comfort in some repaired buildings [30]. It demonstrates how energy-efficient solutions are closely linked to the indoor thermal environment, affected by the occupants ‘behavioral patterns in terms of thermal demands and expectations [33].

1.1.1.4 Net Zero Energy Balance

A Net Zero Energy Building (NZEB) uses the application of renewable energy to generate energy as much as it consumes annually [34]. A NZEB runs with reduced energy requirements resulted in increasingly efficient thermal envelopes, heating, ventilation, and air conditioning (HVAC) systems, and other measures, enabling renewable energy to be generated on-site [35]. Moreover, photovoltaic (PV), solar hot water, wind, hydropower, and biofuels are among the most common renewable energy generation technologies, with roof-top photovoltaic (PV) and solar water heating being the most applicable supply-side technology for the NZEB. In contrast to off-site energy generation, on-site energy production is desirable and in certain cases mandated by some national standards. On-site energy generation is encouraged and in certain cases, required, over off-site energy production. This is primarily to
provide a proper ground for a decrease in building energy consumption before the implementation of the production facility [35]. However, there is no precise explanation of the NZEB. The definition may be influenced by the project’s objective and different owners of buildings. Furthermore, the cost may be a limiting issue for a private owner, while a Net Zero Energy Cost option may be preferred. Depending on other circumstances, the environment may be the most important consideration, for which Net Zero Energy Emissions could be desirable [35].

After reviewing the above-mentioned studies, one can realize that old buildings may need to be renovated after many years. Building materials are worn out due to their limited lifespan and external factors such as moisture. In addition, as the building standard (Eurocodes) [36], [37], [38], and [39] is updated, the need for checking and fulfilling the criteria of the new code for the structure of the old buildings should be considered. Ultimately, by appropriate refurbishment strategies using renewable and sustainable energy resources and investigating building structure through updated Eurocode, we can increase energy performance and carbon reduction of the building and evaluate the structure’s stability, respectively.

1.1.2 Problem Description

These days, there are numerous old school buildings worldwide in which building envelope components are poor in terms of material and energy losses. This means that deficiencies in materials can increase the energy consumption in a building, and maintenance costs, and may extend to health-related issues through surface mold in the internal areas such as walls and ceilings. Moreover, old school buildings’ structures were designed by old standard and codes which are updated after some years. Additionally, adding new materials to the elements of school building increase the dead loads of the structures. Therefore, the need for renovation of a building and structural stability check are important. Using environmentally friendly materials for building and the structural system was not a priority in the past. Most of the building materials were made of non-renewable resources having adverse effects on the environment. As most of the building’s materials are worn out after several years, they need to be replaced by new ones which preferably fulfills environmentally friendly aspect to reduce energy consumption and environmental impacts. For addressing these issues, renovation strategies can be taken in the form of a life cycle assessment for building materials to help save building heating energy and energy cost in the operation stage.
1.2 **Aim and Purpose**

This thesis aims to investigate primary energy use, environmental impacts, and structural stability of a case study retrofitting of an old school building, based on a life cycle assessment and considering structural analysis aspect.

This thesis work can help identify how much primary energy could be saved through new sustainable insulation material and how much carbon emissions decrease regarding the environmental impact of the building materials under production and construction stages. Also, the role of sustainable material in saving heating energy help to figure out the cost-benefit of electricity savings. The school building’s structural components are investigated by the updated Eurocode when new materials loads are added to different parts of the building. The results can show how much adding new materials as new permanent loads affect the structural stability, as well as the behavior of the structure under environmental loads (wind and snow).

1.3 **Scope and Limitations**

The school has four different buildings, and the study is limited to building number 1 because the other buildings have already been demolished to be rebuilt. The main school building which is number 1 is considered for investigation shown in Figure 1. The life cycle analysis of the building is performed according to EN 15978 [40], and we consider the consequential method for life cycle assessment modeling. This means that we estimate the effects of production and product use on global environmental burdens. Different environmental impacts are considered only for global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The concrete building material and masonry brick are not changed as the purpose is the renovation of the building aspect of cost efficiency and heating energy saving. Given the focus of the study, all structural building materials and insulation components are solely considered for life cycle analysis. Changing insulation material for exterior and interior walls is not practical because they are load-bearing elements. However, there is an alternative to add insulation to them internally.

Some data for input calculation such as materials properties, as well as architectural and structural shop drawings, are not available for the basement and other floors. Regarding the Ulriksberg school building, the actual plan and all data are provided by VÖFAB and WSP group and visiting the school. Regarding the investigation boundary, the study is limited to the phases of material production and construction in the life cycle analysis. The Heating and ventilation standard values are not
accessible for the building. Still, existing energy declarations are beneficial to compensate for some missing data but not entirely.

Figure 1: The school buildings’ location plan [41].
2 LITERATURE REVIEW

Research was conducted in Cyprus [10] on the energy consumption of the school buildings to identify prevalent building approaches in the construction of schools in Cyprus’s three climate zone such as inland, coastal, and mountains. In this research, the energy consumption of schools was compared to their construction features. Different scenarios were employed for assessing the energy consumption regarding the construction details. The strategies were related to using insulation materials on building envelopes, removing air-condition split units, installation of photovoltaic (PV) on the roof. After evaluating the construction features of the school buildings and their energy performance, they found that there is a direct relationship between the selection of the appropriate construction elements and design scenarios, which is important for consideration of the renovation and construction stage. The study indicated that the insulation of building envelope components plays a significant role in cooling and heating space. Regarding the construction shape, a horizontal roof was more efficient rather than a sloping one because of easy insulation at less cost. Also, they concluded that the school building built in a single story has less energy demands than a multi-story counterpart, and the rectangular shape of a building is the most energy-efficient.

Another paper by de Santoli et al. [11] indicated that a case study was considered for 1300 structures in Rome. These structures were made of concrete and brick and were considered for analysis of emission factors for renovation based on the energy consumption of the buildings. The energy label of the different schools considered for different scenarios as the reference of consumption of energy was the thermal plant. Also, the emissions were assumed for 20 years. The conclusion of the study showed that the emission reduction needs to consider different factors such as lifestyle behavior to recognize how much energy is consumed. Moreover, the results showed the beneficial cost of renovation for the government and how long it takes for backing expenses [11].

Mora and Righi [42] studied cost-optimal measures for the retrofit of the existing school buildings toward the Near Zero Energy Building in Italy. The method compared various energy retrofitting measures for the interface on the building envelope and system of heating. In this case, cost and energy management were a matter of comparing to find a solution to reach optimum total cost [43]. Regarding establishing a set of 10 energy efficiency measures with the combination of interventions, each component including the external wall, roof, basement, and windows was analyzed in terms of surface percentage incidence and heat losses.
The findings for the two schools’ (Manzoni & Girardini) probable renovation gave a chance to analyze various elements of conversion to Near Zero Energy Building (NZEB). Regarding the scenarios used in this research, the optimum intervention to convert the building into the NZEB had the same configuration. This was due to the high value of incentives, stemming from the high investment cost. Also, the NZEB performance was achievable since the renovation incorporated all technological aspects into the envelope, resulting in cost-effective energy savings. The outcome showed that the Girardini school had the optimum measure for the transition in the NZEB, including interventions on each element, lighting system substitution, and photovoltaic system implementation compared to the Manzoni school.

There was an article related to building renovation in six European countries (Denmark, Austria, Sweden, Czech Republic, Portugal, and Spain). This study was conducted by Almeida et al. [44] for two different functions of the buildings, which were multi-family buildings and school buildings in the case of the Czech Republic. This was about the relevance of embodied energy and carbon emissions for evaluating cost-effectiveness in the building renovation. There was also an aim to assess the environmental performance in the calculation of optimal cost in building rehabilitation initiatives to find changes in results. In this study, the method compared some renovation cases with a reference scenario, known as “anyway renovation”. “Anyway renovation” referred to a retrofit that does not increase the building’s energy efficiency and instead focuses on aesthetic, functional, and structural concerns. The energy use connected with each of the refurbishment packages, and also carbon emissions and global costs must be calculated to compare renovation packages. Regarding the method of energy calculation, this should be utilized in compliance with local thermal standards due based on the variety of climate conditions and construction characteristics where it may be employed.

Regarding the result of the study, the evaluation of embodied energy and carbon emissions did not affect the cost-effectiveness strategies or the renovation packages ranking for the evaluated indicators (carbon emissions, non-renewable primary energy (NRPE), and total primary energy (TPE)). However, when the embodied values were included, there was a significant increase in the indicators. In this respect, integrating embodied energy and carbon emissions in the calculations decreased the possible reduction in the case studies of Austria, Spain, and Portugal when all refurbishment packages were cost-effective. Regarding the school case in the Czech Republic, most of the solutions were cost-effective for all scenarios, and the intervention of embodied energy and carbon emissions in the calculations has a decreasing impact of roughly 5 to 12%. The analyzed indicators (carbon emissions, the NRPE, and TPE) did not influence the results gained without taking into account
the embodied values of renovation packages’ cost efficiency. However, if the embodied energy and carbon emissions were taken into consideration in the calculations, a considerable drop in carbon emissions, the NRPE, and TPE is seen. Additionally, results indicated that when a high proportion of renewable energy is suggested, the embodied factor grows and becomes more evident [44].

There was research conducted in 2019, which was related to the payback time of energy and environment for Net Zero Energy Building retrofit. In this paper, Asdrubali et al. [13] used the method of “cradle to grave” applied to deal with the renovation interventions of a school building in Italy. This assessed the balance between the effects caused by the addition of extra materials, plants, and systems and the resulting decrease in the building’s energy consumption. The modeling of the building was done in simulation software with the technical specification of the Italian standard. In this paper, for several retrofit scenarios, the embodied energy and embodied carbon of the renovating intervention were computed, and the entire building was chosen as a functional unit. The investigated building age was considered 80 years ago with great structure and functional condition. Regarding the assessment of the environmental efficiency of renovation scenarios, two factors were considered: the energy and carbon payback time [13].

This research investigated four retrofit scenarios as a cost-effective solution and system efficiency in the form of renovation interventions that enable the building to comply with the national limit for U-values. The other two retrofit scenarios should meet the NZEB standard, as established by Italian law. The findings indicated that the most cost-effective approach also had the shortest environmental payback time. When a greater level of energy efficiency was required, a reduction in environmental effect may be achieved. The NZEB renovations related to European regulations had longer payback periods than the most cost-effective approach. Regarding the payback time of single interventions, those associated with the lighting and generating system had shorter payback time, hence they must be selected in a short time frame. As the envelope interventions had long payback periods, they were considered less favorable. On the other hand, the interventions including the installation of renewable energy systems indicated a remarkable performance both economically and environmentally, with shorter payback times [13].

Ruggeri et al. [45] investigated the energy retrofit of the material in a different key to figure out a way to save and optimize energy use to produce material. They considered some factors in managing energy consumption to save and recover energy. Research findings and review schemes, building energy modeling assessment, energy retrofit design, decision-making criteria assessment, optimal
allocation of resources, and risk valuation were the methods that they used. These methods investigated the items of demand, supply side, and energy-consuming pattern, compared and ranked energy retrofit to review different aspects of the building based on energy retrofit. This analysis raised the validation percentage of the design, and the estimation techniques for demand gave the strategy for optimization [45].

Regarding the case of an office building in Norway [46], the authors investigated an office building with a concrete structure for two different buildings which were built in 1965 and 2015, respectively. They analyzed the buildings for retrofitting, and they considered an energy simulation method using the building model and optimization scenarios. Also, they conducted various retrofit scenarios in different stages of the buildings to assess the life cycle of both buildings. There were four different scenarios for which the first and second were based on the Norwegian passive house standard for non-residential buildings. The difference between the two scenarios was the type of ventilation system. The two other scenarios were assumed to be optimized models to fulfill the minimum life cycle cost requirement with the consideration of not exceeding the allowable limit of the Norwegian passive house standard for the building energy use of space heating and cooling. Based on their assumptions for calculating the carbon emission for retrofitting, the authors concluded that the total net emissions could be decreased up to 52% from 1,336 to 637 kg CO$_2$-eq/m$^2$. They also figured out the operation energy use decreased in the total CO$_2$-eq emission for which the reference case was 77% while the retrofitting case was 43-46%. Retrofitting had a big range of CO$_2$-eq emissions in the production stage, transport to the construction site, and end-of-life stage and these were 19-23%, 24-31%, and 25%, respectively [46].

An investigation done by Liébana-Durán et al. [47] analyzed 46 school buildings in Spain in 2021 for three different scenarios. The investigation focused on the economical and emission factors of buildings after renovation considering net-zero energy buildings. Three types of a building made of brick and concrete walls for different scenarios were dealt with. A set of 21 renovation strategies were considered to improve thermal envelopes and reach cost and energy savings. The outcome of the different case studies showed that the renovation measures that take the buildings closer to Net Zero Energy Balance entail achieving the most restrictive thermal transmittance values in all thermal envelope components. Also, the cost-optimal measures in 46 analyzed schools resulted in saving money annually (€378,000) and decreasing emissions (720,200 kg CO$_2$) [47].
2.1 Gaps in Previous Studies

Regarding the reviewed previous studies, there are most non-residential buildings and few residential cases considered for renovation scenarios in terms of cost-effectiveness, Net Zero Energy Building, type of primary energy resource, and carbon emissions. The matters of economic, environmental impacts and energy use are the main focus of renovation packages in the conducted studies. However, there were some activities and assumptions such as using sustainable insulation materials and the effect of adding new materials loads on structural analysis disregarded for different scenarios of renovations because there may be a geographical and economic limitations in which different regulations of life cycle assessment and life cycle cost were used. Although in the reviewed previous studies the cost-effectiveness and type of primary energy parts were dealt with, the type of insulation material in terms of their production and environmental impact and electricity scenario, which means that different energy resources for supplying electricity were not significantly investigated or not considered. Furthermore, sustainability in terms of primary energy, environmental impact, and cost of insulation materials is another important factor that needs to be considered in the production stage. The above-mentioned are part of the gap in the previous studies conducted.
3 THEORY

All important theories are covered in this chapter. Different concepts and definitions are covered in the first part.

3.1 Concepts and Definitions

**BBR requirement:** This is the Swedish National Board of Housing, Building, and Planning’s building regulations.

**BBR 29:** This is an energy requirement with a maximum of 75 kWh annual energy consumption per m².

**Climate declaration (Environmental declaration):** This is a document representing a building’s environmental impact from a life cycle perspective.

**CO₂-equ (equivalent):** This is a unit describing the global warming potential and encompasses all greenhouse gases.

**Background data:** Generic data provides average data for the considered case study, and it points out today’s values based on various observations. Some data for energy and materials are used from the VÖFAB report cooperating with the Växjö municipality.

**Environmental Product Declaration (EPD):** This is a document showing the effect of the product’s climate declaration across its whole life cycle.

**Greenhouse gas (GHG):** It is related to several gas molecules that lead to global warming.

**Global warming potential (GWP):** It is related to heat which is absorbed by any greenhouse gas in the atmosphere by the equal mass of carbon dioxide.

**High-performance building envelope:** It refers to the building utilizing the improved insulation materials in its envelopes compared to the BBR (2018) requirement.

**Swedish average electricity:** It reflects the electricity in Sweden coming from renewable primary energy sources such as hydro and nuclear.

**Marginal coal-based electricity:** Producers and consumers are evenly distributed throughout electrical grid networks. In reality, the electrical grid operator must maintain a close bond between power generation capacity and power consumption. As consumer behavior varies over time, manufacturers must adjust their power...
capacity regularly. In this case, some factors including the flexibility of power generation technologies, the operation costs of power plants, electrical grid limits, and the electrical grid operator schedules have a direct effect on adapting power generation. Thus, a marginal source of electricity is defined as a power plant that adjusts its power generating capacity to cover new changes in power demand. The power produced by all marginal sources is referred to as marginal electricity [48].

**U-value:** This is the heat transmission coefficient for which the lower value shows the insulation is more effective.

**Primary energy value:** The building energy performance is measured by this value.

**Anthropogenic activities:** The processes, materials, and impacts stem from human activities which are contradictory to activities happening in natural environments without human effects.

**Photovoltaic panels:** It includes different kinds of cell panels and solar electric panels utilizing sunlight directly as a source of energy for electricity production, assembled in a framework for installation.

**IPCC:** The report to provide policymakers stemming from regular scientific assessments of climate change, the relevant potential future risks, and effects through which IPCC determines the thorough knowledge on climate change.

### 3.1.1 Building Envelope

A physical barrier separates a structure’s indoor and outdoor spaces [49]. Generally, the building envelope is composed of several parts and systems as shown in Figure 2. The building envelope’s role is to protect the inner space from environmental impacts such as wind, humidity, temperature, etc. The inside environment consists of the inhabitants, furniture, construction materials, lighting, and equipment such as machinery, television, and ventilation systems [50]. Regarding the definition of a building envelope, there is an area including low thermal resistance which provides an aground for transferring heat easily. The example of the building envelopes are doors, exterior and interior walls, and windows. There is also a concept of thermal bridge describing parts of the building envelope with the least thermal resistance. Regarding the BBR (2018) standard, the maximum average coefficient of heat transfer that comes from the building envelope components for cold climate regions must not exceed 0.6 [W/m² K] [6]. These days, thanks to technology, there are developed insulation materials used in building envelopes by which the energy efficiency of buildings is increased. In other words, these materials with high thermal insulation which are used in external doors, windows, and exterior and interior walls,
roofs, and foundations, can reduce heat transmittance, especially in exterior elements.

Figure 2: The components of the building envelope [51].

3.1.2 Thermal Bridge Effects

As thermal bridges have several undesirable implications such as increased energy use for both cooling and heating space, inconvenient spaces coming from cold inner surfaces, and poor fulfillment of energy standards, these result in mold and dampness growth coming from condensation on the cold surfaces. Indeed, this can also cause health issues by the poor quality of indoor air. Another demerit of the thermal bridge is causing low-temperature areas on walls and ceiling elements whereby the wall staining appears, called "ghosting" [52]. Furthermore, when the thermal bridge impacts are neglected in buildings, thermal loads are increased up to 35% beyond the earlier estimation [53], so the thermal resistance of building elements decreases gradually. For instance, taking into account the assembly and fixing of building envelopes with insulation materials, minimizing thermal resistance up to 50% [54].

3.1.2.1 Constructional Thermal Bridges

In this part, the penetration of heat is shown from the thermal bridge of the interior to the exterior wall of the building according to Figure 3. In addition, in the layers of insulation gap and discontinuity emerge by thermal bridge effects.

Figure 3: Thermal bridge of construction [55].
3.1.2.2  Geometrical Thermal Bridges

Regarding this case of thermal bridge, it can be seen in the corner, edges of building envelopes premier, see Figure 4. The thermal bridge can be seen at the corner point between the wall connected to other structural elements such as the exterior wall, roof, and floor [55].

![Figure 4: Geometrical thermal bridge [55].](image)

3.1.2.3  Linear Thermal Bridge

In this case, we can calculate the thermal transmittance by using heat flow coming across the thermal bridge of the building assembly. Moreover, there is a difference between the point thermal resistance and the linear one. It is not necessary to know the effective length of thermal bridges to compute the point of thermal transferring. In the building envelope, for example, floor supports are taken into consideration as point thermal bridges while their impact is considered the point thermal transmittance [55].

To calculate the heat transfer, it needs to have data about the linear and point thermal transfer of the thermal bridge, therefore Equation 1 is defined.

\[ Q_0 = U_0 + A_0(T_{in} - T_{out}) \]  \hspace{1cm} (Eq 1)

\[ U_0 = 1/R_0 \]

\[ R_0 = 1/h_{in} + x_n/k_n + 1/h_{out} \]

\[ L_{3D} = Q_t/\Delta T \]

\[ \psi = L_{3D} - U_0A_0/l \]

\[ \chi = (L_{3D} - U_0A_0) \]

\[ Q_t = Q_0 + Q_{tb} \]
\[ Q_{tb} = \sum_{i=1}^{l} \psi_i \cdot l_i + \sum_{i=1}^{j} n_i \cdot \chi_i \]

\[ Q_t = \left( U_0 \cdot A_0 + \sum_{i=1}^{l} \psi_i \cdot l_i + \sum_{i=1}^{j} n_i \cdot \chi_i \right) \cdot (T_{in} - T_{out}) \]

where:

- \( Q_0 \) heat transferring through clear wall [W],
- \( U_0 \) thermal transmittance coefficient of the clear wall [W/m² K],
- \( A_0 \) the area of clear wall surface [m²],
- \( T_{in}, T_{out} \) the temperature of indoor and outdoor [K],
- \( R_0 \) thermal resistance of clear wall [m² K/W],
- \( h_{in}/h_{out} \) the coefficient of indoor and outdoor convection heat transfer [W/m² K],
- \( k_n \) the coefficient of the conduction heat transfer for \( n \) assembly materials [W/m K],
- \( x_n \) the thickness of \( n \) clear wall layers,
- \( \chi \) the point thermal transmission coefficient [W/K],
- \( L_{3D} \) the coefficient of thermal coupling from 3D calculation [W/K],
- \( Q_{tb} \) heat through the assembly through the thermal bridge,
- \( Q_t \) the total heat transferring from assembly [W],
- \( l \) the effective length of the thermal bridge [m], and
- \( n \) the number of point thermal bridges in the assembly.

Regarding thermal bridges, three types are common in buildings [56], categorized as following below.

- Intersection of a wall to floor.
- The intersection of a wall to slab rest on the grade floor.
- Intersection of a wall to roof.
3.1.2.4  Connection of Wall to Roof

The design and the position of building envelope components are important. Figure 5 shows the interaction between the slab and the wall, so the insulation layer should be considered in the area of interaction and both the interior corner of the roof [57].

![Figure 5: interaction between wall and roof [55].](image)

3.1.2.5  The Perimeter of Windows

One of the building envelope components, windows, are mostly exposed to the thermal bridge. It can be seen that some window frames are not the same level as their window meaning that the frame is shifted out architecturally. Moreover, this can cause a gap between the layer of insulations and the penetration point around the window and wall, where the heat transmittance is easily done, (see Figure 6). To solve this issue, different kinds of insulation coat around the windows can be used to prevent heat loss significantly [58].

![Figure 6: Intersection of the perimeter of windows and wall [55].](image)
3.1.3 Indoor Temperature

Indoor climate has a significant impact on the health and welfare of people who spend most of their own time in their homes, schools, and offices as well as the effect on building energy consumption. Although the efficiency of building energy is an essential matter, the interior temperature should be considered a priority as much as the energy efficiency [59]. Four factors include a direct and indirect impact on the thermal comfort of dwellers. These include relative humidity, air velocity, air, and radiant temperature, among which the temperature plays a key role in living comfort [60]. Recent studies have emphasized the importance of indoor temperature to provide useful data for having a better understanding of occupants’ patterns and preferences [61]. Regarding the BBR (2018) [6], the average interior temperatures in school and office buildings were between 20 and 24°C in winter and between 23 and 26°C during summer.

3.1.4 Economic Calculation

Building improvements made to save energy are mainly driven by the project’s perspective of economic advantages. Nevertheless, some key factors can be considered for an energy retrofit, including improved indoor temperature through improved windows, different insulation layers of building envelope components and reducing primary energy use through utilizing renewable resources for material production. Jakob and Nutter [62] studied that quantifying the parameters above-mentioned used in the economic stage may be difficult, but it is included in that study. The building efficiency is increased by these types of improvement, which can be often seen in new buildings, and it can be the most effective for use in buildings renovation [62]. The high retrofit package depending on the sustainable source type of materials may have a higher life cycle cost and energy-saving [63].

3.1.5 Ventilation System

According to the Swedish building code BBR (2018) [6], ventilation systems must be constructed in such a way that the needed amount of external air can be provided to the building. Additionally, the ventilation system must be able to remove harmful toxins, dampness, undesirable odours, wastewater from people and building materials, and other pollutants generated by building operations. The ventilation system is an important factor in the health aspect of a building for air condition. Also, it plays an important role in recovering heating and energy consumption. Regarding a mechanical supply and exhaust air system, two kinds of fans are used in the system. One of which pushes airflow into the building and another suction
out exhaust air-called mechanical supply and exhaust air system. When a system includes heat recovery and heat exchangers, it is called an energy recovery system [6].

3.1.6 Heating System

Some studies show that 27% of the energy consumed for heating is accounted for by non-residential buildings in Sweden. It means that heating plays a significant role in the consumption of energy. Opportunities to improve energy efficiency via system changes should constantly be examined. When necessary, control and monitoring systems should be expanded to guarantee that heat output regulation can be tailored to specific applications and any extra heat [5]. The area of the climate shell which includes the exterior wall, roof, and windows is considered in the heat space calculation. The heat transfer coefficient (U-value) of each material has a key role in the calculation of both heating energy and building energy [6]. Equation 2 shows building energy use.

\[ E_{bea} = E_{uppv} + E_{kyl} + E_{tvv} + E_f \]  

(Eq 2)

where:

- \( E_{bea} \) building energy use (purchased energy) [kWh/year],
- \( E_{uppv} \) energy for space heating [kWh/year],
- \( E_{kyl} \) energy for air conditioning [kWh/year],
- \( E_{tvv} \) energy for hot tap water [kWh/year], and
- \( E_f \) property energy [kWh/year].

The value that expresses the energy performance of a building is called a primary energy number. The primary energy number is calculated by multiplying the building’s energy consumption by a geographical adjustment factor (\( F_{geo} \)), multiplying by a primary energy factor for energy carriers, and distributing the result on \( A_{temp} \) [m²]. The primary energy number (\( EP_{pet} \) [kWh/m²] \( A_{temp} \) per year) is determined based on the following Equation 3 [6].

\[ EP_{pet} = \frac{\sum_{i=1}^{6} \frac{E_{uppv,i}}{F_{geo,i}} + E_{kyl,i} + E_{tvv,i} + E_{f,i} \cdot PE_i}{A_{temp}} \]  

(Eq 3)

where:
the area covered by the inside of the building envelope on all stories, basements and attics is meant to be heated to a temperature greater 10°C for temperature-controlled spaces,

$PE_i$ primary energy factor per energy carrier, and

$F_{geo}$ geographical adjustment factor.

3.1.6.1 Average Heat Transfer Coefficient ($U_m$)

Regarding SS-EN ISO 13789:2007 and SS-EN 24230 [6], the average heat transmission coefficient for building components and thermal bridges [W/m² K] is calculated using Equation 4.

$$U_m = \left( \sum_{i=1}^{n} U_i \cdot A_i + \sum_{k=1}^{m} l_k \cdot \psi_k + \sum_{j=1}^{p} \chi_j \right) / A_{om}$$ (Eq 4)

where:

$U_m$ transfer coefficient for building component [W/m² K],

$A_i$ the surface area of a building component next to heated areas of houses or premises [m²],

$\psi_k$ the heat conductivity for linear bridge $k$ [W/m K],

$l_k$ the length of the linear thermal bridge $k$ [m],

$\chi_j$ heat transfer coefficient for the point thermal bridge $j$ [W/K], and

$A_{om}$ the total surface area of enclosed construction components exposed to heated areas of building or premises. Enclosed building elements are those that extend from heated areas of dwellings or premises to the outside, to the ground or partly heated spaces [m²].

3.1.7 Different Environmental Impacts

The different environmental impacts are categorized for estimating the toxin gases measured for environmental quality [64]. These are global warming potential, acidification potential, and eutrophication potential.
3.1.7.1 Global Warming Potential

Due to an increase in the number of vehicles, population, and building construction materials, the gasses which emit from this process affect the warming of the earth. Carbon emission (CO₂), methane (CH₄), and nitrous oxide (NOₓ) are the gas emissions that have adverse impacts on global warming with an equal unit value of kg CO₂-eq/m² [24]. Table 1 indicates the characterization factor for global warming potential for 100 years and Equation 5 shows the global warming potential [65].

\[ GW_{P\text{total}} = \sum_{i}(m_{i} \cdot GW_{P_{i}}) \]  
(Eq 5)

where:
- \( GW_{P\text{total}} \) global warming potential in kg CO₂-eq of full inventory of GHGs,
- \( m_{i} \) mass (in kg) of inventory flow ‘i’, individual GHG, and
- \( GW_{P_{i}} \) global warming potential of ‘i’, individual GHG.

<table>
<thead>
<tr>
<th>Inventory Flows</th>
<th>Characterization Factor for 100 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>28</td>
</tr>
<tr>
<td>Nitrous oxide (NOₓ)</td>
<td>265</td>
</tr>
</tbody>
</table>

Table 1: Characteristics factor of global warming potential for 100 years [66].

3.1.7.2 Acidification Potential

The gases which contribute to acidification are sulfur dioxide (SO₂), ammonia (NH₄), and nitrogen oxides (NOₓ) with an equal unit value of kg SO₂-eq/m². Acidification causes acidified water in its process which is harmful to humans [66]. The main cause of acidification comes from electricity production, industry, and traffic jam, which affect the pollution of water underneath. The characterization factors in acidification for 100 years are seen in Table 2. Equation 6 shows the acidification potential formula in kg SO₂-eq/m² [66].

\[ AP_{\text{total}} = \sum_{i}(m_{i} \cdot AP_{i}) \]  
(Eq 6)
where:

\[ AP_{total} \] acidification potential in kg SO\(_2\)-eq,

\[ m_i \] mass (in kg) of inventory flow ‘\( i \)’, individual substances, and

\[ AP_i \] kg of sulfur oxide with the same acidification potential as one kg of inventory flow ‘\( i \)’.

<table>
<thead>
<tr>
<th>Inventory Flows</th>
<th>Characterization Factor for 100 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur acid (SO(_2))</td>
<td>1.2</td>
</tr>
<tr>
<td>Nitrous oxide (NO(_x))</td>
<td>0.7</td>
</tr>
<tr>
<td>Ammonia (NH(_4))</td>
<td>1.6</td>
</tr>
</tbody>
</table>

3.1.7.3 Eutrophication Potential

The main reason for eutrophication is excessive nutrients. Increased nutrient levels have detrimental effects on human health and biodiversity. Additionally, it may affect both land, and water. The unit value is kg NO\(_3\)-eq which can be seen in Equation 7 [63] and [66].

\[ EP_{total} = \sum_i (m_i \cdot EP_i) \]  \hspace{1cm} (Eq 7)

where:

\[ EP_{total} \] eutrophication potential in kg NO\(_3\)-eq,

\[ m_i \] mass (in kg) of inventory flow ‘\( i \)’, individual substances, and

\[ AP_i \] kg of nitrogen with the same eutrophication potential as one kg of inventory flow ‘\( i \)’.

Table 3 indicates the characterization factor of eutrophication potential.
Table 3: Characteristics factor of eutrophication potential for 100 years [66].

<table>
<thead>
<tr>
<th>Inventory Flows</th>
<th>Characterization Factor for 100 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrous oxide (NO\textsubscript{x})</td>
<td>1.4</td>
</tr>
<tr>
<td>Ammonia (NH\textsubscript{4})</td>
<td>3.5</td>
</tr>
</tbody>
</table>

3.2 Simulation Program

Excel spreadsheets are used to analyze the energy flows in this project. For computing heating space, energy calculation program [67] program from Boverket [6] is used. Dlubal software [68] is used to model, design and perform structural analysis.

3.3 Structural Analysis

The cornerstone for structural design and analysis is provided by Eurocodes, EN 1990 [37]. In this regard, the verification format, limit state regulations, reliability level, and load combinations variables are stated. It must be confirmed that no limit state has been exceeded. The Eurocodes make use of the idea of limit states, called the ultimate limit state (ULS) and the serviceability limit state (SLS). When the action impacts exceed the structure’s resistance limit state, there is no longer considered to meet the mechanical resistance and stability criteria. According to SS-EN 1990 [37], a structure must be constructed with an adequate degree of reliability to withstand all actions and effects predicted to occur during execution and use, so this relates to the ULS. A structure must also be functional for its construction. This has anything to do with the SLS. A building reaching a limit state does not always imply that it will collapse or become unusable. It shows that the risk of failure is unacceptable, and it does not meet Eurocode’s criteria [37].

3.3.1 Permanent Actions and Variable Actions

The impact of one or more actions on the structure is known as the design action effect. For each action, partial factors and characteristic values are used to determine the design actions. The basic formula to calculate the design value of actions can be considered Equation 8 if the permanent actions are unfavourable; otherwise, Equation 9 is dominant when the permanent actions are favourable. Notably, if the variable action is favourable, it is always removed in a load combination [37].
\[ D_{\text{unf}} = \sum_{j=1}^{m} \gamma_{G,j,\text{sup}} \cdot G_{K,j,\text{sup}} + \gamma_{p} \cdot p + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i=1}^{n} \gamma_{Q,i} \cdot \psi Q_{i} \cdot Q_{k,i} \quad \text{Eq (8)} \]

\[ D_{\text{inf}} = \sum_{j=1}^{m} \gamma_{G,j,\text{inf}} \cdot G_{K,j,\text{inf}} + \gamma_{p} \cdot p + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i=1}^{n} \gamma_{Q,i} \cdot \psi Q_{i} \cdot Q_{k,i} \quad \text{Eq (9)} \]

Regarding the calculation of the structure of building elements, the ULS and the SLS are defined with the permanent actions and variable actions calculated regarding their partial factors in load combinations.

### 3.3.2 Ultimate Limit State (ULS)

The safety of people is the main concern, for which different design scenarios should be considered. The most frequent of them are represented below.

- loss of equilibrium (EQU)
- Structural failure or partial structural failure (STR/GEO)
- Accidental design situation

In this case, the first and second criteria need to be considered. For the first measure, load combinations and the partial factors in the design situation loss of equilibrium and their recommended values according to the Swedish national choice can be seen in Table 4. After calculating all the loads, the load combinations need to be computed to determine the critical load combinations for applying to the structural elements. The load combinations factor (\( \psi \)) in the different building categories can be extracted from EN 1990-91, (see Table 4) [37] and [36].

The partial factor \( \gamma_{d} \) is for reliability class RC1-RC3 including the values 0.83, 0.91, and 1, respectively. For unfavorable permanent action, the partial factor (\( \gamma_{G,\text{sup}} \)) is 1.10 while for favorable one (\( \gamma_{G,\text{inf}} \)) is 0.90, (see Table 5). However, for variable action, we have 1.50 if the impact on the stability of the structure is unfavorable but if its effect is favorable, the factor is considered zero. Table 5 shows the recommended partial factors for the Swedish national choice [37].

| Table 4: Recommended partial factors related to load combination (EQU) [37]. |
|---|---|---|---|---|
| Action | Permanent Actions | Variable Actions |
| | Unfavorable | Favorable | leading | Others |
| 6.10 | \( \gamma_{G,\text{sup}} G_{k,\text{sup}} \) | \( \gamma_{G,\text{inf}} G_{k,\text{inf}} \) | \( \gamma_{Q,1} Q_{k,1} \) | \( \gamma_{Q,1} \psi_{Q,i} Q_{k,i} \) |
| 6.10 | 1.1 \( G_{k,\text{sup}} \) | 0.9 \( G_{k,\text{inf}} \) | \( \gamma_{d} 1.5 Q_{k,1} \) | \( \gamma_{d} 1.5 \psi_{Q,i} Q_{k,i} \) |

26
Table 5: Recommended values of \( \psi \) factors for load combinations for different categories [37].

<table>
<thead>
<tr>
<th>Action</th>
<th>( \psi_0 )</th>
<th>( \psi_1 )</th>
<th>( \psi_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category A: residential areas</td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Category B: office areas</td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Category C: congregation areas</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Regarding the structural failure (STR/GEO) [37], the partial factor and load combinations are considered in the design case of structural failure according to the Swedish national choice shown in Table 6. In this way, Eurocode suggests the two design situation cases (6.10a, 6.10b) [37] instead of using 6.10. There is a difference between 6.10a and 6.10b because in the first one it is assumed that the permanent actions are dominating the action impacts, which means that around 90\% of the effect comes from permanent actions. When the effect of the variable action is more dominating, the partial factor \( \xi \) is introduced in 6.10b. The partial factor \( \gamma_G \) is 1.35 for unfavorable permanent action and 1.00 for a favorable one. The partial factor \( \gamma_Q \) is 1.50 for unfavorable variable action in the design situations. For calculating the design situation both cases must be considered to determine the largest action impacts [37].

Table 6: Recommended design values of partial factors, related to permanent actions \( \gamma_G \) and variable actions \( \gamma_Q \) [37] and [36].

<table>
<thead>
<tr>
<th>Action</th>
<th>Permanent Actions</th>
<th>Variable Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unfavorable</td>
<td>Favorable</td>
</tr>
<tr>
<td>6.10a</td>
<td>1.35 ( \gamma_d G_{ki, sup} )</td>
<td>1.00 ( \gamma_d G_{ki, inf} )</td>
</tr>
<tr>
<td>6.10b</td>
<td>1.20 ( \gamma_d G_{ki, sup} )</td>
<td>1.00 ( G_{ki, inf} )</td>
</tr>
</tbody>
</table>

3.3.2.1 **Bending Moment**

To prove that a structure is on the safe side, the design bending moment \( (M_{Ed}) \) needs to fulfill Equation 10. The \( M_{Ed} \) comes from the calculation part, and it is compared with the limitation value Equation 11 [69].

\[
\frac{M_{Rd}}{M_{Ed}} \geq 1 \quad \text{(Eq 10)}
\]

where:
\[ M_{Rd} = A_s \cdot f_{yd} \cdot (d - a_2) \]  
(Eq 11)

- \( M_{Rd} \) resisting bending moment [kN.m],
- \( A_s \) reinforcement area [m²],
- \( AP_t \) distance from the cross-section edge of top to the center of reinforcement at bottom [m],
- \( f_{yd} \) yield stress of reinforcement [MPa], and
- \( a_2 \) concrete cover from the edge of cross section [m].

### 3.3.2.2 Shear Capacity

To prevent flexural shear failure in a slab, Equation 12 must be fulfilled. This means that the design shear of the slab must be smaller than the shear resistance value [69].

\[ V_{Ed} \leq V_{Rd,c} = C_{Rd,c} \cdot k \cdot (100 \cdot \rho_1 \cdot f_{ck})^{1/3} \cdot b_w \cdot d \]  
(Eq 12)

where:
- \( f_{ck} \) characteristic value of concrete compressive strength [MPa],
- \( k \) \[ 1 + \frac{2}{\sqrt{200/d}} \leq 2.0, \]
- \( \rho_1 \) \[ \frac{A_{s1}}{b_w d} \leq 0.02, \]
- \( A_{s1} \) the area of slab reinforcement [m²],
- \( b_w \) the width of slab [m], and
- \( d \) the mean of the effective depth in orthogonal directions [m].

### 3.3.2.3 Characteristic Compressive Stress of Masonry Wall

For calculating the characteristic compressive strength of masonry wall, Equation 13 represents the formula according to SS-EN 96 [70]:

\[ f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \]  
(Eq 13)

where:


The characteristic compressive strength of the masonry \(f_k\) [N/mm\(^2\)],
constant coefficient [in our case \(K=0.5\)],
the normalized mean compressive strength of the units [N/mm\(^2\)], and
the compressive stress of the mortar [N/mm\(^2\)].

### 3.3.3 Serviceability Limit State (SLS)

The serviceability limit state is concerned with the structure’s operation. According to EN 1990 [37], this state corresponds to a condition under which the requirements of the defined services for a structure or structural part are no longer satisfied. In this respect, deflection, displacements, vibrations, and concrete crack may all be specified criteria.

EN 1990 [37] defines two kinds of the SLS: reversible and irreversible. The irreversible limit state is described as a condition in which some of the effects of activities that exceed a particular service requirement persist even after the actions have been removed. Regarding the reversible SLS, no repercussions of activities that exceed a given limit remain when the acts are withdrawn. The partial factors \(\gamma_Q\) and \(\gamma_G\) should be taken into consideration as 1.0 except they are differently specified in EN 1991 to EN 1999. Therefore, these partial factors are omitted from this limit state design. Moreover, three different combinations of actions are listed in Table 7 coming from Annex (A) of EN 1990 [37]. They are defined as characteristic, quasi-permanent and frequent. Regarding the characteristic, it is usually chosen for the irreversible outcome. The load combination frequent is selected for its reversible effects. For long-term effects of creep and shrinkage, the combination quasi-permanent is used [36].

<table>
<thead>
<tr>
<th>Combination</th>
<th>Permanent Actions</th>
<th>Variable Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unfavorable</td>
<td>Favorable</td>
</tr>
<tr>
<td>Characteristic</td>
<td>(G_{k,up})</td>
<td>(G_{k,inf})</td>
</tr>
<tr>
<td>Frequent</td>
<td>(G_{k,up})</td>
<td>(G_{k,inf})</td>
</tr>
<tr>
<td>Quasi-permanent</td>
<td>(G_{k,up})</td>
<td>(G_{k,inf})</td>
</tr>
</tbody>
</table>

Table 7: Design value of actions in load combination related to SLS [36].
3.3.3.1 Deflection Control

Regarding the Boverket mandatory regulation [6], the recommendation of the deflection control is based on the appearance and comfort that can be provided by the client/owner. As a recommendation, the deflection is usually calculated according to Equation 14.

\[ L = \frac{L_{\text{span}}}{250} \]  
\[ \text{where:} \]
\[ L \] deflection [mm],
\[ L_{\text{span}} \] length of span [mm].

3.3.4 Environmental Loads

3.3.4.1 Snow Load

In buildings, there are some criteria considered for the snow load on the roofs for which the shape of the roof, location of building exposed or sheltered to wind, thermal insulation, and nearby buildings causing additional snow to accumulate on the roof should be investigated based on EN 1991-1-3 [38]. Snow load is considered as a vertical load of linear load kN/m or distributed load kN/m² in the calculations. Equation 15 indicates the characteristic value of the snow load on a roof. Equation 15 is for computing the snow load according to EN1991-1-3 [38]:

\[ S = \mu \cdot C_t \cdot C_e \cdot S_k \]  
\[ \text{where:} \]
\[ S \] the characteristic value of the snow load on the roof,
\[ \mu \] the roof shape coefficient,
\[ C_t \] the thermal coefficient,
\[ C_e \] the exposure coefficient (wind swept, normal, sheltered), and
\[ S_k \] the characteristic value of snow load on the ground.

Table 8 and Figure 7 show the roof shape coefficient related to the Swedish building code for pitched roofs.
Table 8: Snow load shape coefficient [38].

<table>
<thead>
<tr>
<th>Angel of Pitch of Roof $\alpha$</th>
<th>$0^\circ \leq \alpha \leq 30^\circ$</th>
<th>$30^\circ \leq \alpha \leq 60^\circ$</th>
<th>$\alpha \geq 60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_1(\alpha)$</td>
<td>$\mu_1(0^\circ) \geq 0.8$</td>
<td>$\mu_1(0^\circ) (60^\circ - \alpha)/30^\circ$</td>
<td>0.0</td>
</tr>
<tr>
<td>$\mu_2(\alpha)$</td>
<td>0.8</td>
<td>0.8(60$^\circ$ - $\alpha$)/30$^\circ$</td>
<td>0.0</td>
</tr>
<tr>
<td>$\mu_3(\alpha)$</td>
<td>$0.8 + (0.8 \cdot \alpha)/30^\circ$</td>
<td>1.6</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 7: Shape coefficient of the roof in Swedish building code for pitched roofs [38].

The characteristic value of snow load is determined based on figure 8 [71].

Figure 8: Snow zone of Sweden for snow characteristics load [71].
3.3.4.2 Wind Load

Wind load is considered a load case in a horizontal direction for the building. Wind actions computed in accordance with EN1991-1-4 [39] are classified as variable or fixed. They are equivalent to turbulence’s severe impact. The surface roughness rate and the vicinity of the ground can cause a larger turbulent section for the wind load. Table 9 and Figure 9 indicate the external pressure coefficient for vertical walls in different zones area and the pressure coefficient on the facades for rectangular buildings, respectively. The wind velocity and terrain type are determined based on Table 10, and Figure 10, respectively [39] and also the exposure factor can be seen in see Figure 11. Equations 16 and 17 are used for computing the wind load:

\[ w_e = q_{p(ze)} \cdot c_{pe} \]  
Eq (16)

where:

- \( q_{p(ze)} \) the peak velocity pressures,
- \( ze \) the reference height for the external pressure, and
- \( c_{pe} \) the pressure coefficient for the external pressure.

\[ q_{p(ze)} = c_{e(z)} \cdot q_b \]  
Eq (17)

where:

- \( c_{e(z)} \) the exposure factor,
- \( q_b \) the basic velocity pressure \((q_b = \frac{1}{2} \cdot p \cdot v^2)\),
- \( p \) the air density, and
- \( v \) wind velocity.

Table 9: Recommended values of external pressure coefficient for vertical walls of rectangular plan buildings [39].

<table>
<thead>
<tr>
<th>Zone</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h/d )</td>
<td>( c_{pe, 10} )</td>
<td>( c_{pe, 1} )</td>
<td>( c_{pe, 10} )</td>
<td>( c_{pe, 1} )</td>
<td>( c_{pe, 10} )</td>
</tr>
<tr>
<td>5</td>
<td>-1.2</td>
<td>-1.4</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>1</td>
<td>-1.2</td>
<td>-1.4</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>( \leq 0.25 )</td>
<td>-1.2</td>
<td>-1.4</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
Figure 9: Key to pressure coefficient on the facades for a rectangular building [39].

Table 10: Terrain classification and their parameter [39].

<table>
<thead>
<tr>
<th>Zone</th>
<th>Terrain Category</th>
<th>$z_0$ [m]</th>
<th>$z_{min}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sea or coastal area exposed to the open sea.</td>
<td>0.003</td>
<td>1.00</td>
</tr>
<tr>
<td>I</td>
<td>Lakes or flat and horizontal area with negligible vegetation and without obstacles.</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>II</td>
<td>Area with low vegetation such as grass and isolated obstacles (trees, buildings).</td>
<td>0.05</td>
<td>2.00</td>
</tr>
<tr>
<td>III</td>
<td>Area with regular cover of vegetation or buildings with isolated obstacles with separations of a maximum of 20 obstacles heights (such as villages, suburban terrain, permanent forest).</td>
<td>0.30</td>
<td>5.00</td>
</tr>
<tr>
<td>IV</td>
<td>Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m.</td>
<td>1.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>
Figure 10: The wind map, and altitude effects are considered [72].

Figure 11: Illustrations of the exposure factor $C_e(z)$ for $c_0=1$, $kr=1$ [39].
4 CASE STUDY BUILDING

The case study is the Ulriksberg school buildings (Ulriksbergskola) located in the western part of Växjö, Sweden. This includes four buildings, among which building number 1 is investigated for the renovation measures. Figure 12 shows the studied building and all the school buildings’ locations.

Building number 1 as the studied building school is a four-story building composed of concrete and brick materials. There are two basements with the function of heating and mechanical ventilation system installation, consisting of concrete shear and there is a big room as a shelter used in emergency cases. The other two floors which are
placed on the top of the basements have been made of load-bearing brick walls and are used for the function of teaching, studying rooms, and leisure centers. The two basements area is excluded from our studies; therefore, our focus is only on the two floors above the basements. Figure 13 indicates the studied building from different views. For the studied building, the gross floor area of each flat is 650 m², (see Table 11), a total of 13,000 m² for two floors.

![Figure 13: Buildings number 1 in different views.](image)

**Table 11: Type of flat and area of the studied building.**

<table>
<thead>
<tr>
<th>Type of flat</th>
<th>Number of Rooms</th>
<th>Area [m²]</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>650</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>650</td>
<td>50%</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>1300</td>
<td>100%</td>
</tr>
</tbody>
</table>

The floor plan of the studied building is shown in Figure 14 provided by the VÖFAB [73]. This building includes different building envelope components such as exterior doors, external and internal walls, floor, and windows. The building envelope
features for the first and second floors are described in Table 12. The building façade has a brick cladding made 70 years ago, (see Figure 13).

![Figure 14: Floor plan of building number 1 [73].](image)

Table 12: Building envelopes materials for two floors area.

<table>
<thead>
<tr>
<th>Building parts</th>
<th>Type of material</th>
<th>Area [m²]</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior door</td>
<td>Iron and Aluminum frame</td>
<td>12.0</td>
<td>0.2%</td>
</tr>
<tr>
<td>External Wall</td>
<td>Brick</td>
<td>800.0</td>
<td>18.8%</td>
</tr>
<tr>
<td>Internal Wall</td>
<td>Gypsum board and brick</td>
<td>1,260.0</td>
<td>29.7%</td>
</tr>
<tr>
<td>Floor</td>
<td>Linoleum floor cover and limestone tile</td>
<td>1,300.0</td>
<td>30.3%</td>
</tr>
<tr>
<td>Windows</td>
<td>Two and three glass with Wood and Aluminum frame</td>
<td>220.0</td>
<td>5.5%</td>
</tr>
<tr>
<td>Roof</td>
<td>Pine wood</td>
<td>650.0</td>
<td>15.5%</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>4,242</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Regarding the school building documents provided by VÖFAB [73] and WSP group [74], the annual average temperature of the climate zone where the building is located is 7.3°C. The indoor temperature of the school building is 21°C according to
BBR (2018) [6]. The total building heating energy for the existing building including two basements, the first floor and second floor based on the energy declaration [75] is 141 kWh/m²-year. The existing building with its poor building envelopes components fulfills 46% of BBR’s requirement [6] for the heating energy value, which means that the school building’s heating energy is 141 kWh/m²-year, but the BBR (2018) criterion is 75 kWh/m²-year. To meet BBR’s (2018) requirement for the allowable limit of heating energy, different renovation measures can be conducted. Furthermore, U-value as a major coefficient in the building envelope components can directly affect the building heating energy by using improved insulation materials in terms of thermal performance and environmental impacts. Table 13 shows the U-value of the existing school building for the external building envelopes.

<table>
<thead>
<tr>
<th>Building’s part</th>
<th>U-value [W/m² K]</th>
<th>Surface [m²]</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior doors</td>
<td>6.00</td>
<td>12.00</td>
<td>0.40%</td>
</tr>
<tr>
<td>External Wall</td>
<td>0.63</td>
<td>800.00</td>
<td>26.80%</td>
</tr>
<tr>
<td>Floor</td>
<td>0.99</td>
<td>1,300</td>
<td>43.50%</td>
</tr>
<tr>
<td>Windows</td>
<td>1.34</td>
<td>220.00</td>
<td>7.50%</td>
</tr>
<tr>
<td>Roof</td>
<td>0.39</td>
<td>650.00</td>
<td>21.80%</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>2,982</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Regarding the main external door, it was made of glass and an iron frame. The other two exterior doors were made of aluminum and located on the southern side. The main external door is shown in Figure 15. The external walls were composed of masonry bricks and wood wool as an insulation material and reinforcement concrete. Moreover, floor material encompasses reinforcement concrete, furnace slag as filling material, and mineral wool as an insulation material with a finishing of light concrete and linoleum flooring cover and partially limestone tiles. As regards the roof, it includes vertical and horizontal pine wood with wooden beam and mineral wool as an insulation material with improper thickness and with no roof tile as finishing, see Figures 16 and 17 for external wall section and roof materials, respectively.
Since the external and internal walls are load-bearing structural elements, they cannot undergo huge changes, so adding suitable insulation materials from inside the building can provide an effective solution for reducing heating energy losses. Figure 18 shows the windows which have made up more than half of the area of façades, especially on the north, east and south sides. Regarding the windows of the
south and the east, they have recently been renovated, but the windows in the north and west need to be renovated because of poor wooden framed materials and glasses.

![Figure 18: Northern Windows (a), southern windows (b).](image)

4.1 **Building Materials**

In this section, the school building materials which were used for the external and internal walls, roof, floor, windows, and exterior doors are grouped in Table 14. The building materials include brick, light concrete, wood wool, rebar, mineral wool, gypsum board, furnace slag, limestone tile, linoleum cover, glass, slag wool which is made of molten blast-furnace slag [76], wooden beam, wooden truss, and wooden battens.

<table>
<thead>
<tr>
<th>Building parts</th>
<th>Material items</th>
<th>Mass [Kg]</th>
<th>proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Wall</td>
<td>Brick</td>
<td>217,232.50</td>
<td>26.00%</td>
</tr>
<tr>
<td></td>
<td>Light concrete</td>
<td>104,870.00</td>
<td>12.60%</td>
</tr>
<tr>
<td></td>
<td>Rebars</td>
<td>7,790.50</td>
<td>0.90%</td>
</tr>
<tr>
<td></td>
<td>Wood wool</td>
<td>24,969.20</td>
<td>3.00%</td>
</tr>
</tbody>
</table>
### Linnaeus University

**Sweden**

---

<table>
<thead>
<tr>
<th>Internal Wall</th>
<th>Brick</th>
<th>105,052.40</th>
<th>12.60%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Light concrete</td>
<td>41,354.00</td>
<td>5.00%</td>
</tr>
<tr>
<td></td>
<td>Rebars</td>
<td>5,202.60</td>
<td>0.60%</td>
</tr>
<tr>
<td></td>
<td>Mineral wool</td>
<td>1,656.50</td>
<td>0.20%</td>
</tr>
<tr>
<td>Internal Wall</td>
<td>Gypsum board</td>
<td>7,312.20</td>
<td>0.90%</td>
</tr>
<tr>
<td></td>
<td>Timber frame</td>
<td>27,154.50</td>
<td>3.30%</td>
</tr>
<tr>
<td>Floor</td>
<td>Concrete</td>
<td>136,448.80</td>
<td>16.30%</td>
</tr>
<tr>
<td></td>
<td>Rebars</td>
<td>19,812.00</td>
<td>2.40%</td>
</tr>
<tr>
<td></td>
<td>Furnace slag</td>
<td>22,352.00</td>
<td>2.70%</td>
</tr>
<tr>
<td></td>
<td>Membrane insulation</td>
<td>3,640.00</td>
<td>0.40%</td>
</tr>
<tr>
<td></td>
<td>Limestone tile</td>
<td>17,526.00</td>
<td>2.10%</td>
</tr>
<tr>
<td></td>
<td>Lineum cover</td>
<td>3,531.60</td>
<td>0.40%</td>
</tr>
<tr>
<td>Windows</td>
<td>Wood frame</td>
<td>1,286.10</td>
<td>0.15%</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>1,420.80</td>
<td>0.17%</td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete</td>
<td>24,180.00</td>
<td>2.90%</td>
</tr>
<tr>
<td></td>
<td>Slag wool</td>
<td>52,800.00</td>
<td>6.30%</td>
</tr>
<tr>
<td></td>
<td>Wooden beam</td>
<td>3,978.00</td>
<td>0.50%</td>
</tr>
<tr>
<td></td>
<td>Wooden truss</td>
<td>4,666.50</td>
<td>0.60%</td>
</tr>
<tr>
<td></td>
<td>Wooden battens</td>
<td>768.80</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

---

### 4.2 Ventilation System

The building has a ventilation system with a heat recovery system according to the energy declaration [75]. This system refreshes and supplies air through heat recovery. The heat recovery includes two ducts, one of which is for providing fresh air and another one for exhaust air. In this system, the energy saves more than 50% [77] by flowing the air from a warm area to come into a cold place to balance the air condition.
5 METHODS and ASSUMPTIONS

5.1 Design Approaches and Measures

In this chapter, the selected methods and assumptions used for renovation measures and structural analysis of load-bearing elements are described. In this thesis, the existing and new materials for the school building envelope components were dealt with in terms of life cycle assessment investigating primary energy use, and different environmental impacts (global warming potential, acidification potential, eutrophication potential) considering two life cycle stages such as production and construction. Therefore, by using new materials, efficient and optimal renovation measures were established. Furthermore, the cost evaluation for alternative materials and heating energy saving as well as carbon emission reduction by utilizing new materials were considered. The calculation of the energy flows and environmental indicators in the life cycle assessment using energy calculation software [67] and Excel was done [78]. Regarding the structural part, the existing building structure was modeled in Dlubal software [68] and loading criteria were conducted according to the new version of Eurocode 1990-91 [37] and [36]. The load-bearing elements were evaluated under different load combinations which include new materials loads added to the building parts.

5.2 Modeling Approach

The EN standard expresses how process steps in the evaluation must be done (see Figure 19).

Figure 19: Flow chart of LCA process based on EN 15978 [40].

For comparison of life cycle analysis results, a functional unit was presented in this stage. As there was no linear relation between the number of building’s floors and the environmental effects, the floor area including heating space can be a suitable
The functional unit in this study was chosen to be 1 m² of the floor area of the school building.

### 5.2.1 Functional Unit

To investigate the environmental effect categories, the total of all associated emissions was added to an equivalent value. Characterization was the last step of inventory flow translation. The reference compound for global warming potential was CO₂_eq/m² related to the total of five different gas emissions (CO₂, SO₂, NH₄, NOₓ, and CH₄). For calculating the actual impact of the gases on the atmosphere, each emission was multiplied by a characterization factor as it was mentioned in chapter 3.

### 5.3 System Boundary

A system boundary was determined to define the investigation border for the case study. Regarding the system boundary of a life cycle assessment that includes production, construction, service life, end of life, and wastage stages, it was assumed that the system boundary was cradle to site which means that from the production up to the construction stage, (see Figure 20) [65] and [79]. In this respect, the primary energy use, and environmental impacts from raw materials (A1) and their transfer (A2) to the manufacturing (A3) were indicated in the production stage and also transportation (A4) from manufacturing to the construction site and construction activities (A5) were related to the construction phase.

![Figure 20: System boundary modules in LCA of building according to EN 15978 [66].](image)

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5.4 Data Collection

A theoretical and analytical review was considered to collect both input and output data. Data was also divided into several sections that should clarify the theory assumption. The collection process should fulfill the standard requirements such as Eurocodes [36] and EN 15978 [66] for the school building. The assumption for collecting data in the studied case was using background data, primary data, government reports (BBR (2018) standard [6], Environmental Product Declaration [64], Eurocode [36] and [37]), energy declaration of the building from Boverket [6], the calculation, and the database of VÖFAB [73]. We used the above-mentioned database to calculate primary energy use and environmental impacts. Also, Net Zero Energy should be considered as a reference to assume the material with lower primary energy use to reach the goal.

5.5 Production Phase

5.5.1 Primary Energy Use

All activities to produce building materials such as extraction of raw material, transport, and manufacturing that consume energy were considered. The assumption in the school's case was to use the materials which stem from renewable energy resources or the combination of non-renewable and renewable energy resources regarding the material production potential. Using materials that need lower primary energy to produce was another assumption. For the studied building, specific final energy for material production according to Tettey et al., [80] was used whereby the primary energy use was calculated. The following Equation 19 [65] was used to compute the energy production in the calculation.

\[
E_{production} = \sum_i \{ \sum_k [ F_{ik} \cdot (1 + \alpha_k)] + \frac{L_i}{\eta} + B_i \} 
\]  
(Eq 19)

where:

- \(i\) Individual types of materials in the building,
- \(F\) End-use fossil fuel energy used to extract, process and transport the material [kWh],
- \(k\) Fossil fuels: coal, oil, and natural gas,
- \(\alpha\) Fuel cycle energy requirement of the fossil fuel,
- \(L\) End-use electricity to extract, process, and transport the materials [kWh],
\[ \eta \] Conversion efficiency for electricity production, and

\[ B \] Content (lower heating value) of the biofuels used in material processing [kWh].

5.5.2 Greenhouse Gas Emissions

Regarding the production and construction stage, energy supply and activities such as transport, manufacturing materials, and construction process emit greenhouse gas emissions such as CO\(_2\), CH\(_4\), and NO\(_x\) (unit CO\(_2\)-eq/kWh). This depending on which gas related to specific material was considered for all calculations. Regarding different materials aspect of environmental impacts, suitable materials with lower greenhouse gas emissions according to the standards such as BBR (2018) [6] and Environmental Product Declaration [81] can be determined for different school building elements [82]. The greenhouse gas emissions were calculated for material energy resources such as coal (anthracite), oil (heavy fuel oil), natural gas, biofuel (biomass), and electricity coal (lignite coal). Total greenhouse gas emissions were calculated based on the mass balance of materials (kg), specific final energy use of material production (kWh/kg), and the share of the greenhouse gas emissions from fuels. Equation 20 [65] is for the calculation of carbon emission.

\[
C_{production} = \sum_k [C_k \cdot F_k] + \frac{L}{\eta} \cdot C_L \]  
(Eq 20)

where:

- \( C_{production} \) Total CO\(_2\) emissions from material production [kg C],
- \( k \) Fossil fuels: coal, oil, and fossil gas,
- \( C \) Fuel-cycle carbon intensity of the fossil fuel [kg C/kWh] end-use and
- \( F \) End-use fossil fuel energy used to extract, process, and transport the material [kWh].

5.6 Construction Phase

The construction stage included transportation and materials installation. In this stage, we considered the primary energy use and environmental impacts of the construction process by replacing old materials with new materials in building components such as windows, floors, roof, and walls. Regarding the transportation in this stage, this was assumed that all the locations in Sweden, for which primary
energy use and environmental impacts were calculated. For on-site primary energy use and environmental impacts, the Environmental Product Declaration data [83] was used for the selected materials.

5.7 Studied Reference Building

The investigation considered the school building described in chapter 4 as a reference studied building for the life cycle assessment, and structural analysis. For the different parts of the existing building, the old materials with their thickness and density were investigated. Regarding the building envelope components encompassing the roof, floor, windows, external wall, and exterior door, the thermal bridge role was significant in heat transfer from inside the building to outside. This showed that the building envelope elements have poor insulation materials. This reference building anyway required a renovation; thus, the different renovation packages in terms of primary energy use and environmental impacts were considered for the building to identify and compare the effects of the energy efficiency based on retrofit strategies.

5.8 Insulation Materials

The new insulation materials according to Tettey et al. [80] were used for building envelope elements. Regarding the insulation material’s role in improving building energy efficiency levels, their raw materials and primary energy resource were important to be considered apart from physical and thermal properties. The type and shape of insulation material used were also determined by the required application in various building components. Three insulation materials such as cellulose, rock wool, and glass wool are defined below.

5.8.1 Cellulose Fiber

Cellulose fiber is made of recycled or wastepaper that has been shredded and combined with boric acid and borax to enhance its fire-retardant properties [80].

5.8.2 Rock Wool

For manufacturing rock wool, basalt, dolomite, and limestone are the primary raw materials used. The raw materials are melted, often in a coke-fueled cupola furnace, and the emerging mix is spun into fibers with the addition of binders to obtain desired density and structure. After curing the items at around 200°C, they are cut to the desired sizes and forms for packaging and distribution [80].
5.8.3 Glass Wool

Glass wool is manufactured similarly to rock wool, except the primary raw materials including sand and glass cullets, with additional materials such as limestone and soda ash in small quantities [80]. These insulation materials as the most common ones in the market are used in different thicknesses according to BBR (2018) [6] to be investigated in terms of primary energy use and environmental impacts. The thermal conductivity of these materials and their densities are indicated in Table 15.

Table 15: Insulation material properties [84].

<table>
<thead>
<tr>
<th>Insulation Materials</th>
<th>( \lambda ) [W/m K]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose fiber</td>
<td>0.040</td>
<td>48</td>
</tr>
<tr>
<td>Rock wool</td>
<td>0.033</td>
<td>100</td>
</tr>
<tr>
<td>Glass wool</td>
<td>0.035</td>
<td>48</td>
</tr>
</tbody>
</table>

5.9 Building Envelope Components

5.9.1 Windows

A sustainable window representing an eco-energy and environmentally friendly impact was assumed. This window gave lower thermal losses which should be limited to a U-value of 1.2 [W/m² K] according to BBR (2018) [6]. The 3-glass windows and the combination of wood and aluminum frame windows fulfilled the allowable U-value limit based on BBR (2018). The transmission of the sunlight through the glass of the window is an effective factor in the heating increase of the school building, defined as a g-value that is known by solar heat transmission. The range of the g-value is between 0 to 1, in which the latter value is the maximum of solar heat gain [85]. The g-value of new windows for the studied building is 0.64 [6].

The school building had windows made from wood frames with 2-glass layers that were in a poor condition in terms of materials and heat losses. For improving the energy saving of these windows, a window with two different frame materials for outdoor and indoor was considered aluminum and wood respectively. Also, the layers of glasses were increased to three. We assumed that the windows include two
different thicknesses for glass layers, 36 and 48 mm with different U-values, 1.1 and 0.7 [W/m² K], respectively.

The wood frame is eco-energy and is made from renewable energy resources [86]. Although aluminum’s heat transfer is high, it is cheaper than the wood frame and is more resistant to moisture. In addition, insulated glass can be beneficial for thermal performance, and this increases heat efficiency. There is also an air gap between the glasses of 12mm. The combination of aluminum for outdoor and wood for indoor frames was taken into consideration for 3-glass windows [87]. Finally, the two selected windows were compared with each other in the calculation to recommend the best solution in results.

5.9.2 Exterior Door

The exterior door as a climate shell is also an important part of a building, playing a major role in thermal performance. The thermal performance is determined based on the U-value of the door is important for choosing the door.

After visiting the school and investigating the U-value of the exterior door, the BBR (2018) [6] requirement was not fulfilled by the existing exterior doors. The lower amount of U-value of the door, the more heating saving for the building [86]. The existing exterior doors were made of aluminum, iron, and glass materials which were investigated to be replaced by one of the two proposed materials. Two new wood materials such as pine and oak assumed in different thicknesses (150 and 200 mm) were compared with each other for substitution.

5.9.3 External Wall

The external walls which are the main body of the building included poor layers with high thermal losses as was described in chapter 4. They needed to change by adding new insulation materials with appropriate thickness causing a lower heat transfer coefficient. The existing external walls included brick, concrete layers, and insulation materials such as wood wool with 50 mm thickness, which could not provide the proper thermal resistance. To fulfill the BBR (2018) [6] requirement in terms of thermal performance, the three different insulation materials such as cellulose, rock wool, and glass wool were defined and compared with each other in terms of lower primary energy use and environmental impacts.
5.9.4 Floor

The studied area was the first and second floors above the basements. There was no suitable insulation material for floors in the corridors and classrooms. Thus, the need for reducing the heat transfer by changing the floor’s insulation was important. In this case, the three insulation materials above-mentioned were assessed in terms of lower primary energy use and environmental impacts.

5.9.5 Roof

The roof did not have good condition in terms of energy-saving and material layers. In some parts of the roof according to the plans by VÖFAB [73], there were 50 mm mineral wool as an insulation material, pinewood in the truss as a structural element, and also the concrete beams. The three insulation materials above-mentioned were compared to be identified which insulation material has the lowest environmental impacts and primary energy consumption to be used in the roof. Regarding the school visit, there was not any tile on the roof; therefore, two different tiles materials were assumed for the roof as a recommendation, concrete tile, and clay tile.

5.10 Establishment of Energy-Efficient Measures

In this study, the focus was on proposing sustainable renovation measures in terms of lower environmental impacts and primary energy use for the building envelope components. For the thermal envelopes of the school building, three insulation materials based on the combination of renewable and non-renewable primary energy use were considered. Regarding the description of the windows, two different U-values of windows (1.1 and 0.7 [W/m² K]) with wood and aluminum frames were assumed to be combined with other building envelopes elements using new insulation materials. In this case, several scenarios were made to be compared for determining optimal and sustainable renovation measures. The renovation measures are defined in Table 16.

<table>
<thead>
<tr>
<th>Renovation Measures</th>
<th>External wall</th>
<th>Windows U-value 1.1 [W/m² K]</th>
<th>Windows U-value 0.7 [W/m² K]</th>
<th>Exterior door U-value 1.1 [W/m² K]</th>
<th>Exterior door U-value 0.7 [W/m² K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure 1</td>
<td>Cellulose</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Measure 2</td>
<td>Rock wool</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Measure 3</td>
<td>Glass wool</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>
Regarding Table 17, the type of choosing windows and insulation materials is based on fulfilling BBR (2018) requirements [6]. According to the BBR (2018) [6], the minimum requirement for heat transfer value (U-value) and average U-value of new materials for building envelope components used in renovation measures are shown in Table 17.

<table>
<thead>
<tr>
<th>Building parts</th>
<th>U-value [W/m² K] [BBR 2018, Minimum requirement]</th>
<th>Average U-value for renovation measure considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>External wall</td>
<td>0.18</td>
<td>0.178</td>
</tr>
<tr>
<td>Floor</td>
<td>0.15</td>
<td>0.149</td>
</tr>
<tr>
<td>Window (36mm)</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Window (48mm)</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Exterior door</td>
<td>1.2</td>
<td>1</td>
</tr>
</tbody>
</table>

The average U-value indicated in Table 17 is related to the building envelope components using cellulose as insulation materials and windows with 36mm (U-value 1.1 [W/m² K]) and 48mm (U-value 0.7 [W/m² K]) 3-glass layers as well as wood material for the exterior door. Furthermore, the average heat transfer coefficient for external walls, roof, and floors was obtained from the optimum thickness of cellulose insulation materials used in our calculation.

Regarding cellulose, it is derived from pine trees. This is made of recycled newspapers which help save 4,000 kWh of energy and 19 trees. In addition, the electricity for the production plant of this insulation is supplied through wind and hydropower (Swedish average electricity) [88].
5.11 Electricity

Energy supply is a vital part that can remarkably affect the life cycle assessment’s results. Regarding the European countries, electricity production is derived from different sources of energy. In Sweden, the fuel resources for producing electricity are usually based on the Swedish average electricity [89]. The energy use of electricity production depends on the amount of demand in the country [90]. The energy supply of electricity in the Nordic area gives rise to a big achievement aspect of sustainability to decrease expenses, GHG emissions, and reach renewable energy. In addition, the amount of carbon emissions is hopefully placed at the standard level, which is another benefit of the combination of Nordic countries to supply the energy. Hence, the accuracy of electricity sources in the Nordic region is not recognizable precisely but the Swedish average electricity scenario is a mix of energy sources to decrease the consumption of non-renewable energy resources [91]. Regarding this case study, the Swedish average electricity was common to supply electricity assumed [92]. It was assumed that the electricity used for the material and equipment was supplied from this source [93]. Two different electricity scenarios were considered for producing electricity [94] including the Swedish average electricity and marginal coal-based electricity. These were compared with each other to be determined which sources for producing electricity were beneficial environmentally and economically.

5.11.1 Swedish Average Electricity

Regarding the Swedish average electricity, it consists of a mix of energy resources such as hydropower, nuclear power, and biofuels, (See Table18). We assumed the Swedish average in this case study. Also, the gases such as CO₂, NOₓ, CH₄, and SO₂ [83] were considered for calculating environmental impacts, with the electricity conversion efficiency of 90% and transition [95], distribution for efficiency of 93% and 10% [65] fuel cycle energy input for the production phase of energy flow.

Table 18: Swedish average electricity mix of different resources [89] and [94].

<table>
<thead>
<tr>
<th>Source</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro Power</td>
<td>49%</td>
</tr>
<tr>
<td>Nuclear Power</td>
<td>44%</td>
</tr>
<tr>
<td>Biofuel</td>
<td>7%</td>
</tr>
</tbody>
</table>
5.11.2 Marginal Coal-based Electricity

Marginal coal-based electricity is generated through all marginal sources [96]. This is employed when there is an increased demand for electricity which can be based on political decisions, energy prices, weather, etc. Marginal coal-based electricity was used to compare as a sensitivity analysis with the Swedish average electricity to figure out the difference in energy resources. In this assumption, the gas emissions of marginal including CO$_2$, CH$_4$, NO$_x$, NH$_4$, and SO$_2$ were considered for calculating environmental impacts [89] and [92]. The most source of marginal was coal from the coal power plant [97] with an electricity conversion efficiency of 40% [95] and transition, distribution for efficiency of 93%, and 10% [65] fuel cycle energy input.

5.12 Material Costs

For the cost aspect, the evaluation was carried out based on materials performance and their price according to the present Swedish market value (SEK) per square meter of the studied building. Insulation materials costs are represented in Table 19. For windows, it was assumed that two types of windows with different glass thicknesses but with the same interior and exterior frame (see Table 20). Regarding the exterior door investigation, Table 21 represents the price for two types of them.

5.13 Energy cost

The total price for electricity consumption was variable depending on the type of consumption in the school building, but the average price of district heating was assumed at 1.05 SEK/kWh [73]. In this case, there were limited electricity bills provided by the VÖFAB [73] for the school building. By investigating the building heating energy and energy cost in the material production stage, one can see how the energy cost was changed when building heating energy decreased through using renovation measures.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>240.57</td>
<td>119</td>
<td>79.95</td>
<td>900</td>
<td>216,513</td>
<td>107,100</td>
<td>71,955</td>
</tr>
<tr>
<td>Floor</td>
<td>240.57</td>
<td>119</td>
<td>79.95</td>
<td>1300</td>
<td>312,741</td>
<td>154,700</td>
<td>103,935</td>
</tr>
</tbody>
</table>
Roof | 240.57 | 129 | 99.95 | 650 | 156,370 | 83,850 | 65,000
---|---|---|---|---|---|---|---

Table 20: Windows cost based on the Swedish market database (SEK) [101].

<table>
<thead>
<tr>
<th>Material</th>
<th>Area [m²]</th>
<th>Number of Windows</th>
<th>Price for one window (36mm) [SEK]</th>
<th>Price for one window (48mm) [SEK]</th>
<th>Total price (36mm) [SEK]</th>
<th>Total price (48mm) [SEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>96e-2</td>
<td>32</td>
<td>5,601</td>
<td>9,351</td>
<td>190,434</td>
<td>299,232</td>
</tr>
<tr>
<td></td>
<td>196e-2</td>
<td>13</td>
<td>7,809</td>
<td>13,068</td>
<td>101,517</td>
<td>169,884</td>
</tr>
</tbody>
</table>

Table 21: Exterior door cost [102].

<table>
<thead>
<tr>
<th>Building Part</th>
<th>Area [m²]</th>
<th>Number of doors</th>
<th>Price one door (92mm) [SEK]</th>
<th>Price one door (105mm) [SEK]</th>
<th>Total price (92mm) [SEK]</th>
<th>Total price (105mm) [SEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior door</td>
<td>264e-2</td>
<td>30</td>
<td>9,583</td>
<td>14,501</td>
<td>28,749</td>
<td>43,503</td>
</tr>
</tbody>
</table>

5.14 Labor cost

Regarding the construction stage, the installation cost including labor price was another factor that needed to be considered in the calculation. This means that the working time of labor was calculated based on SEK hourly [103] and then was added to the final cost. Tables 22 and 23 indicate the labor cost of material installation and site equipment cost used in the installation step, respectively. Moreover, we established different cost scenarios based on renovation measures to compare with each other to identify an optimum cost scenario. Table 24 including cost scenarios was made based on renovation measures. In this regard, the combination of different insulation materials, two types of windows, and exterior doors were accounted for in the investigation of the total renovation cost.

Table 22: Labor cost in installation stage for overall renovation [103], [104] and [105].

<p>| Building Components | Specification | Overall time required [hour] | Overall labor cost [SEK] | Unit | Total cost [SEK] |</p>
<table>
<thead>
<tr>
<th>components</th>
<th>Specification</th>
<th>Overall time required [hour]</th>
<th>Overall labor cost [SEK]</th>
<th>Unit</th>
<th>Total cost [SEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site equipment- safety switch</td>
<td>Change 1-phase, 16A</td>
<td>0.74</td>
<td>370</td>
<td>st</td>
<td>370</td>
</tr>
<tr>
<td>Site equipment-engine protection</td>
<td>Change &lt; 10A</td>
<td>0.74</td>
<td>370</td>
<td>st</td>
<td>370</td>
</tr>
<tr>
<td>Site equipment-transforms</td>
<td>Replacement protective 25VA</td>
<td>0.76</td>
<td>380</td>
<td>st</td>
<td>380</td>
</tr>
</tbody>
</table>

Table 23: Labor cost and site equipment cost in installation stage for overall renovation [103], [104] and [105].

<table>
<thead>
<tr>
<th>Cost Measures</th>
<th>Replaced materials in building envelope components</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Cellulose + window 36mm + standard exterior door</td>
</tr>
<tr>
<td>M2</td>
<td>Rock wool + window 36mm + standard exterior door</td>
</tr>
<tr>
<td>M3</td>
<td>Glass wool + window 36mm + standard exterior door</td>
</tr>
<tr>
<td>M4</td>
<td>Cellulose + window 48mm + passive exterior door</td>
</tr>
<tr>
<td>M5</td>
<td>Rock wool + window 48mm + passive exterior door</td>
</tr>
<tr>
<td>M6</td>
<td>Glass wool + window 48mm + passive exterior door</td>
</tr>
</tbody>
</table>

5.15 Transportation
Transportation is one of the important parts of the building life cycle. In the material construction phases [106], transportation was a significant part. Regarding the transportation in the production stage, it was included in the data coming for specific end-use energy \([\text{kWh}_{\text{end-use}}/\text{kg}]\). In the construction stage, it was considered that the assumption of transportation was reasonable which means that all the locations were selected in Sweden. In the construction stage, the transportation’s primary energy use and its environmental impacts were computed [78]. Regarding environmental impacts of transportation, most vehicles used fuels from non-renewable energy. It is to be noted that we considered transportation in a single way. All transportation was supposed to take place by diesel truck. The distance from the manufacturer to Växjö was considered separately for each material according to the relevant database. Regarding the location within 20 km, the diesel consumption was considered \(7.08\times10^{-5}\) [liter/kg per km] while this for longer distances, less and more than 100 km, was calculated at \(4.25\times10^{-5}\) and \(2.83\times10^{-5}\) [liter/kg per km], respectively [107]. For the studied building, transportation of employees to and from the plant and construction site was excluded according to EN 15978 [65]. The gas emissions which were considered for transportation in the calculation part included CO\(_2\), NO\(_x\), and SO\(_2\) with the unit of kWh/kg per km. Equation 21 is for transport calculation [108].

\[
P_T = E_c \cdot T_D \quad \text{(Eq 21)}
\]

where:

- \(P_T\) Total primary energy for transportation [kWh],
- \(E_c\) Energy consumption [kWh/kg per km], and
- \(T_D\) Material transported distance [kg per km].

5.16 Structural Analysis

Regarding the structural aspect, the school building was built 70 years ago and new loads are added by renovation measures, so the structural elements of the building must fulfill the requirements of the updated EN 1990-1991 [37] and [36]. The structural components need to be strong and resistant to critical loads combination when they are investigated under both ultimate limit state (ULS) and serviceability limit state (SLS) criteria. The structural elements of the studied building included shear walls in the basement, load-bearing brick walls for two floors with concrete slabs, and a wooden truss on the roof. This part aims to investigate the structural
analysis of load-bearing elements when new materials are added to the building envelopes.

5.16.1 Building Information Modeling

The school building was modeled in Dlubal software, and the materials were defined for each structural element. We first defined the structural elements including supports, shear walls, slabs, external and internal walls, and a truss for the roof. The building was summarized in two-story above the basement with an attic roof. In the basement, the shear wall was defined with concrete material as a linear elastic with type C25/30 using the module of elasticity 31,000 MPa and the characteristic compressive strength of 30 MPa. All the supports were assumed as rigid supports. Regarding the slab material, it was defined as concrete material with the same characterization values as concrete shear walls. For the load-bearing walls, the linear isotropic material was defined as masonry brick with the module of elasticity 7,000 MPa. The characteristic compressive strength of the brick wall was calculated based on SS-EN 96 [70]. In the roof part, the pine wooden truss was considered a structural element. Moreover, there was no tile at the top of the roof. The pine wood density was 510 kg/m³ with a module of elasticity and shear module of 12,000 MPa and 666 MPa, respectively. The building area was 650 m² with a height of 8 m for two floors and 1.2 m for the maximum height of the attic roof. The building model is shown in Figure 21.

Figure 21: 3D structural model.

5.16.2 Loading

Load definition and calculation were carried out for structural elements. EN 1990 [36] provides the foundation for structural design in accordance with the Eurocodes. There were four different types of load actions that should be calculated in this case according to EN 1991-1992 [37] and [69]. In this respect, the permanent loads were
calculated for the load-bearing elements for building components e.g., partition walls, surface finishing, etc., and imposed loads are related to people, furniture, stored materials as well as other loads coming from the occupancy, building use, and other construction work. There were also environmental loads including wind and snow loads. Furthermore, for the calculation of imposed load, the function of the building needed to be determined by the proper value for calculation. Table 26 shows the categories of imposed loads according to EN 1990-1991 [37] and [36]. The studied building was categorized in the field of C, C₁ for the school case.

Table 26: The major classification for imposed loads [36].

<table>
<thead>
<tr>
<th>Category</th>
<th>Specific use</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area for domestic and residential activities.</td>
<td>Rooms in residential buildings and houses include bedrooms and wards in hospitals; bedrooms in hotels and hostels kitchens and toilets.</td>
</tr>
<tr>
<td>B</td>
<td>Office areas.</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Areas where people may congregate (except A, B, and D areas).</td>
<td>C₁: Areas with tables, e.g., areas in schools, cafes, restaurants, dining halls, reading room receptions.</td>
</tr>
<tr>
<td>D</td>
<td>Shopping areas.</td>
<td>D₁: Areas in general retail shops.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D₂: Areas in department stores.</td>
</tr>
</tbody>
</table>

Regarding the imposed loads in buildings, the characteristic values as a distributed load in kN/m² are represented in Table 27. In this case, the characteristic value of the imposed load for the studied building was considered 3.0 kN/m² according to Table 27.

Table 27: Characteristic values for imposed loads of buildings [36].

<table>
<thead>
<tr>
<th>Category</th>
<th>( q_e ) [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floors (A)</td>
<td>1.5 to 2.0</td>
</tr>
<tr>
<td>Stairs (A)</td>
<td>2.0 to 4.0</td>
</tr>
</tbody>
</table>
5.16.2.1 Snow Load

Regarding the school building, the roof shape was the attic roof with angle $\alpha = 15^\circ$, and the shape coefficient of the roof was considered $\mu = 0.80$ according to the Eurocode for pitched roofs [38]. The thermal coefficient of snow for our case study was considered $C_t = 1.00$ according to SS-EN1991-1-3.5.2.2 [38] because the U-value of the roof was less than 1.00 [W/m²K]. The value of the exposure coefficient, $C_e = 1.00$ was considered a normal condition. Regarding the studied building located in Växjö, the characteristic snow load is $S_k = 2.00$ kN/m² [71].

5.16.2.2 Wind Load

Since the school building was surrounded by other buildings, the wind load zone was calculated for two zones, D and E (see Table 9 in the theory part). Regarding the height (8.80 m) and width (10.00 m) of the building, the value of the pressure coefficient $c_{pi} = 0.80$ for zone D and $c_{pi} = -0.50$ for zone E was considered. The peak velocity based was calculated based on Växjö, $q_p(z_e) = 0.72$ kN/m². Regarding the terrain type, this was assumed type III, so the velocity of wind was obtained at 24.00 m/s [39] and the exposure factor was, $ce(z) = 3.00$, and the recommended value for density ($p$) was 1.25 kg/m³. Total loads including permanent loads, imposed loads and environmental loads are represented in Table 28.
Table 28: Total loads considered for the studied building

<table>
<thead>
<tr>
<th>Permanent loads</th>
<th>Imposed loads</th>
<th>Environmental loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load (floor)</td>
<td>5.50 kN/m²</td>
<td>Snow load (roof)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.63 kN/m²</td>
</tr>
<tr>
<td>Dead load (roof)</td>
<td>1.78 kN/m²</td>
<td>Wind load (façade)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.57 kN/m² (D zone)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.36 kN/m² (E zone)</td>
</tr>
<tr>
<td>Live load (school)</td>
<td>3.00 kN/m²</td>
<td></td>
</tr>
</tbody>
</table>

5.16.3 Ultimate Limit State Control

5.16.3.1 Bending Moment

For investigating the maximum bending moment design value, the value in the middle of the slab was obtained from the finite element model [68] and this was compared with the bending moment resistance $M_{Rd}$ [69].

5.16.3.2 Shear Capacity

In this part, the shear design value at $d$ (the mean of the effective depth in orthogonal directions of cross-section) distance from support was compared with the shear capacity in the slab [69].

5.16.3.3 Characteristic Compressive Stress of Masonry Wall

Regarding the design compressive stress of masonry walls, this value was obtained from the finite element model and was compared with the allowable limit calculated according to SS-EN 96 [70].

5.16.4 Serviceability Limit State Control

5.16.4.1 Deflection Control

The deflection of slab and displacement of load-bearing walls were compared with the allowable limit according to the Boverket [6]. The different types of loading including dead loads, snow loads, live loads, wind loads in $x$-direction and wind loads in $y$-direction based on the finite element model are represented in Figures 22, 23, 24, 25, and 26, respectively.
Figure 22 shows the dead loads as vertical loads in z-direction imposed on the floors and the roof based on the finite element model.

Figure 23 shows the snow loads as a distributed loads in z-direction imposed on the roof based on the finite element model. In Figure 24, live loads for each floor and the roof are represented.
Figure 25 and 26 shows the wind loads as surface loads in $x$-direction and $y$-direction imposed on the façade based on the finite element model, respectively.

Figure 25: Wind loads in $x$-direction.

Figure 26: Wind loads in $y$-direction.
6 RESULTS

6.1 Life Cycle Assessment

6.1.1 Total Primary Energy Use and Environmental Impacts of Insulation Materials

Regarding the different insulation materials with various thicknesses investigated for building envelopes, the primary energy use according to BBR (2018) [6] and environmental impacts were calculated. The insulation materials with their optimal thickness are shown in Table 29. Cellulose fiber for all building envelopes has a thickness, ranging from 185 to 320 mm. In contrast, its total primary energy use has the lowest value for, internal walls, roof, floor, and external walls, with the value of 4 kWh/m², 5 kWh/m², 8 kWh/m², and 11 kWh/m², respectively (see Table 30). Notably, glass wool insulation material has the most total primary energy use for all building components.

Table 29: Insulation materials with required thickness in different building envelopes according to BBR (2018) [6].

<table>
<thead>
<tr>
<th>Building part</th>
<th>Insulation Material</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BBR (2018)</td>
</tr>
<tr>
<td>External Wall</td>
<td>Cellulose</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>Rock wool</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>Glass Wool</td>
<td>165</td>
</tr>
<tr>
<td>Internal Wall</td>
<td>Cellulose</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>Rock Wool</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>Glass Wool</td>
<td>162</td>
</tr>
<tr>
<td>Floor</td>
<td>Cellulose</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>Rock Wool</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>Glass Wool</td>
<td>200</td>
</tr>
<tr>
<td>Roof</td>
<td>Cellulose</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>Rock Wool</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>Glass Wool</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 30: Environmental impacts of material production for different insulation materials.

<table>
<thead>
<tr>
<th>Insulation Material For Renovating Building</th>
<th>Global Warming Potential [kg CO₂-eq/m²]</th>
<th>Acidification Potential [kg SO₂-eq/m²]</th>
<th>Eutrophication Potential [kg NO₃-eq/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>8.90</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Rock Wool</td>
<td>56.80</td>
<td>0.20</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Table 30 indicates the environmental impacts including global warming potential, acidification potential, and eutrophication potential for three insulation materials, in which the highest impact comes from rock wool but the lowest one is for cellulose insulation material.

![Figure 27: Total material production primary energy use of insulation materials.](image)

Regarding Figure 27, the external wall requires the highest production of primary energy with 70 kWh/m², 65 kWh/m² and 11 kWh/m² for glass wool, rock wool, and cellulose, respectively. Since the U-value and the thickness of the internal wall are lower than the external envelopes, it has the lowest primary energy use for three different insulation materials.

In the roof, cellulose plays a significant role in the insulation part with a value of 5 kWh/m² primary energy use of material production, while glass wool and rock wool have the primary energy use of 32 and 30 kWh/m², respectively (see Figure 27). Moreover, the similarity in the material production primary energy use of rock wool and glass wool stems from approximately the exact value of specific end-use energy, including fossil fuels [80].
6.1.2 Total Primary Energy Use and Environmental Impacts of Windows

Regarding the window materials investigation as one of the important building envelope components, windows with 3-glass layers (U-value 1.1 [W/m² K]) have lower primary energy use of material production than the same windows with 3-glass of 48 mm layers (U-value 0.7 [W/m² K]). Although different U-values of these windows can affect thermal bridges and both windows fulfill the BBR (2018) [6] requirement, windows with higher U-values provide lower primary energy use. Table 31 shows the total primary energy use of material production and their environmental impacts for two different windows.

Table 31: Total material production primary energy use and their environmental effects of two new windows.

<table>
<thead>
<tr>
<th>Windows type</th>
<th>Total Primary Energy Use [kWh/m²]</th>
<th>Global Warming Potential [kg CO₂eq/m²]</th>
<th>Acidification Potential [kg SO₂eq/m²]</th>
<th>Eutrophication Potential [kg NO₃eq/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows 36 mm 3-glass</td>
<td>106.50</td>
<td>2.35</td>
<td>0.48e-2</td>
<td>0.08e-2</td>
</tr>
<tr>
<td>Windows 48 mm 3-glass</td>
<td>164.00</td>
<td>3.40</td>
<td>0.60e-2</td>
<td>0.08e-2</td>
</tr>
</tbody>
</table>

Regarding Table 31, one can see that the total material production primary energy use of windows with a U-value of 1.1 [W/m² K] is greatly lower than that of U-value 0.7 [W/m² K], with the values 106.5 and 164.0 kWh/m², respectively. Notably, the global warming potential of two windows, especially for 48 mm is much more than 36 mm, around 1.50 times bigger, at around 3.50 and 2.35 kg CO₂eq/m², respectively. After investigating the insulation materials in terms of environmental aspects, one can see how these insulation materials play a significant role in selecting renovation measures.

6.1.3 Total Primary Energy Use of Exterior Door

The exterior door investigated are standard door (U-value 1.1 [W/m² K]) and passive door (U-value 0.7 [W/m² K]) which meet the BBR (2018) [6] requirement, (see Table 32).
Table 32: Total material production primary energy and U-value of new exterior doors.

<table>
<thead>
<tr>
<th>Material</th>
<th>U-value [W/m² K]</th>
<th>Total Primary Energy Use [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Doors- Standard (92 mm) (U-value 1.1 W/m² K)</td>
<td>1.10</td>
<td>3.55</td>
</tr>
<tr>
<td>Exterior Doors- Passive (115 mm) (U-value 0.7 W/m² K)</td>
<td>0.70</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Table 32 indicates that although the exterior door (standard type) has a higher U-value than the passive one, the total primary energy of the standard exterior door is lower than the passive type with the value of 3.55 and 4.50 kWh/m², respectively. In this respect, the thickness factor is an important role in increasing the total primary energy use of the passive exterior door.

### 6.1.4 Total Primary Energy Use of Renovation Measures

In this part, the share of total primary energy use in material production and construction phases for various renovation strategies are compared in Figure 28.

![Figure 28: Total primary energy use of retrofit measures in material production and construction stages.](image)

Regarding material primary energy use, there is a huge gap between the production stage and construction one for different retrofit measures according to Figure 28. Scenario 1 encompassing cellulose insulation material plus window 36 mm 3-glass
layers gives the lowest primary energy in the production phase, at around 137 kWh/m². However, scenario 6 with glass wool plus window 48 mm 3-glass layers gives the highest primary energy consumption with 307 kWh/m². It is notable that those scenarios using the same insulation materials but with different windows and exterior doors type have similar behaviors in primary energy use of both stages. For example, scenario 5 with rock wool insulation material indicates a little bit higher primary energy use than scenario 2. This is because two different types of windows and exterior doors are included in two scenarios. Regarding the construction phase, scenarios 4, 5, and 6 follow a similar trend corresponding to scenarios 1, 2, and 3. For instance, scenarios 1 and 4 have the highest primary energy use, at 99 kWh/m² in the construction stage because of cellulose transportation.

6.2 Total Emission of Renovation Measures in Two Life Cycle Analysis Stages

The total environmental impact of material production and construction stages are presented in Figures 29 and 30, and Table 33 for the combinations of the different insulation materials and types of windows and exterior doors.

Figure 29: GWP 100 years for six renovation strategies in material production and construction phases.
Figure 29 shows the global warming potential of different retrofit measures in two stages. In material production stage, significant emission calculated for global warming potential is 61.55 kg CO₂-eq/m² for scenario 5 where rock wool material, window 48 mm 3-glass layers (U-value 0.7 [W/m² K]) and passive exterior door (U-value 0.7 [W/m² K]) are used. Furthermore, the lowest global warming potential comes from scenario 1 utilizing cellulose material with window 36 mm 3-glass layers (U-value 1.1 [W/m² K]), at 13.50 kg CO₂-eq/m². However, the construction stage indicates an opposite trend for different scenarios. Therefore, scenarios 4 and 3 give the highest and lowest global warming potential, respectively. Scenario 1 has different behaviors in the material production and construction stage. This stems from transportation’s role in the construction stage causing increasing global warming potential.

Regarding acidification potential and eutrophication potential, Figure 30 and Table 33 indicate the relevant environmental impact changes, respectively.

Figure 30: Acidification potential for six renovation strategies in material production and construction phases.

Figure 30 indicates that the trend in acidification potential is similar to the global warming potential for retrofit measures with the lowest impact for scenarios 1 and 3 in material production and construction stages, at 0.060 and 0.008 kg SO₂-eq/m², respectively. Notably, scenarios 2 and 5 stand at the highest emission with 26 and
24% of total acidification potential. The difference in emission between material production and construction stage for cellulose insulation materials used in scenarios 1 and 4 comes from the transportation role in the construction phase. This is because the location of the manufacturer for cellulose production is too far from the building site compared to other insulation materials. Eutrophication potential follows the above-mentioned environmental impacts trend in which cellulose (scenario 1) has the lowest emission with 6% of total eutrophication emission while scenario 5 shows the biggest impact of eutrophication potential with 32.50% for the material production stage (see Table 33).

Table 33: Eutrophication potential for six retrofit strategies.

<table>
<thead>
<tr>
<th>Renovation Measures</th>
<th>Eutrophication Potential [kg NO₃-eq/m²]</th>
<th>Eutrophication Potential [kg NO₃-eq/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production stage</td>
<td>Construction stage</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Cellulose + Window 36 mm + Standard exterior door</td>
<td>0.061</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Rock wool + window 36 mm + Standard exterior door</td>
<td>0.323</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Glass wool + window 36 mm + Standard exterior door</td>
<td>0.241</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Cellulose + window 48 mm + passive exterior door</td>
<td>0.063</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>Rock wool + window 48 mm + passive exterior door</td>
<td>0.325</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>Glass wool + window 48 mm + passive exterior door</td>
<td>0.245</td>
</tr>
</tbody>
</table>

The results for site activity in the construction stage show that the primary energy consumption and environmental impacts are negligible compared to the transportation share in that stage.
6.3 Transportation

As energy consumption of site activity is negligible, the significant effect of transportation can be seen in the construction stage where the value of scenario 4 gives the greatest primary energy consumption and environmental impacts among others, (see Figures 28 and 29). Furthermore, the distance from the factory producing cellulose insulation is more than other insulation materials, so this transportation consumes more primary energy in the construction stage.

6.4 Building Heating Energy

Figure 31 shows the comparison of building heating energy for the retrofit strategies conducted for the building envelope elements.

![Graph showing building heating energy for different renovation measures](image_url)

Figure 31: Building heating energy for different renovation measures in the operation stage.

The existing building heating energy at 94 kWh/m²-year does not fulfill BBR (2018) requirement (75 kWh/m²-year) [6]. For various renovation strategies utilizing different types of insulation materials, windows, and exterior doors, the building heating energy can be divided into two cases. Case one is related to the windows and exterior doors with a U-value of 1.1 [W/m²K] and case two with the windows and exterior doors with a U-value of 0.7 [W/m² K]. Each case is combined with three insulation materials, for which building heating energy varies. In Figure 31, the difference is between the two cases in which the type of glass with its thickness plays a decisive role in reducing building heating energy. However, as the thermal
conductivity of insulation materials is nearly in a similar range, with an average of 0.038 [W/m K], different insulation materials provide the same building heating energy for each case meeting BBR (2018) [6] requirements. Furthermore, these scenarios such as cases one and two save about 50 and 60 kWh/m²-year of building heating energy, respectively.

6.4.1 Comparison of Material Production Primary Energy Use with Heating Energy Saving of Operation Phase for Renovation Strategies

Using renovation measures including improved insulation materials has a direct effect on reducing building heating energy in the operation phase. Table 34 shows the comparison between material production primary energy use and building heating energy in the operation stage.

<table>
<thead>
<tr>
<th>Renovation Measures</th>
<th>Material Production Primary Energy Use [kWh/m²]</th>
<th>Heating Energy Saving after 50 years [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production stage</td>
<td>Operation stage</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>136.6</td>
<td>2,680</td>
</tr>
<tr>
<td>(Cellulose + Window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>293.8</td>
<td>2,685</td>
</tr>
<tr>
<td>(Rock wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3</td>
<td>305.0</td>
<td>2,680</td>
</tr>
<tr>
<td>(Glass wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>149.7</td>
<td>3,045</td>
</tr>
<tr>
<td>(Cellulose + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 5</td>
<td>305.7</td>
<td>3,050</td>
</tr>
<tr>
<td>(Rock wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 6</td>
<td>314.7</td>
<td>3,045</td>
</tr>
<tr>
<td>(Glass wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regarding Table 34, one can see that primary energy use of material production gives different values for retrofit strategies. Although renovation measures consume
higher primary energy use for material production, heating energy saving is increased significantly through renovation strategies in the operation stage.

6.5 Cost

6.5.1 Material, Labor, and Installation Costs

In this part, the results for total cost per square meter of insulation materials, installation and construction equipment combined in the form of renovation measures cost are compared in Figure 32.

![Figure 32: Renovation measures cost.](image)

In Figure 32, the highest cost of renovation measures is dedicated to scenario 4 including cellulose, windows 48mm 3-glass layers, and passive door, with a value of 1,120 SEK/m². In contrast, the lowest renovation measure cost is for scenario 3 where the glass wool, windows 36mm 3-glass layers, and standard door are used, at 580 SEK/m². For scenario 1 which includes cellulose as a sustainable energy resource, the total cost is 870 SEK/m² compared to scenario 5, with rock wool insulation, windows 48 mm 3-glass layers and passive door at 859 SEK/m².

6.5.2 Energy Cost

The results of energy cost show that using improved renovation measures can reduce the building heating energy whereby the energy cost decrease in the operation phase. Table 35 indicates building heating energy and energy cost for the existing school building and the case of renovation measures employed.
Table 35: Building heating energy and energy cost for the case of exiting and renovated building.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Building</td>
<td>93.8</td>
<td>1.05</td>
<td>98.5</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>40.2</td>
<td>1.05</td>
<td>42.2</td>
</tr>
<tr>
<td>(Cellulose + Window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>40.1</td>
<td>1.05</td>
<td>42.1</td>
</tr>
<tr>
<td>(Rock wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3</td>
<td>40.2</td>
<td>1.05</td>
<td>42.2</td>
</tr>
<tr>
<td>(Glass wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>32.9</td>
<td>1.05</td>
<td>34.5</td>
</tr>
<tr>
<td>(Cellulose + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 5</td>
<td>32.8</td>
<td>1.05</td>
<td>34.4</td>
</tr>
<tr>
<td>(Rock wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 6</td>
<td>32.9</td>
<td>1.05</td>
<td>34.5</td>
</tr>
<tr>
<td>(Glass wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regarding Table 35, a significant reduction can be seen in building heating energy and energy cost when the retrofit scenarios are conducted. This means that there is a direct relationship between building heating energy and energy cost, which are affected by retrofit measures. For instance, scenarios 1, 2, and 3 give building heating energy at 4 kWh/m² while the other scenarios give an average lower value at around 33 kWh/m² because of using improved materials with lower U-value. Thus, the energy cost of retrofit scenarios 1, 2, and 3 is 42 SEK/m² and for scenarios 4, 5, and 6 is 34 SEK/m². However, the exiting building consumes 94 kWh/m² of heating energy with an energy cost of 98 SEK per square meter. Notably, one can see that the energy cost saving is around 50 SEK/m².
6.5.3 Comparison of Renovation Cost and Energy Cost Saving

The benefit of using renovation measures in terms of cost for saving energy in the operation phase after 50 years is compared and represented in Table 36.

<table>
<thead>
<tr>
<th>Renovation Measures</th>
<th>Renovation Cost [SEK/m²]</th>
<th>Energy Cost [SEK/m²-year]</th>
<th>Energy cost saving [SEK/m²-year]</th>
<th>Energy Cost saving after 50 years [SEK/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Building</td>
<td>-</td>
<td>98.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>868.0</td>
<td>42.2</td>
<td>56.3</td>
<td>2,815.0</td>
</tr>
<tr>
<td>(Cellulose + Window36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>712.0</td>
<td>42.1</td>
<td>56.4</td>
<td>2,820.0</td>
</tr>
<tr>
<td>(Rock wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3</td>
<td>576.0</td>
<td>42.2</td>
<td>56.3</td>
<td>2,815.0</td>
</tr>
<tr>
<td>(Glass wool + window 36 mm + Standard exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>1,121.0</td>
<td>34.5</td>
<td>64.0</td>
<td>3,200.0</td>
</tr>
<tr>
<td>(Cellulose + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 5</td>
<td>859.0</td>
<td>34.4</td>
<td>64.1</td>
<td>3,205.0</td>
</tr>
<tr>
<td>(Rock wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 6</td>
<td>723.0</td>
<td>34.5</td>
<td>64.0</td>
<td>3,200.0</td>
</tr>
<tr>
<td>(Glass wool + window 48 mm + passive exterior door)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regarding Table 36, there is a relation between renovation cost and energy cost saving. Although renovation scenarios increase costs at first, energy cost is significantly reduced after 50 years. This means that it seems costly through performing renovation scenarios to save building heating energy in the operation
stage. However, energy cost decreased yearly, and this saved averagely 3 times more than the initial cost of renovation after 50 years, therefore it makes renovation cost reasonable.

6.6 Structural Analysis

The building structure was modeled and analyzed by Dlubal software, and the structural analysis results are indicated in this part. Based on SS-EN 90-91 [36], several load combinations have been defined for the ultimate limit state (ULS) and serviceability limit state (SLS), in which the critical load combinations are represented in Table 37.

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Critical Load Combinations Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1.35 DL + 1.05SL + 1.5LL + 1.35 Self-Wight + 1.35 StL</td>
</tr>
<tr>
<td>SLS</td>
<td>DL + SL+ LL+ Self-Wight + StL</td>
</tr>
</tbody>
</table>

The analysis of structure based on the ULS and the SLS shows that the critical load combination happened with dead loads, live load, and snow load with corresponding coefficients in the ULS and without coefficients in the SLS according to SS-EN 90-91 [36] and [37].

6.6.1 Maximum Bending Moment in Slab

The maximum bending moment under critical ULS load combination in the middle of the slab is shown in Figure 33. The maximum bending moment for the longest span of the slab at 10 m is $M_{Ed} = 50.5 \text{ kN.m}$. This must be smaller than bending moment resistance $M_{Rd}$ which is 51 kN.m.
6.6.2 Maximum Deflection and Displacement in Slab and Load-Bearing Walls

Regarding the SLS criteria, the maximum displacement in the load-bearing wall with a span of 10 m gives the value of 2.1 mm in y-direction at the wall located on the edge of the building, (see Figure 34). The limited value of displacement for the wall is 14 mm which is fulfilled. Moreover, the deflection in the slab with a 9.50 m span under SLS critical load combinations gives the value of 17.50 mm smaller than the allowable limit of slab deflection is 37 mm. Figure 35 shows the slab deflection under the critical SLS load combinations.

![Figure 34: Load-bearing wall displacement.](image1)

Regarding the load-bearing brick wall (Figure 36), the maximum design compressive stress is 7.50 MPa, which fulfills the limitation criteria for the brick wall resulting in $f_k = 9.50$ MPa, which represents the compressive resistance stress.

![Figure 35: Deflection in the slab (SLS).](image2)
6.6.3 Shear Control in Slab

After investigation of the moment in the slab, shear resistance and design must also fulfill Eurocode [69] criteria. The maximum shear force considered in the slab happened at a distance of \(d\) (the mean of the effective depth in orthogonal directions of cross-section) from the support, (see Figure 37). In this case, the maximum shear force is \(V_{Ed} = 72\) kN/m and shear resistance is \(V_{Rd,c} = 80\) kN/m. This indicates that the corresponding criteria are fulfilled, and the slab does not have flexural shear failure.

The internal forces for different load combinations are shown in Table 38. One can see that the maximum bending moment of the structure is related to the critical load combinations coming from ultimate limit state such as 1.35DL+1.5LL+1.05SL. For deflection, the maximum one comes from the critical SLS load combination,
DL+LL+SL. From the shear force and normal force perspective, both maximum values are dedicated to the ULS critical load combination.

Table 3: Internal forces for different load combinations (ULS and SLS).

<table>
<thead>
<tr>
<th>Load combination cases</th>
<th>Bending moment (y-direction) [kN.m]</th>
<th>Shear force (y-direction) [kN/m]</th>
<th>Normal force (y-direction) [kN/m]</th>
<th>Deflection in Slab [mm] (z-direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.35DL+1.5LL+1.05SL</td>
<td>43.5</td>
<td>64.8</td>
<td>63.9</td>
<td>23.9</td>
</tr>
<tr>
<td>1.35DL+1.5LL+1.05WL (2)</td>
<td>41.2</td>
<td>61.8</td>
<td>60.2</td>
<td>23.6</td>
</tr>
<tr>
<td>1.35DL+1.5LL+1.05WL (1)</td>
<td>49.1</td>
<td>60.4</td>
<td>59.8</td>
<td>23.7</td>
</tr>
<tr>
<td>1.35DL+1.5WL (1)</td>
<td>45.7</td>
<td>65.7</td>
<td>65.4</td>
<td>22.9</td>
</tr>
<tr>
<td></td>
<td>+1.05SL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.35DL+1.05SL+1.5LL</td>
<td>50.6</td>
<td>71.8</td>
<td>71.5</td>
<td>24.2</td>
</tr>
<tr>
<td>DL+LL+WL</td>
<td>35.8</td>
<td>51.8</td>
<td>51.2</td>
<td>17.2</td>
</tr>
<tr>
<td>DL+LL+SL</td>
<td>38.7</td>
<td>55.4</td>
<td>54.8</td>
<td>17.8</td>
</tr>
</tbody>
</table>
7 SENSITIVITY ANALYSIS

In the inventory analysis, there are various uncertainties and sensitive parameters. The sensitive elements in this study refer to the source of electricity and roof materials. Two distinct sensitive analyses are performed in the section below.

7.1 Electricity Scenarios

7.1.1 Primary Energy Use of Material Production and Environmental Impacts

Regarding the electricity resources of material production, we assumed two scenarios including the Swedish electricity average and marginal coal-based electricity. The amount of electricity consumed during the production of insulation materials depending on the type of source is compared with each other. Figure 38 shows the comparison of the primary energy use of insulation material production when using the Swedish average electricity and marginal coal-based electricity. Regarding the Swedish average electricity use, glass wool gives 195 kWh/m² material production primary energy use more than rock wool and cellulose with 155 and 25 kWh/m², respectively.

![Swedish Electricity Average and Marginal Coal-Based Electricity](image)

Figure 38: Primary energy use of material production based on Swedish average and marginal coal-based electricity.
In Figure 38, it is notable that there is a huge gap between the primary energy use, depending on the source of electricity supply for material production. The difference is around twice for the primary energy use when marginal coal-based electricity is assumed.

Electricity source for window material production plays an important role in reducing primary energy use and environmental impacts. Figure 39 shows the comparison of the total primary energy use of material production for two types of windows, utilizing the Swedish average electricity and marginal coal-based electricity.

![Electricity Scenarios](image.png)

Figure 39: Primary energy use of windows material production based on Swedish average and marginal coal-based electricity.

Regarding the source of electricity supply for windows, the results for Swedish average electricity are towards low primary energy use. Furthermore, windows with 36 mm 3-glass layers have lower total primary energy use at around 107 kWh/m² when the electricity is based on the Swedish average, while the marginal coal-based electricity gives primary energy use of 220 kWh/m². There is a similar trend for windows 48 mm 3-glass layers when two electricity sources are compared. It might be notable that the emissions from the above-mentioned windows have a significant impact on global warming. The comparison of the environmental impacts between the two types of windows is shown in Table 39.
Table 39: Environmental impacts of electricity resource as primary energy for windows production.

<table>
<thead>
<tr>
<th>Material - Source of Electricity</th>
<th>Global Warming Potential [kg CO₂-eq/m²]</th>
<th>Acidification Potential [kg SO₂-eq/m²]</th>
<th>Eutrophication Potential [kg NO₃-eq/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Swedish average electricity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows scenario 36 mm (U-value 1.1 [W/m² K])</td>
<td>3.0</td>
<td>0.5e-2</td>
<td>0.8e-3</td>
</tr>
<tr>
<td>Windows scenario 48 mm (U-value 0.7 [W/m² K])</td>
<td>4.5</td>
<td>0.9 e-2</td>
<td>0.7 e-2</td>
</tr>
<tr>
<td><strong>Marginal coal electricity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows scenario 36 mm (U-value 1.1 [W/m² K])</td>
<td>89.0</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Windows scenario 48 mm (U-value 0.7 [W/m² K])</td>
<td>127.3</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Windows production using the Swedish average electricity, affect the environment considerably much less than those using marginal coal-based electricity. The global warming potential value of windows 36 mm 3-glass layers (U-value 1.1 [W/m² K]) with the Swedish average electricity and marginal coal-based electricity are 3 and 4.5 kg CO₂-eq/m², respectively. However, there is a big difference in environmental impacts of windows 36 and 48 mm 3-glass layers in marginal coal-based electricity case with the value of 89.0 and 128.0 kg CO₂-eq/m² for global warming potential. Regarding acidification and eutrophication potential for window 48 mm, marginal coal-based electricity source gives the highest emission at 0.5 kg SO₂-eq/m² and 0.7 kg NO₃-eq/m², respectively.

7.1.2 Environmental Impacts of Renovation Scenarios

We compared the total environmental impacts of the two electricity accounting methods for the renovation scenarios. Figures 40, 41, and 42 show the global warming potential, acidification potential, and eutrophication potential, respectively.
Figure 40: 100-year GWP of material production for three renovation measures using two different electricity resources.

Figure 40 indicates that the global warming potential of all scenarios using marginal coal-based electricity is more than those of using the Swedish average electricity. Scenario 3 shows the most global warming potential with 217 and 46 kg CO₂-eq/m² for marginal coal-based electricity and the Swedish average electricity, respectively.

Figure 41: Acidification potential of material production for three renovation measures using two different electricity resources.
Regarding Figure 41, renovation measures using the Swedish average electricity emit less SO2-eq than those using the marginal coal-based electricity. The biggest impact is related to scenario 3 for the marginal coal-based electricity at 0.60 kg SO2-eq/m². In contrast, scenario 2 has the greatest effect on the Swedish average electricity at 0.25 kg SO2-eq/m².

![Eutrophication Potential Diagram]

Figure 42: Eutrophication potential of material production for three renovation measures using two different electricity resources.

For eutrophication potential, the results nearly follow the acidification potential trend and the significant difference among renovation measures can be seen in scenario 3 where there is a huge gap between Swedish electricity average and marginal coal one, with the values of 0.25 and 0.65 kg NO3-eq/m², respectively.

### 7.2 Roof Tile Material

As there is no tile for the roof of the existing school, two scenarios were selected to insulate the top of the roof better to help save energy. In these scenarios, two materials, concrete tile, and clay tile were considered for the roof. Table 40 compares the two scenarios and indicates that clay tile gives lower material production primary energy use than concrete tile with values of 5 and 11 kWh/m².
Table 40: Total primary energy of material production and environmental impacts comparison for two purposed roof tiles.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total primary energy use [kWh/m²]</th>
<th>Global Warming Potential [kg CO₂-eq/m²]</th>
<th>Acidification Potential [kg SO₂-eq/m²]</th>
<th>Eutrophication Potential [kg NO₃-eq/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof with concrete tile</td>
<td>10.95</td>
<td>1.60</td>
<td>0.64e-2</td>
<td>0.79e-2</td>
</tr>
<tr>
<td>Roof with clay tile</td>
<td>5.05</td>
<td>0.98</td>
<td>0.35e-2</td>
<td>0.52e-2</td>
</tr>
</tbody>
</table>

Regarding environmental impacts, concrete tiles show a more damaging impact with higher global warming potential. For clay tile, global warming potential is around 1.00 kg CO₂-eq/m² while the concrete tile emits 1.60 kg CO₂-eq/m². Acidification and eutrophication potential follow a similar trend for clay and concrete tile.
8 DISCUSSION

8.1 Material Production Burdens

As different renovation measures have been assessed for the school building envelope components, the results showed that using appropriate insulation materials in terms of renewable primary energy use and carbon reduction can help save the building’s heating energy. In this respect, the results emphasize that insulation materials production accounts for a great share of using primary energy and also environmental effects. Moreover, the life cycle assessment of the material production stage indicates that scenario 6 using glass wool, windows with a U-value of 0.7 [W/m² K], and passive exterior doors give the highest primary energy use. In contrast, scenario 4 gives the highest primary energy use in the construction stage. Regarding the environmental impacts, scenario 5 gives the biggest one in the material production stage. This is because of the bigger mass of rock wool coming from its higher density compared to glass wool. However, the proportion of fossil fuels used in glass wool insulation material is significantly more than the rock wool and cellulose insulation materials.

Regarding the type of windows, the results showed that windows with a U-value of 0.7 [W/m² K] consume more primary energy and give a considerable global warming potential in the production phase.

The lowest primary energy use and environmental impacts in the production stage are dedicated to scenarios 1 and 4 utilizing cellulose insulation material with windows of 36 mm glass (U-value 1.1 [W/m² K]). The source of primary energy for cellulose insulation material is obtained from the combination of renewable and non-renewable energy with the lowest use of fossil fuels among mentioned insulation materials.

Regarding the sensitivity analysis carried out for the electricity sources for material production for the renovation scenarios, the results showed that the retrofit measures using the marginal coal-based electricity have more total primary energy use and environmental impacts. However, when the marginal coal-based electricity is replaced by the Swedish average electricity as a source of energy, the results of the production stage are significantly reduced in terms of total primary energy use and environmental impacts. The reason for this benefit is that the Swedish average comes from renewable energy resources such as hydropower and nuclear while marginal electricity uses fossil fuel sources.
8.2 Construction Stage

The energy which is used in this stage is quite different for insulation materials. Regarding transportation part (A4), the primary energy consumption of cellulose insulation material transportation is significant since the location of manufacturers assumed is too far away from the construction site. This results in increased environmental impacts during the transportation of material. For the installation part (A5), the total primary energy use of all materials is negligible compared to the production stage. In the construction phase, the only factor playing a key role in primary energy use and environmental impacts is material transportation but it is not as much amount as that in the production stage.

8.3 Heating Energy in Operation Phase

Regarding the building heating energy in the operation stage after the renovation measures, the results showed that we can divide the scenarios into two cases, one of which is related to the scenarios using windows and exterior doors with a U-value of 1.1 [W/m² K] and the other one for those of U-value of 0.7 [W/m² K]. In this part, three insulation materials used in each scenario provide the same building heating energy. However, the main difference is that using two types of windows and exterior doors with a U-value of 0.7 [W/m² K] gives rise to a marked reduction. However, as the part of the thesis goal is toward preferably using sustainable primary energy resources with lower environmental impacts for material production, the scenario utilizing cellulose plus windows and exterior doors with a U-value of 1.1 [W/m² K] can be categorized as a sustainable option with the lowest primary energy use and environmental effects.

8.4 Materials, Labor, and Installation Costs

The results of cost calculations for different renovation measures indicated that the scenarios utilizing cellulose material and windows 36 mm glass layers and standard exterior doors are approximately costly. In contrast, the costs are reduced if the scenarios with glass wool are selected. In this respect, although the cost-effectiveness is part of the aim and goal of the school building retrofitting, the more focus has been on using materials coming from renewable energy resources with lower environmental impacts based on fulfilling BBR (2018) requirements [6]. If the renovation consideration is oriented toward reducing building heating energy in the service stage with sustainable materials, primary energy use of materials and their environmental impacts are placed at the center of attention. Thus, when the building
heating energy decreases, the cost of district heating is automatically minimized during the operation phase. In fact, by using improved insulation materials with lower energy resource use and environmental effects, besides their higher cost, we recover the cost by reducing heat losses to save energy in the service phase after 50 years.

8.5 Structural Analysis

After adding new insulation materials as permanent loads to building envelope components, structural analysis based on the Eurocode [37] was checked. Regarding the structural analysis, the maximum bending moment and deflection in the slab located in the middle of the structure are smaller than the allowable limit according to the Eurocode [69]. For load-bearing brick walls, the displacement is smaller than the allowable limit based on Eurocode [70]. Furthermore, the new snow and wind loads were imposed on the structure, for which the maximum bending moment, deflection, and displacement in slab and walls are satisfied for critical load combinations in the ultimate limit state (ULS) and serviceability limit state (SLS), respectively [39] and [38].

Although insulation materials loads are added to the structural elements, the main structural elements just undergo slight changes which do not have significant effects on the stability of the structure.
9 CONCLUSIONS

In this study, a life cycle assessment for the renovation of the Ulriksberg school building was conducted. The school building is located in Vaxjo, Sweden, and different retrofit measures using various insulation materials, and improved window and exterior door types were investigated from primary energy use and environmental impacts perspectives. Two life cycle stages, production, and construction were included with some limitations due to lack of data and delimitation. There has been no similar case study of school renovation in Sweden, to the best of our knowledge. This means that this assessment can be used as a case for similar assessments.

This research provides the primary energy consumption and the global warming potential, acidification potential, and eutrophication potential for building envelope components and insulation materials which are defined in the form of various renovation measures and evaluated considering two life cycle analysis stages.

The following conclusions are derived from this study:

- The material production phase (A1-A3) shows the most primary energy use and environmental impacts.
- Cellulose insulation material is from renewable energy resources and gives the lowest primary energy use for the building renovation.
- Glass wool and rock wool use a lot of non-renewable energy resources and fossil fuels and give bigger environmental impacts.
- Transportation plays a remarkable role in increasing environmental impacts and energy consumption in the construction stage.
- The source of electricity is a sensitive factor for primary energy use and environmental impacts of materials production.
- Using renovation strategies reduces the building heating energy in the operation stage, and energy cost savings are realized after 50 years.
- Cellulose as an insulation material has the highest cost due to renewable energy resource use.
- Material installation in the construction stage gives negligible primary energy use and environmental impacts in this study.
- The renovation scenario including cellulose insulation material, windows with U-value of 1.1 [W/m²K] and exterior standard door gives the optimal renovation cost regarding significant energy savings after 50 years.
- The renovation scenario including cellulose, window 48mm and passive exterior door gives the highest renovation cost and the most energy savings.
- Adding new roof tile and insulation materials loads does not have significant effects on the stability of the studied structure.
- The building structure under investigation of the Eurocode criteria remains stable after the application of the studied renovation measures.
References


## Appendices

Appendix 1: Emission

<table>
<thead>
<tr>
<th>Material resource</th>
<th>Kg CO₂/kWh</th>
<th>Kg CH₄/kWh</th>
<th>Kg NOₓ/kWh</th>
<th>Kg SO₂/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>0.4</td>
<td>0.00108</td>
<td>0.0000054</td>
<td>-</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>0.3</td>
<td>0.00108</td>
<td>0.0000054</td>
<td>-</td>
</tr>
<tr>
<td>Lignite coal</td>
<td>0.4</td>
<td>0.00108</td>
<td>0.0000054</td>
<td>-</td>
</tr>
<tr>
<td>Coke</td>
<td>0.4</td>
<td>0.00004</td>
<td>0.0000054</td>
<td>-</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.2</td>
<td>0.00004</td>
<td>0.0000022</td>
<td>-</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>0.3</td>
<td>0.00004</td>
<td>0.0000022</td>
<td>-</td>
</tr>
<tr>
<td>Biomass, wood or solid</td>
<td>0.3</td>
<td>0.00004</td>
<td>0.0000022</td>
<td>-</td>
</tr>
<tr>
<td>Biomass sustainable forest</td>
<td>0.4</td>
<td>0.00108</td>
<td>0.00000144</td>
<td>-</td>
</tr>
<tr>
<td>Coal</td>
<td>0.0</td>
<td>0.0000</td>
<td>-</td>
<td>0.00062136</td>
</tr>
<tr>
<td>Wooden fuel</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.00000936</td>
</tr>
<tr>
<td>Natural gas</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.00007092</td>
</tr>
<tr>
<td>Light heating oil</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.00049752</td>
</tr>
<tr>
<td>Electricity Swedish average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.00002268</td>
</tr>
</tbody>
</table>
Table 2: Greenhouse gas emissions of material production for windows 36 mm

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon emission (kg CO₂/m²)</th>
<th>CH₄ emission (kg CH₄/m²)</th>
<th>NOₓ emission (kg NOₓ/m²)</th>
<th>SO₂ emission (kg SO₂/m²)</th>
<th>NH₄ emission (kg NH₄/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame-Wood (pine)</td>
<td>0.25</td>
<td>0.00061</td>
<td>9E-6</td>
<td>7.15E-5</td>
<td>-</td>
</tr>
<tr>
<td>3-Glass-36mm aluminum edging</td>
<td>1.49</td>
<td>0.002</td>
<td>2E-5</td>
<td>0.0021</td>
<td>0.002</td>
</tr>
<tr>
<td>Frame-Aluminum Total</td>
<td>0.3</td>
<td>0.0005</td>
<td>0.0006</td>
<td>0.0022</td>
<td>-</td>
</tr>
<tr>
<td>Frame-Wood (pine)</td>
<td>0.25</td>
<td>0.0006</td>
<td>9E-6</td>
<td>7.15E-5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3: Greenhouse gas emissions of material production for windows 48 mm

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon emission (kg CO₂/m²)</th>
<th>CH₄ emission (kg CH₄/m²)</th>
<th>NOₓ emission (kg NOₓ/m²)</th>
<th>SO₂ emission (kg SO₂/m²)</th>
<th>NH₄ emission (kg NH₄/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame-Wood (pine)</td>
<td>0.26</td>
<td>0.000616</td>
<td>1.85E-5</td>
<td>7.16E-5</td>
<td>-</td>
</tr>
<tr>
<td>3-Glass-48mm aluminum edging</td>
<td>2.21</td>
<td>0.003</td>
<td>6.4E-5</td>
<td>0.0032</td>
<td>0.0035</td>
</tr>
<tr>
<td>Frame-Aluminium Total</td>
<td>0.35</td>
<td>0.000525</td>
<td>0.0011</td>
<td>0.0024</td>
<td>-</td>
</tr>
<tr>
<td>Frame-Wood (pine)</td>
<td>2.21</td>
<td>0.00061</td>
<td>1.85E-5</td>
<td>0.0056</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4: Greenhouse gas emissions of insulation materials

<table>
<thead>
<tr>
<th>Insulation Material (Renovating Building)</th>
<th>Carbon emission (kg CO₂/m²)</th>
<th>CH₄ emission (kg CH₄/m²)</th>
<th>NOₓ emission (kg NOₓ/m²)</th>
<th>SO₂ emission (kg SO₂/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Wool</td>
<td>8.91</td>
<td>0.023</td>
<td>0.0026</td>
<td>0.0152</td>
</tr>
<tr>
<td>Cellulose</td>
<td>1.49</td>
<td>0.003</td>
<td>0.00141</td>
<td>0.0023</td>
</tr>
<tr>
<td>Glass Wool</td>
<td>6.41</td>
<td>0.017</td>
<td>2.8E-5</td>
<td>0.0114</td>
</tr>
</tbody>
</table>

Final energy use:

Table 5: Final energy use for different insulation materials in different building parts.

<table>
<thead>
<tr>
<th>Insulation Material (Renovating Building)</th>
<th>Total Final Energy External Wall (KWh/m²)</th>
<th>Total Final Energy Floor (KWh/m²)</th>
<th>Total Final Energy Internal Wall (KWh/m²)</th>
<th>Final Energy Roof (KWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>10</td>
<td>9.35</td>
<td>3.45</td>
<td>4.41</td>
</tr>
<tr>
<td>Rock Wool</td>
<td>58.3</td>
<td>57.63</td>
<td>20.9</td>
<td>26.91</td>
</tr>
<tr>
<td>Glass Wool</td>
<td>60.1</td>
<td>57.1</td>
<td>20.9</td>
<td>26.98</td>
</tr>
</tbody>
</table>
Structural part:

**Live load**

**Floor**

\[ q_{l,\text{floor}} = 3 \text{ kN/m}^2 \]

Page 27
1991-1-1 table 6.2

**Roof**

\[ q_{l,\text{roof}} = 0.5 \text{ kN/m}^2 \]

Table 6.10 page
33-SS EN
1991-1-1

**Dead load**

**Floor**

Effective area of the floor

\[ b_{\text{floor}} = 10 \text{ m} \]
\[ t = 20 \text{ cm} = 0.2 \text{ m} \quad \text{Slab thickness} \]
\[ L_{\text{floor}} = 65 \text{ m} \]

Density of floor = 25 \text{ kN/m}^2

Volume = \[ b_{\text{floor}} \times t \times L_{\text{floor}} = 130 \text{ m}^3 \]

Self w. floor = Density \times t = 5 \times \frac{1}{m^2} \cdot \text{kN}

Total Self w. floor = Self w. floor \times 1.01 \cdot \text{kN}

Final Self w. floor = Total Self w. floor \times \text{factor} = 5.5 \times \frac{1}{m^2} \cdot \text{kN}
**Roof**

- **concretecalc.:** 2500 kg
  \[
  \frac{2500}{650 \cdot 100} = 0.038 \text{ kN} \text{ m}^{-2}
  \]

- **Truss:** 77 kg
  \[
  \frac{77}{6 \cdot 100} = 0.128 \text{ kN} \text{ m}^{-2}
  \]

- **Slag_furnace:** 13000 kg
  \[
  \frac{13000}{650 \cdot 100} = 0.2 \text{ kN} \text{ m}^{-2}
  \]

- **Mineral_wool:** 57600 kg
  \[
  \frac{57600}{412 \cdot 100} = 1.398 \text{ kN} \text{ m}^{-2}
  \]

- **Concrete:** 5 \( \text{kN m}^{-2} \) (it is calculated by software)

- **Sum_Deadload:** 0.04 + 0.128 + 0.2 + 1.4 = 1.768 \( \text{kN m}^{-2} \)

**Snow load Calculation**

- **Växjö**
  \[
  S_t = 2 \text{ kN m}^{-2}
  \]

- **EN91-1-3 page 24(8)**

- **b:** 65 m

- **EN91-1-3 page 24(table 5.1)**

- **L:** 10 m

- **EN91-1-3 Tabell 5.2**

- **area:** \( b \cdot L = 650 \text{ m}^2 \)

- **\( S = M \cdot C_t \cdot C_x \cdot S_t = 1.6 \text{ kN m}^{-2} \)**
Wind load Calculation

\[ q_0 = \frac{1}{2} \cdot \rho \cdot v^2 = 0.36 \frac{kN}{m^2} \]
\[ q_1 = q_0 \cdot c_{c d} = 0.72 \frac{kN}{m^2} \]
\[ w_{v \text{ir}_{\text{smooth}}} = q_0 \cdot c_{p_{v \text{ir}_{\text{smooth}}}} = -0.36 \frac{kN}{m^2} \]
\[ w_{v\text{ir}_{\text{smoothD}}} = q_0 \cdot c_{p_{v \text{ir}_{\text{smoothD}}}} = 0.576 \frac{kN}{m^2} \]