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Life cycle analyses of CO2 emissions of alternative retrofitting measures

Thesis for the degree of Philosophiae Doctor

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Norwegian University of Science and Technology
Faculty of Architecture and Fine Art
Department of Architectural Design, History and Technology
The Research Centre on Zero Emission Buildings

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Dedication

This thesis is dedicated to my parents.

Their support, encouragement, and constant love have sustained me throughout my life.

Abstract

The greenhouse gas emissions from the building sector are considered by the scientific community as one of the most important causes of the current climate change. As reported by the Intergovernmental Panel for the Climate Change (IPCC) the future trend of the global climate is determined by the now-occurring emissions of CO_2, of which the building sector takes an important part.

The latest European energy codes for buildings have implemented the concepts of low-energy houses, and passive houses are one answer to reduce the building stock energy need. However, these standards and regulations do not fully consider the aspects of embodied emissions of the building construction phase. As shown in many studies, the embodied energy and emissions of the construction materials gain more relevance when the energy need for building operation is reduced. Since the newest building regulations are heading towards stricter limits for energy use in order to comply with the Kyoto Protocol, the share of embodied energy and emissions will have more influence in the total energy balance of future constructions. In this perspective, the current energy-efficiency standards do not suffice to describe the complex issues of assessing the lifecycle energy of residential buildings. New and recently developed concepts, such as the zero energy building, zero emission building, and lifecycle zero energy building, have been introduced to better fit the path to a low-carbon built environment.

The current practice of building energy upgrade considers the use of thick layers of insulation in order to comply with the energy codes. This aspect is very relevant for the Norwegian building stock because the local climate requires the use of strict measures in order to reduce the energy use. As a consequence, the trend of the national energy codes for residential buildings is moving forward to very low U-values for the building envelopes. Even if it is beyond any doubt that the use of thick insulation layers is advantageous for the reduction of the building energy use in cold climates, this measure might actually be disadvantageous when considering the CO_2 emissions due to the production of the materials used in such retrofitting activities.

The aim of this research is therefore to study the effect that different energy retrofitting alternatives have on the lifecycle CO_2 emissions of an apartment building in Oslo, Norway. Specifically, this research focuses on assessing the most important aspects that characterize the energy upgrade of the facades of an apartment building using lifecycle emission calculations. The building façades are the focus of this research, since they are the parts where the energy exchanges, the embodied CO_2 emissions and the architectural appearance converge. This has been highlighted by the current trend in architecture, which often defers the whole architectural expression to the appearance of façade systems.

The aspects that characterize the energy upgrade of the facades are framed under two main criteria of analysis called the *technical approach* and the *architectural approach*. As a consequence, the alternatives for energy retrofitting are chosen

using both a technical approach and an architectural approach. The first considers the choices of the insulation materials, for the opaque and the transparent surfaces of the building facades. The second consider the choices that define the façade appearance, such as the finishing, the relationship between the glazed and the opaque part of the façade, and the presence of balconies or sunspaces. In such a perspective, the energy retrofitting alternatives proposed in this work either maximize the choice of façade appearances, or the choice of energy saving solutions. Several sensitivity analyses are introduced to better understand to what extent factors, such as the replacement rate of the building materials, the building lifetime, and the electricity-to-emissions conversion factor, influence the lifecycle emissions of each energy retrofitting alternative. Each combination of the aspects listed in the technical and architectural approaches, and the factors given by the sensitivity analyses defines an energy retrofitting alternative. The results of all the proposed energy retrofitting alternatives, given as kg of CO_2 emissions, are collected into a matrix, called *matrix of choices.*

The findings of this research show that it is not possible to find an optimal solution for the energy retrofitting of an apartment building that results in minimal CO_2 emissions. These conclusions somehow contradict the policies of energy savings in buildings that have been proposed in Norway in the past years. According to these policies many energy-saving regulations were proposed based on the fact that the buildings, either new or renovated, were optimized in order to reduce their energy use for operation. The results show, instead, that the best practice for energy retrofitting apartment buildings in Norway will depend on how much emissions will derive from the use of energy from the grid and on the location of the production plants for materials and components. The results presented in this work show that in future buildings the embodied emissions of materials might be as critical as the energy use.

Given the results and the limitations of this work, it is pointed out that a further investigation on other insulation materials and other residential building types is a development worth being considered. This will give a better understanding on the effects on the lifecycle CO_2 emissions that the energy retrofitting has on different building types.

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List of contents

List of figures

List of tables

1. Introduction

1.1. Energy use and emissions in the building sector

The greenhouse gas emissions from the building sector are considered by the scientific community as one of the most important causes of the current climate change. As reported by the Intergovernmental Panel for the Climate Change (IPCC) the future trend of the global climate is determined by the now-occurring emissions of CO_2, of which the building sector takes an important part. An extract from the Energy Efficiency in Building Report from the World Business Council for Sustainable Development, released in 2008, states:

> *These climate changes are caused mainly by increased concentration of greenhouse gases in the atmosphere due to human activity. Carbon dioxide (CO_2) is the most important greenhouse gas and its concentration is more than a third higher than before the industrial revolution, so that it is now higher than at any time over the last 650,000 years. Annual CO_2 emissions from fossil fuel increased from an average of 6.4 gigatons of carbon (GtC) in the 1990s, to 7.2 GtC in 2000-2005 – and the rate of increase has accelerated* [1].

Both the building industry and the building stock are energy-intensive sectors and origin of high greenhouse gas emissions. The production, installation, transportation and disposal of building materials and the use of energy to deliver thermally conformable buildings cause the current high rate of energy use. According to many sources [1-3] 40% of the total primary energy use for building operation in the EU is attributed to the building sector and is the cause of approximately 25% of the total CO_2 emissions [4]. To follow the path towards the global greenhouse gas emission abatement established with the Kyoto Protocol, several European countries have adopted various measures and regulations that address energy-saving strategies in the residential sector. However, the newest building standards do not alone suffice to meet the environmental targets if a consistent campaign of renovation of residential buildings is not commenced. A study by Nemry et al. shows that the shares of energy use and CO_2 emissions of the newest residential constructions of the EU-25 countries are negligible values, as shown in Figure 1 [5].

A more-in-depth observation of the residential composition shows that the environmental impact due to single-family-house types constitutes up to 64% of the total stock, followed by multi-apartment buildings with 32%. The main cause of these differences is attributed to the ratio of exposed-surface/heated-volume, which defines the construction compactness and determines the amount of energy losses through the building envelope. Accordingly, the building geometrical diversity also has an influence on the way the building loses energy. According to Nemry's study, single-family houses have major losses through their building components (in this case mostly roof and basement) independently of the climatic zone. On the other hand, in high-rise and multi-family buildings most energy losses occur in the ventilation system and in the facades [5].

The need for retrofitting the existing stock is an urgent issue for the European countries, particularly because space heating is responsible for a high share of the total energy use in buildings, especially in cold climates. Even so, the combination of poor insulation and construction quality of most existing homes with the current technical solutions for building renovation represents a high potential of energy saving for the current residential stock.

1.2. The potential of energy retrofitting in the residential sector

According to the current trend, the building sector is expecting to face a low-rate growth due to little new construction activity, while it will be characterized by an increasing living area per unit and, consequently, increasing energy use per residence. Due to the low construction rate, the future stock will be represented mostly by buildings that have already been erected and that often have very little thermal insulation. As a consequence, if radical measures are not introduced in the near future, the residential stock in need of renovation will grow consistently.

According to Uihlein and Eder, in the next 50 years the EU-27 residential stock will probably see an annual increase of its total living area by 1.46%, the dwelling size is estimated to grow by 0.9%, and the number of persons per household is projected to decrease by 0.5% per year. This analysis shows that the rate of new construction (which considers only the units added to the existing stock) will grow by 1.5% in the next 50 years, while the rate of renovation will increase by between 1.6% and 1.8% from 2000 to 2060 [2]. Uihlein and Eder's study also describes the possible increase of the level of energy efficiency in buildings by applying different retrofitting scenarios to the residential building stock in the EU-27 countries. Uihlein and Eder present two retrofitting scenarios aimed at improving and optimizing the energy saving measures proposed in the building directive (EPBD) recast: these are the *cost-optimal* and *cost-optimal with acceleration* (Figure 2). Both scenarios project different time targets for achieving various levels of energy efficiency of residential buildings. Each level consists of four renovation packages that, according to the three main climatic zones in which Europe is divided, include different insulation thicknesses in walls and roofs and different U-values of windows. The results presented by Uihlein and Eder show that between 2010 and 2060 the *cost-optimal* and the *cost-optimal with acceleration* scenarios save 30% and 37% of the annual energy demand of the EPBD scenario, respectively [2]. The optimized scenarios favour a drastic reduction in energy use until 2050, while they converge to the EPBD scenario from 2050 to 2060. Thus, they show a high potential for environmental impact and cost savings for the existing residential stock in the EU.

The McKinsey & Company report, issued in 2009, *Pathways to a Low-Carbon Economy*, assesses the costs of applying different energy saving measures: from substituting incandescent bulbs with LEDs to retrofitting gas-fired power plants.

Among the energy saving measures related to residential buildings, those aimed at increasing the thermal resistance of the building envelope are the most cost-effective, as shown in Figure 3. According to this report, improving the insulation layer in the external walls and roofs saves up to EUR 30 per ton of CO_2 that is not released into the atmosphere. In contrast, the application of photovoltaic panels costs between EUR 10 and 20 per avoided ton of CO_2 [6].

As stated above, different building geometries have a strong influence on the way the construction loses energy. Nemry et al. attempt to give an answer to which retrofitting strategy performs better in the residential stock by analysing the influence that different renovation packages have on greenhouse gas emissions savings in the EU residential stock. The retrofitting solutions vary from applying additional insulation in the roof, or in the façade, or both, to increasing the building air tightness to reduce the infiltration losses. Generally, the improved roof insulation presents the highest environmental savings potential for single-family houses, while the multi-family buildings benefit more from increasing the thickness of the façade insulation and increasing the air tightness, which represents the lowest initial investment cost. By summing up all the proposed retrofitting packages, the savings are at least as much as 20% of the greenhouse gas emission of the non-renovated reference case, and when considering all the measures for all the building typologies in the EU, a yearly reduction of 360 Mt $CO_{2\text{-eq}}$ is achieved. [5].

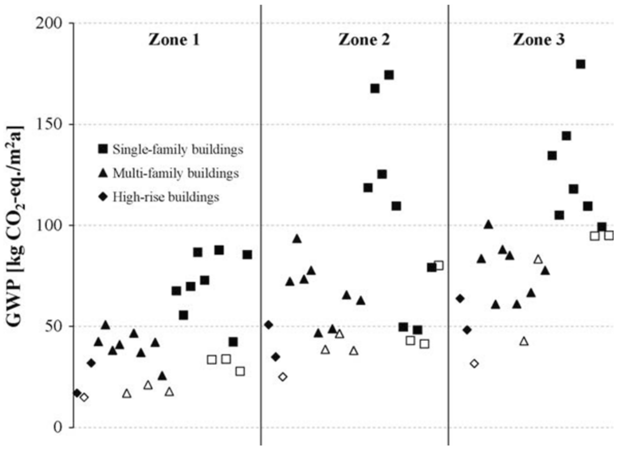


Figure 1. CO_2 emissions from the European building stock. The marks with no filling represent new buildings. The marks with black filling represent existing buildings. Zone 1, 2, and 3 represent South European, Central European, and North European countries, respectively. From [5].

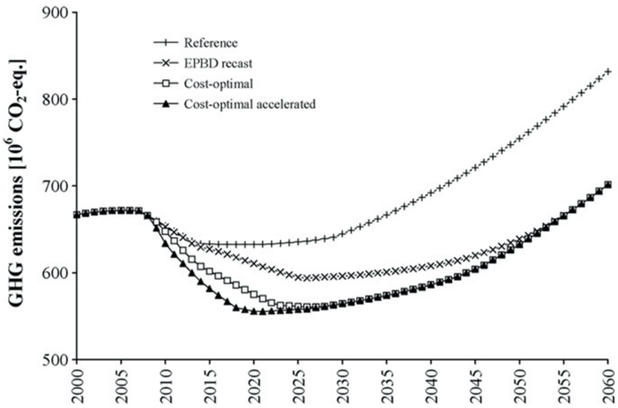


Figure 2. CO_2 emissions from future retrofitting scenarios for the European residential stock. From [2].

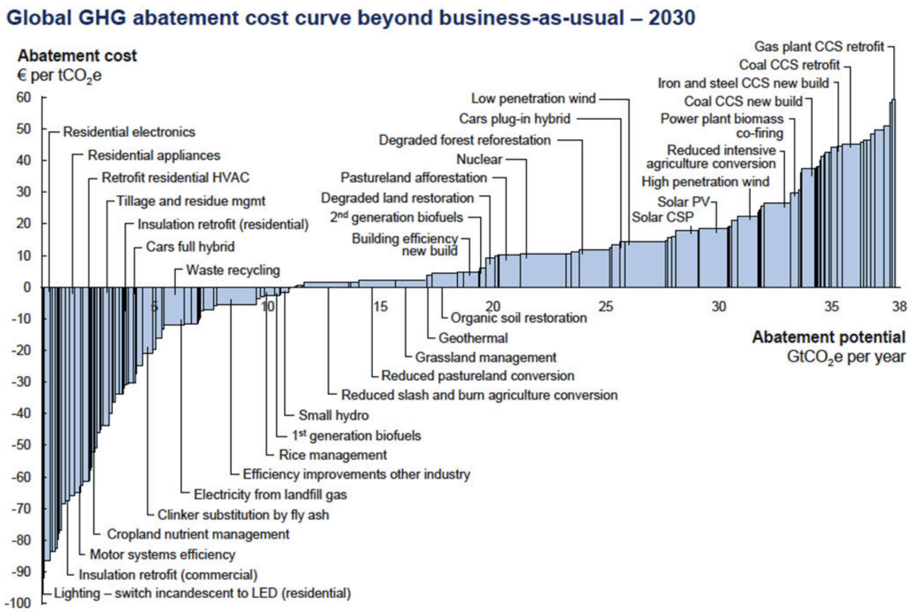


Figure 3. Carbon emissions and costs abatement potential of several intervention strategies. From [6].

In conclusion, these studies show how a consistent campaign of energy retrofitting of the European residential stock has a high potential for reducing their environmental impact. It is clear that a package of measures of energy conservation, through renovation activities, is decisive for reducing the global energy use for space heating. Consequently, it is effective in abating CO_2 emissions. To achieve such an effective reduction of the energy use in the EU buildings the residential stock should be improved towards higher classes of energy efficiency, such A and A+. However, as many studies show, the use of energy retrofitting measures, such as improved insulation or on-site renewable energy harvesting (e.g. photovoltaic and solar thermal technologies), influences the balance between the energy use for building operation and the energy use for the production of the building components (embodied energy). This aspect may result in other strategies for an effective greenhouse gas emissions abatement and introduces the need for other tools than those that only address the building energy demand.

1.3. Embodied energy and energy use in buildings

The use of lifecycle assessment for analysing the environmental impact of buildings has given results that show that the recently introduced energy-saving codes in the building regulations have a great influence on the share of the energy use for the building material production. Several studies show that when the energy use for building operation is reduced because of a well insulated building envelope and a highly efficient energy system, the share of embodied energy of the components and materials increases, and eventually influences the lifecycle energy used in the building. As stressed by Thormark in several works [7-10], low-energy and sustainable designs employ strategies that result in equalizing the ratio between the energy used for operating the building and the energy used in the material production. According to Adalberth, a prefabricated wooden house built in the early 1990s in compliance with the Swedish building code and with a lifetime of 50 years has a share for manufacturing, transportation and building operation between 10% and 11% of the total energy use [11]. Similar results are presented by Winther and Hestnes, who report a variation between 10% and 15% for the share of embodied energy in some wooden row houses built according to the Norwegian Building Code of the mid 1990s [12]. On the other hand, when considering a super-insulated building [12] or a low-energy house [9], these have a contribution of embodied energy which can vary between 30% and 60% of the total energy use. Clearly due to a lower energy need for building operation and a greater amount of insulation materials (which often are rather energy intensive in production), the life-cycle embodied energy in such buildings have as an average a 40% of share, as reported by Sartori and Hestnes [13] and by Blengini and Di Carlo [14].

The choice of materials and components composing the envelope, structure and systems of low-energy houses will have a greater influence on the final lifecycle energy balance than that in conventional buildings. This is because in highly energy-efficient buildings the energy use for the production phase and the disposal phase of materials and components gives a greater contribution to the lifecycle energy. This aspect has been investigated by Thormark [9, 10] and Blengini [15] who carried out some studies on the recycling potential of construction materials. Thormark defines the recycling potential as the embodied energy of buildings or components that is left after the building demolition and that is still claimable through recycling. This is expressed as Equation 1:

Equation 1 $R_{pot} = \sum_{i=1}^{n} EE_i \cdot Lifetime_i - E_{rec.proc\,i}$ [9]

Where n is the number of material/building component, i is the building material under study, EE_i is the embodied energy of the material i, $Lifetime_i$ is the lifetime of the material *i* and $E_{rec.proc\ i}$ is the energy use for the processes of recycling, upgrading or reusing the selected material *i*, including its transportation and dismantling. The recycling potential is strictly related to the end-of-life phase of the selected material or component and varies according to which kind of process of waste management is used. Thormark considers three possible scenarios for the end-of-life phase of a low-energy house in Sweden: burning for energy recovery, material recycling, and material reuse. Results shows that around 40% of the building lifecycle energy is attributed to its embodied energy, of which between 37% and 42% can be eventually recovered if these scenarios are applied before demolition. When including the energy use for the processes of reuse, recycling or combustion in the calculation, the resulting recycling potential is reduced to between 15% and 17% of the total energy use in a 50-year lifecycle.

Similarly, Blengini has carried out an analysis of the possible environmental benefits of applying recycling scenarios during the demolition process of a residential building in Torino, Italy [15]. His study is aimed at determining to what extent the recycling of building waste is effective in terms of environmental impact abatement. A comparison of two scenarios of building waste treatment (recycling and 100% landfilling) shows that the 100% landfilling scenario has higher environmental impacts in the end-of-life phase for all the environmental indicators considered in the analysis. The 100% landfilling scenario is responsible for approximately a 17% higher photochemical ozone depletion potential and approximately a 55% higher eutrophication potential. Blengini specifically examines the recycling potential of the steel and cement-aggregate products, which represented the highest mass of the demolished building, and analysed these materials according to two mid-point indicators (the gross energy requirement and the global warming potential) and an end-point indicator (the eco-indicator 99). It shows that when the landfilling disposal scenario is substituted with material recycling the recycling potential of such materials is small and only accounts for between 0.2% and 2.6% of the whole life cycle impact. On the other hand, when the recycling potential of the same materials is calculated for the energy use of only the pre-use phase (manufacturing of materials and transportation to the building site), this increases to 30%. Since the building did not have any energy saving features, the high energy demand associated with the use phase was greater than the embodied energy, and consequently the recycling potential of the two building materials was minimal [15]. These findings confirm the fact that, as reported by Thormark, in low-energy buildings the recycling potential of the building materials has a greater importance than that in standard buildings, due to the greater amount of material (especially insulation) used.

This analysis can be extended to determine the recycling potential of the load-bearing structure, comparing and assessing the environmental impact of different structural systems. Gao et al. [16] studied the whole construction system of a detached-house in Japan and examined the energy use due to different end-of-life scenarios of wood and steel construction systems. The basis of their work is the assumption that building materials can undergo three main processes of recycling: *feedstock recycling*, *material recycling* and *product recycling*. *Feedstock recycling* is a process in which the material's final use differs from its original one, such as recycling a glass bottle to use it as an aggregate for concrete. *Material recycling* refers to using the recycled material to match its original purpose, for instance by recycling a glass bottle as glass. *Product recycling* applies to reusing the material or the component without doing major changes, such as reusing a glass bottle as a glass bottle. Gao et al.'s method consists of calculating the energy use and the material flows for each process from material production to recycling, as expressed in Equation 2:

Equation 2 $E_c = (E_s + E_1) \cdot m_b + (E_k + E_a) \cdot m_a + E_2$ [16]

E_c represents the final energy use expressed in $MJkg^{-1}$. E_s is the energy use for the raw material production. E_1 is the energy used to manufacture the building material m_b from the raw material E_s. E_2 is the energy used to assemble the building component from the building materials. E_k is the energy use for disassembly of building materials m_b. E_a is the energy used to transform the disassembled material into the down-cycled material m_a. Three examples of different construction types are examined in order to determine the potential embodied energy savings by applying each of the above-described recycling processes. According to Gao et al. the light steel-frame construction system has the highest recycling potential. When reusing the steel-frame construction this reduces the total embodied energy by 25%, while the reuse of the conventional wooden construction reduces the total embodied energy by 16.5%. On the other hand, the reuse of the wood-frame system reduces the lifecycle energy only by 10%, because the large use of adhesives limits the reusing of the whole structure. It must be noted that the authors do not specify the exact difference between the conventional wooden construction and the wood-frame system. They specify that the wood-frame system has a higher quantity of wafer boards than the conventional wooden construction. At the final stage of the recycling process the embodied energy of both the steel-frame and the traditional wooden construction systems is approximately 2300 MJm^{-2}, even if the embodied energy of the steel frame initially was much higher than that of the wooden system. [16].

The feasibility and the cost of a specific end-of-life scenario for construction materials play a role in determining the life-cycle impact of low-energy buildings. The options in end-of-life scenarios are linked to the current country-specific construction and demolition waste (C&D) activities. Bohne et al. [17] and Bergsdal et al. [18, 19] developed some models for the prediction of the C&D waste flows in Norway and the evaluation of their environmental impact. Bohne et al. test and evaluate different scenarios for waste management according to their potential eco-efficiency. This is used as a tool to compare the costs and the environmental impact of the end-of-life processes of building components. The term *costs* describes all the economic transactions occurring at each step of the material lifecycle. The sorting criterion for the eco-efficiency potential becomes a powerful decision-making tool when different scenarios for waste-management are compared and eventually ranked into a one-dimensional value, the $EuroPt^{-1}$, according to their economic costs and environmental impacts. Bohne et al. uses this tool to analyse the C&D waste flows of various building materials, such as brick, concrete, wood, gypsum, cardboard, plastic, glass and metals in Trondheim, Norway for the period 2003-2018. Results show that in all cases the options which maximize reusing or recycling of construction materials are the most economically profitable and less environmentally damaging [17].

It is clear that the path towards a consistent reduction of the energy need for buildings is a complex issue that involves more factors than the energy use for building operation. The energy use, which is "hidden" in the building lifecycle, can diminish or eventually overturn the efficacy of the currently applied measures of energy reduction in the building sector. However, the complexity of this issue cannot be solved by applying a "magic recipe" due to the many factors involved. It is necessary to investigate the building production more thoroughly by considering the energy flows and the emissions balance for the lifecycle of a building.

1.4. Towards Zero Energy Buildings

The latest European energy codes for buildings have implemented the concepts of low-energy houses, and passive houses are one answer to reduce the building stock energy need. However, these standards and regulations do not fully consider the aspects of embodied energy and emissions of the building construction phase. As shown in the previous section, the embodied energy and emissions of the construction materials gain more relevance when the energy need for building operation is reduced. This has been demonstrated for residential buildings that use as little energy as a passive house or a low-energy building. In these cases the embodied energy of the construction itself account for between 40% and 60% of the total lifecycle energy for a lifetime of 50 years [9]. Since the newest building regulations are heading towards stricter limits for energy use in order to comply with the Kyoto Protocol, the share of embodied energy will have more influence in the total energy balance of future constructions. In this perspective, the current energy-efficiency standards do not suffice to describe the complex issues of assessing the lifecycle energy of residential buildings. New and recently developed concepts, such as the zero energy building, zero emission building, and lifecycle zero energy building, have been introduced to better fit the path to a low-carbon built environment.

The zero energy building (ZEB) idea is based on equipping buildings, which already have very high energy-performance, such a passive house, with renewable energy-harvesting technologies to balance and possibly exceed the energy demand of the building itself. Among all the possible solutions for ZEBs, as described by Torcellini et al. [20], the most recently promoted is to link these buildings to the existing power grid. This has two positive effects. First, it avoids the use of energy storage systems, such as batteries, where use involves the problem of future disposal. Second, the power gird is planned, at least in the EU countries, to rely on greener energy harvesting sources, such as photovoltaic plants and wind turbines fields, in the next future. This will reduce the emissions from the buildings energy use. In such a way, the power grid works as a storage system that imports and exports energy according to the need for energy and availability of renewably sourced energy. To ease the balance between the on-site energy production and the building energy demand, the zero emission building needs very little energy for space heating, cooling and use of domestic appliances, due to a very well insulated envelope and highly efficient energy-supply systems and appliances.

The ZEB concept is applicable to both new and to-be-retrofitted buildings. However, some differences occur in the way the energy performance of the building and the efficiency of the energy-harvesting devices are designed and optimized. According to Sartori et al. [21], the best path to a retrofitted-ZEB is first to reduce the energy demand of the building and second to provide a site-sourced energy system to offset the residual needs, as shown in Figure 4. The energy balance is dependent on which elements are included within the system boundaries. These are defined to cover the common uses of energy in buildings, such as heating, cooling, use of mechanical ventilation, use of domestic hot water, lighting, cooking, and use of electric appliances and devices. But, also the embodied energy of the building components, their installation and disposal can be included in the balance. This suggests the need for a comprehensive life cycle assessment (LCA) of the building from the material production to the demolition and waste treatment phase.

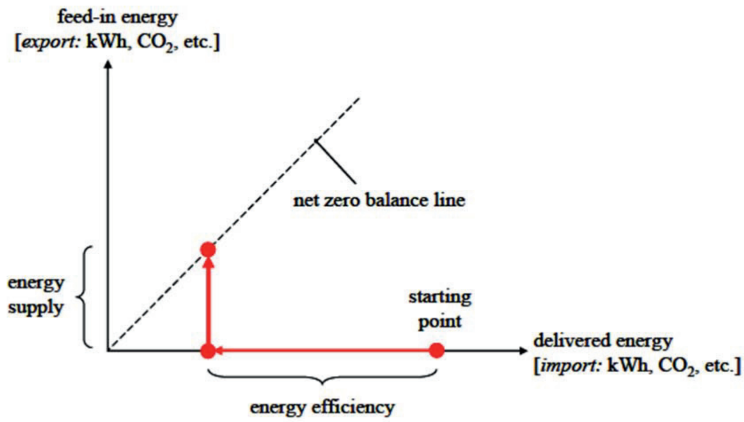


Figure 4. Curve representing the net zero balance of a ZEB. From [21].

The ZEB concept still lacks a common agreement about calculation methods and boundary conditions, and in most cases the embodied energy of building components and installations are still not considered. Clearly, a zero balance between energy harvesting and primary energy demand is the minimum requirement and the first step to a ZEB. So, it is necessary to also consider the embodied energy of ZEB components and materials in a lifecycle assessment in order to get more accurate values for energy use in the future building stock.

1.5. Current practice of energy retrofitting

When addressing the issue of energy savings in connection with building renovation, a variety of terminologies is used: eco-refurbishment, sustainable renovation, energy upgrade, energy retrofitting, and so on. The drivers behind a building upgrade can be failures of the technical performance of the building, changes in the local legislation, and pursuit of higher revenues for the owners. In the first case, when the building components that do not directly involve the load-bearing structure itself fail to perform their specific tasks, a program of upgrading may be promoted. Such activities may involve the substitution and the upgrading of the insulation layers and weather-proofing layers in facades, roofs, cellars, basement, etc., the substitution of windows and balconies to limit the thermal bridging in the facades, and the substitution of mechanical systems. Renovation activities can be pursued also due to change in the national energy codes and due to governmental benefits given to promote economical boosts to stagnating economies, or because of a change of the building use aiming at higher retail incomes.

The following examples, which are extracted from the International Energy Agency Solar Heating & Cooling Programme (IEA-SHC), are meant to briefly show some of the technical and architectural aspects of such renovation activities.

1.5.1. Apartment building in Brogården, Alingsås, Sweden

The Brogården complex was built in 1970 within the governmental Swedish housing programme called "the million-programme", developed during the years 1963-1973. The Brogården housing complex consists of 300 apartments divided in long 3-floors high buildings, which, after 40 years of operation, failed to provide a comfortable indoor environment for the users due to the poor air tightness, the small amount of thermal insulation, and the layout, which is not suitable for elderly and disabled persons. For these reasons, it was decided to pursue a stricter energy code upgrading of one of the building with 18 apartments to passive house standards and to include such a project in the International Energy Agency Solar Heating and Cooling programme Task 37 (IEA-SHC). The main renovation measures dealt with the issues of the poor thermal insulation and air tightness of the building envelope by wrapping and equipping the facades, the floor construction and the attic floor with thicker mineral wool layers and a continuous weather-proof layer. The U-values of the floor, the walls and the attic were reduced to 0.26 $Wm^{-2}K^{-1}$, 0.12 $Wm^{-2}K^{-1}$, and 0.10 $Wm^{-2}K^{-1}$ respectively [22]. In addition, new, better insulating windows were installed, and new balconies were mounted externally on the façade. The old loggias were demolished, and the space that originally was occupied by the loggias was closed and given to the apartments (Figure 5). A new ventilation system with a nominal 85%-efficiency heat exchanger was installed in each apartment, and solar collectors for domestic hot water were mounted on the roof. The energy saving due to these measures is estimated to be up to 62% of the original energy use for space heating and domestic hot water [22].

Figure 5. The Brågarden housing complex as original (left) and after the renovation (right). From [22].

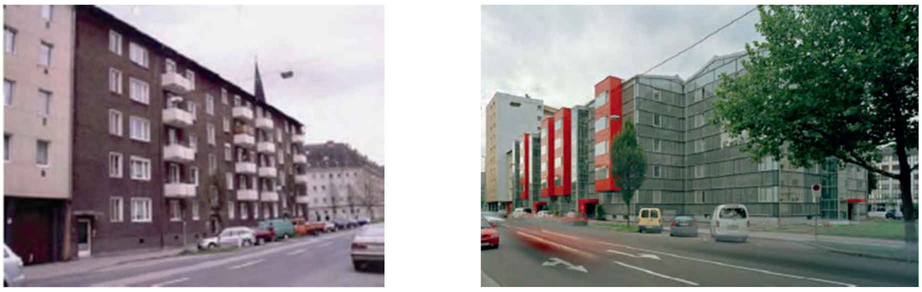


Figure 6. The apartment building in Linz before (left) and after (right) the renovation. From [23].

1.5.2. Apartment block in Linz, Austria

This block of apartment was built in Linz, Austria, 50 years ago. Because the wall structure is made of on-site casted concrete, it has quite poor thermal insulation (1.40 $Wm^{-2}K^{-1}$). In this perspective, the architectural office Arch+More and the contractor opted for a renovation package that could minimize the thermal losses of the facades while concurrently improving the architectural aspect of the building and easing the renovation work through large use of prefabricated elements. The U-values of the floor, wall and basement constructions were reduced to 0.20 $Wm^{-2}K^{-1}$, 0.16 $Wm^{-2}K^{-1}$, and 0.09 $Wm^{-2}K^{-1}$ respectively [23]. The insulation of the street-facing façade of the building has been technically solved by using a honeycomb material which collects solar energy. This technology consists of placing a thick slab of a honeycomb-structure material outside the external face of the façade and capping the whole package with a transparent material. The solar radiation, once trespassing the external transparent layer, reaches the honeycomb structure and heats up the air which is trapped within. The effect of this is to wrap a layer of hot air (up to 50 C) around the façade and, in conjunction with the thermal mass of the wall structure (concrete in this case), this results in a dynamic insulation value of an average 0.08 $Wm^{-2}K^{-1}$ [23]. The use of this system requires to finishing the whole façade with a layer of glass and, considering that the existing balconies were fully closed, this results in a widely changed appearance of the building after the renovation, as shown in Figure 6. The energy simulations indicated a 91% saving in the space heating demand, which decreased from 179.0 $kWhm^{-2}y^{-1}$ down to 14.4 $kWhm^{-2}y^{-1}$.

1.5.3. Apartment building in Albertslund, Denmark

The third example from the IEA-SHC Task 37 here presented is the renovation of 14 of apartment buildings owned by the Albertslund Housing Company and the Vridsløselille Housing Cooperative (Figure 7). The units were originally built between 1966 and 1969. Due the bad condition of the building envelope and the low market value of the too small apartments, the owners decided to opt for the renovation of the buildings. The main issues were to aggregate the small flats into large units to increase their market value, to provide flats accessible to disabled persons, and to reduce the energy use for building operation by improving the insulation layer of the facades and of the ground floor and by substituting the original windows [24]. The original architectural appearance of the façades was maintained by substituting the black wood cladding with dark-grey tile stones. However, the addition of coloured balconies and the different partition of windows, due to the different combinations of apartments, give the renovated building a very different outlook. Since the building had already undergone some renovation activities which involved the insulation of the roof, the energy saving of the new intervention is limited to 14%.

Figure 7. Renovation of the apartment blocks in Albertslund, Denmark. On the left the facades before the renovation and on the right the building after the upgrade. From [24].

1.6. The relevance of apartment buildings retrofitting

These examples of energy upgrade of apartment buildings show that the architectural appearance and the interventions that maximize the energy performance of a building are strongly interweaved. The Brogården example clearly represents those retrofitting cases in which the upgrade of the energy performance of the buildings is not coupled with a substantial change of the appearance of the facades, as Figure 5 shows. On the other hand, the case of the renovation of the apartment building in Linz shows that the technology installed to increase the insulation value of the façade greatly influences the building’s appearance. This differs from the building in Albertslund, where the appearance of the facades was changed by adding new elements (the balconies), by changing the façade glazing ratio, the windows arrangement, and their shape. In such a perspective, these buildings represent three different examples of the relationship between the architectural appearance of a building and the solutions used to improve its energy performance. This relationship has more visible effects for apartment buildings than for detached houses. This is due to the fact that the facades in apartment buildings represent the physical interface where both the building appearance is expressed and most of the energy exchanges occur. Clearly, the façade's influence on the building energy performance is greater in apartment buildings than in detached houses, because the facades mostly represent the area of thermal enclosure in respect to the volume of an apartment building. In addition, the façade is clearly the main face of an apartment building, as most of the architectural characteristics of the building are related to the façade appearance.

Another reason that make apartment buildings an important research topic relates to the importance that such dwelling types have represented in Europe as an innovative answer to the debate around the "modern" life style of Western society. The massive development of state-subsidized houses in the early decades of the post-WWII period originated from the economical and social situation in Europe. A large part of the European population was left homeless because of the severe damages to the residential stock, especially in main cities. These also experienced an extensive immigration from rural areas and ex-colonies. In addition, the existing housing facilities from the Industrial Revolution were not fitting the desire for a modern home-lifestyle anymore and were not easy to upgrade without relocation of the residents. This, as well as trust in technocratic and public-driven solutions, led most European governments to adopt a large scale campaign of demolition and reconstruction to regenerate the residential stock during the 1960s [25].

In such a perspective, the post-WWII period experienced an interesting and passionate debate for the definition of a new, "modern" lifestyle, pushed by the opinion that the domestic physical environment shapes people's lifestyle. The international debate among architects and social scientists on the aspects of modern living was rooted in the pre-war years, when Le Corbusier, Gropius, Breuer and their followers constituted two main trends: the Bauhaus-oriented architects active in Germany, Switzerland, Holland and East Europe, and the French architects who adhered to Le Corbusier's ideas. The discussion was then condensed in regular meetings which were the core of the *Congrès International d'Architecture Moderne* (CIAM), founded in 1928, in Switzerland. At the heart of every CIAM's reunion was the search for a new approach to architecture and urbanism, where the reshaping of contemporary cities and living style should address the social needs of masses, as identified by socialist and Marxists theories [26]. This was possible by linking architecture to economical production, based on Taylor's idea of efficiency and rationalization of industrial processes, and, thus, to abandon the traditional relation to the Beaux-Art schools. Henceforth, modern cities became the place where novel architectural theories drove residential developments and urban infrastructures. During the second congress of CIAM, held in Frankfurt-am-Main in October 1929, the modern home-life was translated into an innovative design for a dwelling type, named The Minimum Dwelling (*Die*

Wohnung für das Existenzminimum). This was the answer to the unhealthy living conditions of the 19th century tenements. Between 1927 and 1930 several housing settlement projects were sponsored by German municipalities in Frankfurt, Berlin and Leipzig. In these the principles of rational plans and access to daylight and view formulated by Klein and the CIAM architects were put into practice [27]. It resulted in isolated and linear multi-storey buildings surrounded by communal gardens and collective facilities and spaces [26].

Social housing production of the post-war years was largely influenced by the outcomes of the CIAM meetings. Simple and rigid site plans fit the principles of mass production, prefabrication and cost saving of 1960s and 1970s, validating the ideas of planning along *Zeilenbau* lines, as expressed by Le Corbusier in the III Congress held in Brussels, in 1930 [26]. However, the extensive use of prefabrication and the adoption of high-rise and massive-block typologies led to monotonous and impersonal residential settlements and betrayed the original concept of rational and harmonious planning, thus fostering disaffection, unease and social imbalance among the dwellers [25, 28].

1.7. Summary

As the last IPCC report states, the unprecedented release of green house gases into the atmosphere due to human activities is with a high level of confidence linked to the changes of the surface global temperatures. These emissions are for a large part attributed to the energy use in buildings, which, considering their current poor thermal performance, have a strong potential for CO_2 abatement. In addition, among all the possible measures of greenhouse gas reduction, the energy retrofit of buildings is shown in the *Pathways to a Low-Carbon Economy* report of the McKinsey&Company as one of the most economically advantageous measures.

Once these measures are applied to residential buildings, it has been demonstrated that the share of embodied energy and emissions gains weight while the emissions related to the energy use for building operation are drastically reduced. This underlines the important role that materials play in architecture, not only from an aesthetical perspective, as has been theorized since in the *The Four Elements of Architecture and Other Writings* by Gottfried Semper, but also from an environmental point of view. This connection is even stronger for apartment buildings, in which the physical interface where the majority of the energy exchange occur and thus where a consistent potential of energy saving lies, coincides with the aesthetical interface of the building itself, the façade. Three examples of energy retrofit of apartment buildings have been presented to show the connection between the energy saving interventions and the final aesthetical appearance. However, a thorough study of the environmental effects and specifically the greenhouse gas emissions that such interventions may have on such buildings is still missing. This research therefore includes a parametric study of energy retrofitting interventions in order to study the relationship between the building lifecycle emissions and the technical characteristics and the appearance of the facades of an apartment building in Oslo, Norway.

2. Research frame (methodology)

2.1. Objective

Buildings are often considered first as technical systems in which the quantifiable measuring of comfort and energy use define the optimal operative frame, leaving behind, though, the qualitative and aesthetical character of the building itself. In the pursuit of a normed indoor environment, modern architecture has responded through standardization of construction systems, recurring architectural solutions and wide use of technical installations, denying the geographically suitable features of vernacular architecture, which attributed the indoor comfort to building shape, orientation and use of materials. Traditional solutions cannot cope with the high expectation of contemporary comfort requirements and strict national energy codes, but clearly the architectural quality of contemporary residential building production still remains an issue not fully considered. Besides very few examples of high-quality architecture in which there is clear evidence of a thorough research into "different" architectural concepts for domestic environments (Figure 8), most of the residential building production is ruled by standardization of solutions with very little consideration for the quality of materials and construction details used.

Figure 8. Left: "Bosco Verticale" in Milan, by Stefano Boeri. A project aimed at developing metropolitan reforestation and urban biodiversity. Middle and right: "Garden and House" in Tokyo, by Ryue Nishizawa. This building has no opaque partitions but only glass walls. The building façade is represented by the gardens located at each floor.

The introduction of stricter regulations of energy use in buildings and the use of environmental impact assessment tools, such as BREEAM, have in most European countries somehow turned the architectural debate from architectural quality to eco-sustainability and energy efficiency. In such a perspective, the technical aspects with which contemporary buildings are featured have to a certain extent become the synonym of architectural quality. For this reason, "eco-friendly" architects are encouraged to push towards energy-oriented solutions, especially for renovation, in the attempt to achieve high scores on the energy labelling scales.

However, it must be noted that an activity of energy retrofitting certainly represents a good opportunity for researching into new architectural languages and expressions. This can be done by changing and improving the appearance of the façade of a residential building. In such a perspective, architects can make use of many different options, such as changing the finishing material for the facades, adding or changing balconies and sunspaces, adding new volumes to the building, and changing the shape and number of windows, in order to propose alternative architectural expressions. In a lifecycle perspective, these measures have an effect on the total energy use of the building. This is due to the fact that the use of different material for the façade finishing has an influence on the building embodied energy not only because of the energy used for the production of these materials, but also because of their different service lives. It is therefore interesting to study the influence that such options have on the building lifecycle impact.

The current practice of building energy upgrade considers the use of thick layers of insulation in order to comply with the energy codes. This aspect is very relevant for the Norwegian building stock because the local climate requires the use of strict measures in order to reduce the energy use. As a consequence, the trend of the national energy codes for residential buildings is moving forward to very low U-values for the building envelopes. As an example, the required U-values for the external walls set in the NS 3700:2010 are ≤ 0.15 $Wm^{-2}K^{-1}$ for the passive house standard and ≤ 0.18 $Wm^{-2}K^{-1}$ for the class-1 low-energy standard [29]. Even if it is beyond any doubt that the use of thick insulation layers is advantageous for the reduction of the building energy use in cold climates, this measure might actually be disadvantageous when considering the emissions due to the production of the materials used in such retrofitting activities.

Due to the technological development of insulation materials, a wide range of materials can now be applied in the energy retrofitting of buildings. The most commonly used are mineral wool and expanded polystyrene (EPS) but new and more advanced materials, such as vacuum insulation panels (VIP) and aerogel, have been presented as more competitive solutions. Both aerogel and VIPs offer very high thermal resistance, which is a favourable characteristic in energy upgrading as the same insulation level can be achieved with thinner insulation layers. Thinner components also have other advantages, such as being used in prefabricated components and easing the installation and dismounting during renovation activities. However, these materials are highly energy-intensive in the production phase, so they might not in reality be competitive.

Considering then the above aspects of the energy reduction and the architectural improvement from the perspective of a lifecycle analysis, it is interesting to evaluate the advantages and disadvantages in terms of emissions of different alternative scenarios of energy retrofitting. This leads to the main research question:

> What are the lifecycle CO_2 emissions of a residential building when using alternative energy retrofitting measures?

From this two sub-research questions can be stated:

> To what extent will the choice of architectural solutions for the façade's appearance affect the emissions of the building?

> To what extent is the use of advanced insulation materials advantageous in the energy retrofitting of apartment buildings?

As stated above, the façades of an apartment building are the focus of this research, since they are the building parts where the energy exchanges, the embodied energies and the architectural appearance converge. This has been highlighted by the current trend in architecture, which often defers the whole architectural expression to the appearance of façade systems. This has been recently confirmed by the increased use of energy harvesting technologies, such as photovoltaic panels, on building facades. It is interesting, therefore, to study to which extent different alternatives for energy upgrades of apartment buildings are competitive in terms of lifecycle emissions. The alternatives proposed in this work either maximize the choice of façade appearances, or the choice of energy saving solutions.

The work is aimed at assessing the most important aspects that characterize the energy upgrade of the facades of an apartment building using lifecycle emission calculations. The alternatives for energy retrofitting are chosen using both a technical approach and an architectural approach. The first considers the choices of the insulation materials for the building facades. The second consider the choices that define the façade appearance, such as the finishing, the relationship between the glazed and the opaque part of the façade, and the presence of balconies or sunspaces.

The proposed methodology combines two goals: to evaluate the lifecycle emissions of energy saving measures and to propose alternative architectural solutions of building facades. Both goals are achieved through the two approaches. The *technical approach* defines the materials and technical solutions that optimize the energy and emission abatement for the proposed building upgrades. The insulation materials used for the opaque and transparent surfaces (walls and windows) of the building facades are largely credited for their role in providing satisfactory thermal resistance to the building envelope. Therefore, the insulation materials are considered the key factor on which the technical approach is based. The thickness and physical characteristics of the insulation layer for each retrofit solution determines the building's energy use and emissions. For this reason, the characteristics that are considered the most important for the choice of the insulation materials cover the aspects of thermal resistance, availability and diffusion in the market, and flexibility of use. The emissions for each retrofit solution are calculated by lifecycle assessment. The three criteria on which the selection of the insulation materials is based are:

- *Market diffusion and availability*. Mineral wool is selected as representing one of the materials that is most commonly used for thermal insulation of buildings.
- *Flexibility of use*. Aerogel, is selected as it has entered the market of insulation materials for buildings very recently and as it has the special characteristic of being either opaque or transparent, depending on the production process. This characteristic makes aerogel well suited as the insulation of both walls and windows (as a monolithic layer between two glass panes).
- *Thermal resistance*. Vacuum insulation panels are selected as they represent the most advanced solution for achieving a high thermal resistance within minimal thicknesses. This characteristic turns out to be very useful when applying such a material in energy retrofitting, since its very limited dimension reduces the thickness of the walls after renovation.

Different combination of insulation solutions	**Mineral wool**	**Vacuum insulation panels**	**Aerogel**	**Standard glazing**	**Aerogel glazing**
Reference building	YES	NO	NO	YES	NO
Alternative 1	NO	YES	NO	YES	NO
Alternative 2	NO	NO	YES	YES	NO
Alternative 3	YES	NO	NO	NO	YES
Alternative 4	NO	YES	NO	NO	YES
Alternative 5	NO	NO	YES	NO	YES

Table 1. List of the alternatives for the insulation materials in both opaque and transparent surfaces.

The *architectural approach* defines the façade components that shape the appearance of the façade for each retrofit alternative. The appearance of the facades, which is the result of the combination of the façade characteristics (glazing ratio, finishing, balconies, and sunspaces), represents the potential of the architectural expressions of the building. This is an obvious simplification of the possible architectural expressions of an apartment building, because many other aspects, such as the building shape and volume, the layout, the partition and distribution of the façade elements, and so on, are not considered. However, in this study the characteristics that are chosen to define the façade appearance are limited to the ones which have a noticeable influence on the lifecycle emissions of the building.

It is important to notice that the combinations of the above components that shape the building façade determine both the final greenhouse gas emissions and the qualitative appearance of the façade. This will lead to the difficult situation of comparing two sets of values (the emissions and façade appearance) that are *per se* dissimilar. For this reason, the greenhouse gas emissions of the façade solutions will be assessed through the well-established procedure of lifecycle assessment, while the architectural potential will not be evaluated nor rated. The architectural potential will instead be presented as a palette of the possible architectural solutions that are feasible in the renovation of an apartment building. This palette consists of the combination of the features that both characterize the appearance of the façade and their influence on its total lifecycle emissions. A survey of existing examples of energy retrofits of apartment buildings is used as guideline to define the most relevant façade features that are subject to changes during an energy upgrade. The survey is based on 32 examples of residential buildings found in the report from the IEA-SHC Task 37, and for each one the main changes are listed in terms of new architectural features and technical solutions. The list of the architectural components and the list of the technical solutions adopted in some of the IEA-SHC task 37 examples are presented in Table I- a and Table I- b, both in Appendix I. The features that define the façade appearance are chosen according to three criteria:

- *Relationship between openings and closures*. The ratio of the glazed to the opaque part of a building façade is a substantial characteristic because it defines the "transparency" of the building envelope. It also influences the energy use of the building and its eventual lifecycle emissions. For these reasons three different glazing ratios are chosen: 24%, 33%, and 50%. The glazing ratio is limited to 50% because a higher value would be not feasible for an apartment building, due to the limited surface for placing furniture and fittings.

- *Façade finishing*. The variation of the outermost layer of a façade has a critical effect on the appearance of a building. A sleek surface made of steel sheeting and a rough surface made of wood cladding give different results. Moreover, the choice of the finishing material influences the building lifecycle emissions due to the different needs for maintenance of the finishing layer. Five different finishing are chosen:

    - *Concrete-based tiles and paint*. A basic alternative for façade finishing.
    - *Untreated wood*. Wood cladding is a typical solution for finishing in Norway and has a very low environmental impact.
    - *Copper-impregnated wood and wood preservative*. Similarly to untreated wood, copper impregnated wood is a common solution in Nordic countries. The copper impregnation and the wood preservative maintain the technical characteristic of the cladding.

- *Mineral-wool-insulated sandwich panels with steel sheeting*. This alternative involves applying a ready-made insulation and finishing layer to the façade. It is a fast and easy-to-apply solution for retrofitting.
- *Polymer-cement-based tiles and paint*. This is a low-environmental-impact alternative to the concrete-based tiles.

- *Façade volumes*. The relationship between the façade surface and the abutting volumes is also important in defining the building appearance. Moreover, balconies and loggias are often replaced in energy retrofitting because their connection with the load-bearing structure is a source of thermal losses. Two types of balcony/sunspace are chosen:

  - *Standard balcony* structurally detached from the building.
  - *Sunspace* structurally detached from the building. The possibility of glazing the balcony from floor to ceiling defines a space that works as both an indoor and an outdoor space. Moreover, the use of sunspaces reduces the thermal losses of the corresponding part of the façade.

Table 2 shows the list of the changes of the façade components that defines the architectural approach. The array of different designs, given by the combination of the above components, represents a wide range of architectural alternatives in terms of appearance of the building facades, or, as mentioned above, defines the architectural potential of a specific building. The above alternatives from the *technical approach* and from the *architectural approach* are combined in a framework for a parametric study, where each combination of the above parameters defines a retrofitting solution. The building energy use and lifecycle emissions are evaluated for each alternative through an energy and a greenhouse gas analysis. This data is represented by a numerical parameter which expresses the amount of greenhouse gas emission per square meter of building heated area. The data is then visualized in a chart, the *matrix of choices*, (Figure 9) which condenses the relevant aspects of energy retrofitting, as defined in this research. In such a perspective it is possible to illustrate the connection between the greenhouse gas emissions and the aesthetics of a series of different energy retrofitting solutions, and to determine to what extent an architectural-oriented design differs in terms of its environmental impact from an energy-saving-oriented design.

Different combination of architectural features	Variation of glazing ratio from the original design	Substitution existing balconies	Addition of new balconies	Addition of sunspaces	Variation façade finishing
Reference building	NO	YES	NO	NO	NO
Alternative 1	YES	YES	NO	NO	NO
Alternative 2	NO	YES	YES	NO	NO
Alternative 3	YES	YES	YES	NO	NO
Alternative 4	NO	YES	YES	YES	NO
Alternative 5	YES	YES	YES	YES	NO
Alternative 6	NO	YES	YES	YES	YES
Alternative 7	YES	YES	YES	YES	YES

Table 2. List of the alternatives of the architectural features applied to the case study.

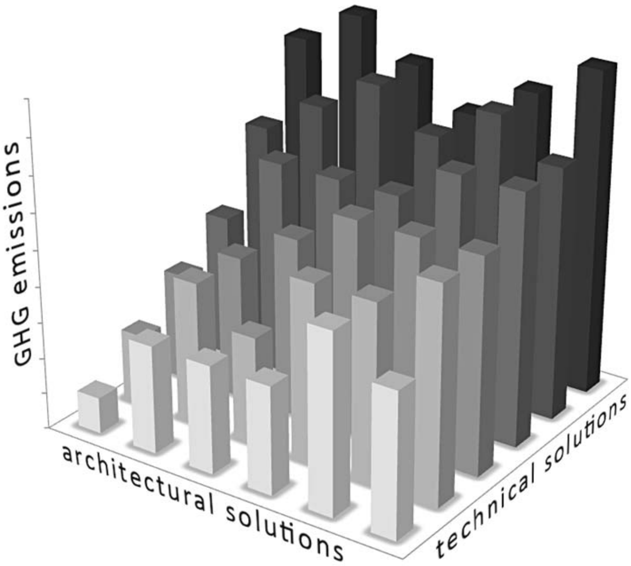


Figure 9. Matrix of choices. On the right axis, the variation in insulation materials gives the technical solutions. On the left axis, the variation in facades composition gives the architectural solutions. On the vertical axis, the resulting CO_2 emissions from the combination of the above.

2.2. The reference building

An apartment building in Oslo, Norway, the Myhrerenga Borettslag (housing cooperative), is used as reference building in the energy and greenhouse gas analysis. Conforming to the building trend of post-war decades, the Myhrerenga Housing Cooperative represents one of several examples of residential buildings that have being shaping the urban landscape of most Norwegian towns and currently share approximately 23% of the entire Norwegian dwelling stock [30, 31]. The Myhrerenga Housing Cooperative, which was built in 1967, is located 15 km north of Oslo, along the main connection road E6 (Åsenhagen 3-15, 2020 Skedsmokorset, Norway). Due to its linear arrangement, the apartments are served by different stairwells which divide the building into sections with two columns of dwellings each. Each of the seven building is approximately 65 m long and 10 m wide and has 24 apartments divided in eight units per floor plus a basement. The apartments, which face both East and West, vary from 54 m^2 (six units per block) to 68 m^2 (18 units per block) and are served by four stairwells positioned on the East side of the building. Partially enclosed balconies (loggias) lie on the West façade (Figure 10).

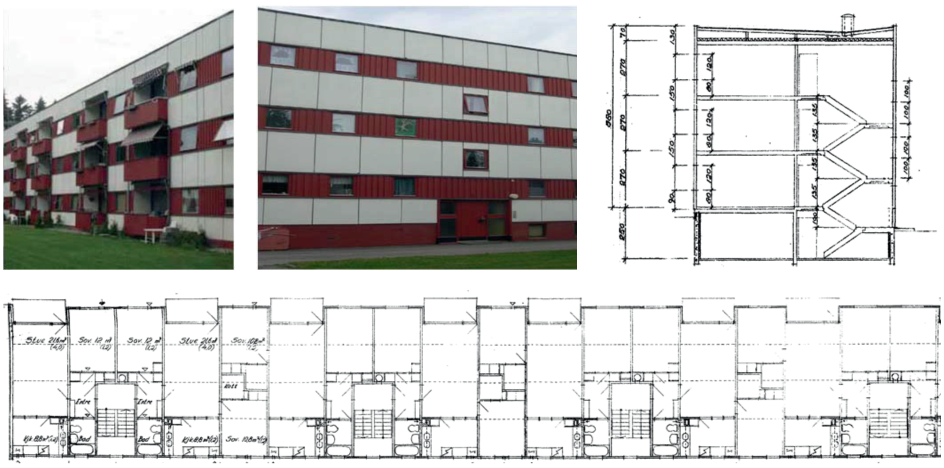


Figure 10. Top left and centre: the West and East façades of the Myhrerenga Borettslag before renovation. Top right: the original drawing of the cross section of one the apartment buildings. Bottom: the original drawing of the plan of one of the apartment buildings. Courtesy of Sintef Byggforsk.

The building structure is composed of an array of parallel reinforced concrete walls which delimit each apartment and constitute, with the concrete floors, the load bearing structure. The external walls on the East and West sides mainly consist of a timber frame system covered with wood cladding, which is still commonly used in Norway. The wall construction is a wooden framework of 5x10 cm studs spaced every 60 cm. The cavity within the studs is filled with 10 cm thick mineral wool bats, and the internal and external finishing are made of gypsum plasterboards and wood sidings, respectively [32, 33]. The North and South walls, which do not have any openings, are built with concrete sandwich panels with 8 cm of insulation. The windows, located on the East and West façades only, have been replaced in the 1980's and consist of a wooden frame with double glass panes with a heat transfer coefficient of approximately 2.6 $Wm^{-2}K^{-1}$ [33, 34]. The roof construction is composed of a wooden frame, insulated with 10 cm of mineral wool, which stands on a load-bearing concrete slab. The floor of the basement is a concrete slab insulated with 5 cm of expanded polystyrene.

The whole complex of buildings has undergone a renovation process that started in February 2010. This was needed due to the very poor thermal performance of the buildings and the very high energy-use for heating. The balcony slabs were fully exposed and abutting the concrete floors, which resulted in problems of thermal bridging occurring at all the structural connections. The existing energy supply system consisted of an inefficient central electric oil boiler which delivers heat to the building through a hydronic system with radiators in each apartment. As result of the very poor thermal insulation of the external envelope, the consistent presence of thermal bridges along windows and balcony joints, and the low air tightness of the window frames and walls, the measured delivered energy demand reached 300 $kWhm^{-2}y^{-1}$ [33]. The full description of the renovation package proposed for the Myhrerenga Housing Cooperative can be found in [33]. This energy renovation, which upgraded all of the seven buildings to passive house standards, represent the starting point, for this research. It is termed the *reference building*, and the alternative technical and architectural approaches studied are based on this.

2.3. The energy model

Extreme accuracy in the energy models does not necessarily give better results while a too simple model can lack enough geometrical data and can give poor information about the energy transfers and the temperature ranges in different parts of a building. The compromise between geometrical complexity and richness of energy information depends on how detailed is the focus of the investigation and how accurate the energy analysis has to be. As stated previously, this research focuses on the influence that facades have on the energy performance of apartment buildings. The complexity of the building geometry is therefore simplified by only using the geometrical coordinates necessary for this specific task.

In this research, the seven identical buildings of the Myhrerenga Housing Cooperative are simplified into a model that details the interior arrangement of the apartments for one building only. The other buildings are not modelled at all. Considering that the apartments located on the ends of each building have a special condition, these have been fully described as separate units in the energy model. Of the 18 middle apartments, only the central six units are considered as separate thermal zones. The remaining 12 units are aggregated into two adiabatic zones. The indoor partitions in each residential unit are not geometrically described but their approximate thermal mass is included in the model. Similarly for the apartments, the basement, which is modelled as a continuous uniform space without any internal partition, is divided in five blocks, two of which are adiabatic zones, as shown in Figure 11. The four stairwells are included in the energy model as unheated thermal zones. According to the original drawings, which have been used to draw the CAD model, the terrain gently slopes down towards the East side of the building. This difference is not considered in the model, however, and the basement walls are considered to be fully exposed. The settings of the indoor environmental controls and variables are tuned according to the Norwegian Standards NS 3700 and NS 3031 [29, 35] and are summarized in Table II- a in Appendix II.

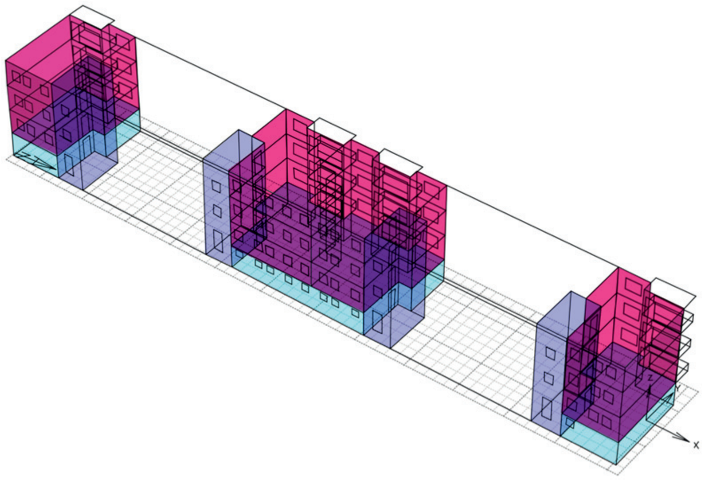


Figure 11. A CAD drawing of the energy model of the Myhrerenga Borettslag. The apartments are in purple. The stairwells and the basements are modelled as unheated spaces and are in blue and cyan, respectively. The rest of the building is modelled as two adiabatic zones.

Calculations are performed using EnergyPlus [36] and are based on yearly energy use for heating, ventilation fans, water pumps, electric appliances, lighting appliances, heat pumps, and DHW. Energy use for cooling is not included as the summer outdoor temperatures in Oslo are supposed to be low enough for natural ventilation to suffice. The results are normalized to $1m^2$ of building conditioned area. The heating system is modelled as a single air-to-water heat pump that is linked to a single radiator in each apartment. Ventilation is provided by variable air volume units, which deliver fresh air at 0.023 $m^3s^{-1}m^{-2}$ in the 54-m^2 apartments and 0.026 $m^3s^{-1}m^{-2}$ in the 64-m^2 apartments. A heat recovery system, consisting of a flat plate unit with 83% nominal efficiency, is linked to the ventilation system.

2.4. Lifecycle assessment, LCA

The greenhouse gas analysis is based on a lifecycle assessment. The following sections give an overview of such a method of analysis and its application to buildings.

LCA is part of a wider family of instruments, such as the environmental impact assessment (EIA), the ecological risk assessment (ERA), the material flow analysis (MFA), and the cost benefit analysis (CBA), which relate to the appraisal of the environmental impact or the economical risk of a product. An LCA is designed to frame and examine the processes and services, from the extraction of raw materials to the storage and delivery of finished products, that occur within an industrial system. For such reasons, an LCA can be applied to every activity that takes place within the technical sphere of human enterprise for a specific product, and its application can be extended to determine such a product's final impact on the natural environment in terms of pollution and detriment of the natural system. In this perspective, the system boundaries of an LCA can be expanded from the industrial activities to the delivery, selling, use and disposal of the finished product, making this tool a powerful instrument for comparing a variety of impact factors.

The LCA method was developed in the late 1960s to optimize the production of packaging products for beverages. The Coca-Cola Company commissioned a study for substituting the renowned glass bottle with the plastic ones, and similar studies were promoted in the UK, Germany and Sweden, where TetraPack was interested in developing PVC bottles. During the oil-crisis of mid 1970s, the need of optimizing industrial processes became urgent and LCAs were broadly commissioned [37]. More recently, the pressing commitment of reducing the energy demand of buildings has triggered the interest in developing LCA models for housing units and more specifically for low-energy buildings.

The method is framed within a series of international standards, like the ISO 14040, released from 1997 onwards [38]. According to these the LCA is defined as a technique for assessing the environmental aspects and potential impacts associated with a product through a series of consecutive steps. These steps are [37]:

- Definition of the object of study, where the goals and deliverables are decided and the product system boundaries and the limitations of the study are set.
- Compiling the product's inventory, where the most relevant inputs and outputs of the product system take place.
- Evaluation of the potential environmental impacts associated with those inputs and outputs.
- Interpretation of the results of the inventory analysis and the impact assessment in relation to the previously set objectives of the study.

The second step, called life cycle inventory (LCI), is technically a model that covers the flows of materials and energy related to the manufacturing of the product of study. Such flows are schematized into a chart, which is based on the quantified use of resources and energy consumption collected according to the settings defined in the first step, called the goal and scope definition stage [37]. However, such a flow chart is limited to describe only the energy and mass flows of the most relevant processes, because a complete description of these would require an effort that is not worth the accuracy of the outcome. For this reason, the inventory analysis delineates an incomplete system of mass and energy, which is limited by the boundaries that are set in the goal and scope definition stage [37, 38]. In such a perspective, several schemes and outcomes are possible and depend on the scope of the analysis [39].

A cradle-to-gate LCA covers the activities occurring in the industrial system only and produces results that often are employed in environmental material databases. A cradle-to-grave LCA includes the whole lifecycle of a product and stresses the comparison between its manufacturing phase and its use phase. A cradle-to-cradle LCA extends the boundaries of the previous system to include the future use of the disposed product by considering the environmental impact of its different disposal scenarios, and specifically its recycling and reusing. Finally, a gate-to-gate LCA focuses mostly on optimizing the sub-processes that occur within an industrial activity.

Regardless of the system boundaries used, the inventory analysis is always based on three main steps [37]:

- Setting of the flow chart model, which describes and documents all the activities occurring within the product system boundaries. Depending on the product, such activities usually cover five main phases of its life cycle: production, manufacturing, transportation, use, and disposal.
- Collection of data for such activities in terms of inputs and outputs of raw materials, energy, products, solid waste, emission to air, and emission to water.
- Computing the use of natural resources and amount of polluting emissions related to inputs and outputs of the system.

Consequential to the LCI is the impact assessment, which has a two-fold objective. First, at this stage the energy and mass data, gathered in the inventory analysis, is converted into environmentally relevant and user friendly information. Second, the large quantity of data on emissions and resource use is condensed into a few simple parameters. Such aggregated information is easier to handle and more convenient for comparing similar products, which is the main objective of an LCA.

Besides the limitation in the description of the flows occurring in the product system boundaries, there are some other limitations that specifically concern the system itself, as described by Chevalier and Le Téno [40]:

- Time stability: the product system is considered stable over time, which means that technologies and procedures available at the time of analysis are supposed not to have changed when the product is disposed of. This is a powerful statement, since it renders the product system into an instant picture. However, due to this assumption any technological development within the product lifecycle is excluded, which is clearly not realistic. For long lifetime products, such as buildings, this assumption may produce improbable outcomes.
- Separability: the product system is assumed separated and independent from any other processes outside the system, and any mutual influence is excluded. However, this supposition is unrealistic since every industrial or economical process has many ramifications that connect to other processes. However, this limitation is necessary to accomplish a life cycle assessment, but it may lead to a poor description of the real mass and energy flows of multi-composed products, such as buildings, which are based on interweaved industrial processes.

2.5. LCA applied to buildings

A building is a complex system, of which system analysis is more prone to render an incomplete image, because of the above-described limitations of the LCA method. In addition, an LCA can only describe the few functions and uses of a product that are set in the goal and scope definition. This aspect leads to a poor description of the characteristics of a building which, differently from a simple product, has to fulfil many requirements. These vary from the technical requirements of materials, such as thermal transmittance and fire resistance, to architectural performance, such as building accessibility and functionality. For this reason, the functional unit describing a building may cover some aspects but not all of them. To overcome this complexity two ways of description of the building product system have been proposed: a top-down approach and a bottom-up approach [41]. The first considers the building as an indivisible unit that is subjected to further improvements and changes. The second recognizes the building as the composition of its components that are separately assessed for their environmental impact. When employing a bottom-up approach, the model may not fully describe all the building functions, such as the indoor air-quality and the thermal comfort, which are key aspects of the product itself [42]. On the other hand, the multitude of aspects that describe a building cannot all be quantified and compared in terms of environmental impact. So, how to overcome such an obstacle? Some authors [41-43] propose a top-down approach in which the building's physical construction and its functions are separated. Each stage of the building lifetime, from its construction to its demolition, is considered as a finite system and is examined separately in the inventory analysis, which leads to a sequential lifecycle model [41]. For each phase the environmental impacts are calculated, added together and normalized to the whole building, which constitutes the functional unit of the product system [42, 44]. Using this approach, there are several methods for rating the lifecycle energy of buildings, such as the one proposed by Hernandez and Kelly [43]. They assess the environmental impact of different energy codes applied to a standardized house type. On the other hand, the authors who propose a bottom-up approach credit the building component itself with the environmental impact of the lifetime phases of the building. In this perspective, some functions, such as thermal comfort, cannot be directly included in the description of the environmental impact of the single component [45], but are introduced as an indirect influence on the building product, as proposed by Crawford et al. [46].

Despite the above limitations, an LCA model still gives a comprehensive overview of the processes occurring in the building-product system and provides detailed information about energy and mass flows at every step of the product lifecycle. This method is therefore still a valuable tool to compare and evaluate different energy-saving solutions for buildings and unveil their impacts on the environment.

2.6. The LCA model used

A descriptive lifecycle of a building cover the following stages: material production, transportation, construction, building use and maintenance, demolition, transportation and end-of-life (EOL) [41, 45, 47-49]. We have previously seen how the production and the EOL phases gain increasing importance for the lifecycle impact of low-energy buildings [3, 9, 12-14, 49-52]. Because of the increased importance of the embodied energy, the decisions taken at the final step of the building lifecycle has a strong influence on the final impact [7, 8, 10, 17]. However, since this research is focused on comparing the CO_2 emissions of different façade solutions applied to an existing apartment building, the lifecycle model has been simplified to exclude from the calculation the construction and the demolition phases of the building itself, while it includes all the stages, from material production to demolition, of the façade components, as shown in Figure 12.

As previously introduced, the results from the LCI are classified into impact categories to assess their environmental effects. Currently, two methods have been developed to represent the impact potential of the environmental stressors: the *environmental theme* approach and the *damage function* method [53]. In the first, the results from the LCI are itemized into impact categories at mid-point level, and so called mid-point categories [54], which attribute an environmental impact to the LCI results. When the global warming potential (GWP) is the calculated environmental impact, the mid-point impact category is quantified as kg of $CO_{2\text{-eq}}$ emissions released into the atmosphere. However, the mid-point categories do not give information that describes the final environmental consequences of the impact. To describe the final impact on the environment the mid-point categories are further aggregated to end-point categories, which are called *areas of protection* (AoPs) [55]. The AoPs give user-friendly information on the environmental damages and losses due to the specific impact of the human activities [53]. Since the damage-oriented categories provide highly aggregated information, they incur in a harsh simplification of the complex reality of the environmental damages, and for this reason often render a high level of uncertainty [54]. Moreover, the mid-point categories are widely used in many studies, and the greenhouse gases as a metric has been widely applied in recent research of environmental impact assessment of buildings. For this reason all the numerical results of the analysis in this research will be normalized to $kgCO_{2\text{-}eq}$ per m^2 of building heated area.

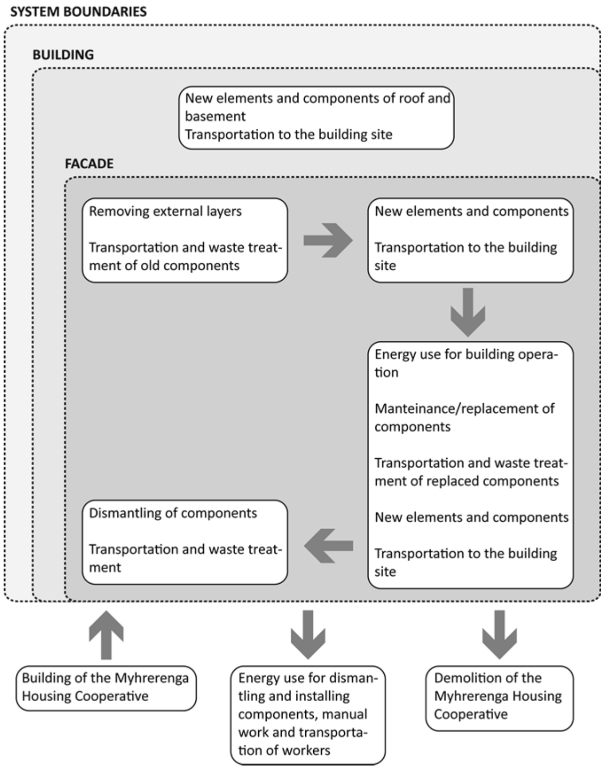


Figure 12. System boundaries of the LCA model for the retrofitting solutions of the Myhrerenga Housing Cooperative. The flows outside the grey squares are not included in the calculation.

The activities included in the lifecycle model used in this research, as shown in Figure 12, are derived from a study by Adalberth, who has pioneered the application of LCA to residential buildings and developed its general framework [47]. She has also developed an LCA model for producing an estimate of the energy use in the life cycle of a residential building. According to Adalberth, the term *life cycle of a building* refers to the temporal phases, such as the processes of building construction, use and demolition. According to Adalberth's model, the first step is the manufacturing of the building materials, followed by their transportation to the building site, the site excavation and the construction activities(Q_{erect}). The energy use for manufacturing each building element (Q_{manuf}), in kWh, is expressed by the Equation *3*:

Equation 3 $$Q_{manuf} = \sum_{i=1}^{n} m_i \cdot \left(1 + \frac{w_i}{100}\right) \cdot M_i$$ [47]

The energy use for transporting the building materials from the production site to the building site is expressed in Equation *4*:

Equation 4 $Q_{transp.erect} = \sum_{i=1}^{n} m_i \cdot \left(1 + \frac{w_i}{100}\right) \cdot d_i \cdot T_c$ [47]

Where n identifies the number of materials, i is the building material, m_i is the mass in tons of the building material i, w_i is the percentage of construction waste related to material i, M_i refers to the energy use in kWh for manufacturing the material i, d_i is the distance in km from the manufacturer of material i to the building site, and T_c is the energy use for the means of transportation, expressed in $kWhton^{-1}km^{-1}$.

The second stage includes the building management phase, where the energy use for the renovation processes is calculated. The energy for manufacturing of building elements during the renovation phase ($Q_{manuf.renov}$) includes the maintenance cycle, calculated as the ratio between the service life of the building and the service life of the material, as expressed in Equation *5*:

Equation 5 $Q_{manuf.renov} = \sum_{i=1}^{n} m_i \cdot \left(1 + \frac{w_i}{100}\right) \cdot M_i \cdot \left(\frac{life\ span\ of\ building}{life\ span\ of\ material} - 1\right)$ [47]

The energy use for the transportation of building materials during the maintenance phase, is calculated according to Equation *6*:

Equation 6 $Q_{transp.renov} = \sum_{i=1}^{n} m_i \cdot \left(1 + \frac{w_i}{100}\right) \cdot \left(\frac{life\ span\ of\ building}{life\ span\ of\ material} - 1\right) \cdot (d_i + d_{di}) \cdot T_c$ [47]

Where n identifies the number of materials, i is the building material, m_i is the mass in tons of the building material i, w_i is the percentage of construction waste related to material i, M_i refers to the energy use in kWh for manufacturing the material i, d_i is the distance in km from the manufacturer of material i to the building site, T_c is the energy use for the means of transportation, expressed in $kWhton^{-1}km^{-1}$, and d_{di} is the distance in km for disposing the material i from the building site. During the construction phase, the energy use for machinery, for lighting the building site and so on are also included in the calculation, but the energy use for the manual labour is not considered because enough information could not be found. The occupation phase is characterized by the energy use for space heating, ventilation, domestic hot water (DHW), for lighting, and appliances. The occupation phase is expressed in kWh in Equation *7*:

Equation 7 $Q_{occup} = Q_{occup.year} \cdot building\ lifetime$ [47]

The last step is the building end-of-life (EOL) phase, which includes the building demolition activities and the removal and transportation of the waste to a dump site or a reprocessing centre. These activities are expressed in kWh according to Equation *8* and Equation *9*:

Equation 8 $Q_{transp.renov} = \sum_{i=1}^{n} m_i \cdot \left(1 + \frac{w_i}{100}\right) \cdot d_{di} \cdot T_c$ [47]

Equation 9 $Q_{demol} = \sum_{j=1}^{m} p_j \cdot P_j$ [47]

The term *n* identifies the number of materials, *i* is the building material, m_i is the mass in tons of the building material *i*, w_i is the percentage of construction waste related to material *i*, T_c is the energy use for transportation, expressed in $kWh ton^{-1} km^{-1}$, d_{di} is the distance in km for disposing the material *i* from the building site, *m* and *j* refer to the number and the type of demolition process, p_j relates to the quantity of the process *j* (in ton, m^3 or m^2) and P_j is the energy use of the process *j* (in kWh).

The total energy use of the building lifecycle is calculated as the sum of all the above-described phases, according to *Equation 10*, and is expressed in kWh:

$Equation$ 10 $Q_{life\ cycle} = Q_{manuf} + Q_{transp.erect} + Q_{erect} + Q_{occ} + (Q_{manuf.renov} + Q_{transp.renov}) + Q_{demol} + Q_{transp.renov}$ [47]

2.7. Retrofitting actions

As described in the first section of this chapter, the retrofitting alternatives, which are applied to the Myhrerenga Housing Cooperative, follow the criteria set in both the technical and the architectural approach. In this section, such alternatives are itemized and detailed.

2.7.1. Technical approach: proposed alternatives

The technical approach considers the variation of the insulation layer of the facades of the Myhrerenga Housing Cooperative. The alternatives represent improvements of the thermal resistance of the *reference building*, which correspond to the current retrofitting solution of the building. To comply with the latest energy regulation adopted for Norwegian buildings, the energy retrofitting actions proposed in this study fulfil the requirements of Norwegian Standard NS 3700:2010, *Criteria for passive houses and low energy houses - Residential buildings*. According to the NS 3700:2010 the U-values of exterior walls, roof, floor and windows have to be equal to or less than 0.15, 0.13, 0.15 and 0.80 $W \cdot m^{-2} \cdot K^{-1}$ respectively to achieve the Passive House Standard [29]. To reduce the number of variables in the calculation, the thermal resistance of the external walls of all the improved solutions is set to 0.10 $Wm^{-2}K^{-1}$, while the U-value of the external walls of the *reference building* is 0.12 $Wm^{-2}K^{-1}$. Considering that the insulation materials used in this study, mineral wool slabs, VIP panels, and aerogel mats, have different thermal transmittances, the corresponding thicknesses of the insulation layers have been chosen to match the desired final thermal resistance of the wall.

The East and West walls of the building are stripped down, and the timber frame with the mineral wool filling is left bare. Oriented strand board (OSB) panels are attached to the external layer of the timber-frame structure. The new insulation layer is then attached to the outside of the OSB panels. In the solution called *reference building* a new timber frame structure is placed on the external side of the existing structure to hold the 200-mm-thick mineral wool layer. Further 18-mm-thick wooden horizontal spacers are placed externally to carry the external finishing cement plates. The solution called *Rockwool* differs from the above because the thicknesses of the timber frame structure and the insulation layer are both 250 mm.

In the solution called *VIP* the 60-mm-thick VIP panels are carried by steel plates which are fixed to the OSB board to minimize the air gap between each panel and the resulting thermal bridges [56]. In the solution called *aerogel* the 100-mm-thick aerogel mats are held by a steel net which is also nailed to the OSB panels [57]. In the alternatives both with VIP panels and aerogel mats the new externally added timber framework has a thickness of 100 mm. Table II- b in Appendix II presents details of the façade construction for the different insulation alternatives.

Similarly to the East and West walls, in the North and South walls the existing structure is kept and the insulation layers (Rockwool, VIP or Aerogel) are added externally. The walls that separate the apartments from the stairwells consist of 130-mm-thick concrete partitions, which are insulated either with 140 mm of mineral wool slabs, or with 40 mm of VIP panels, or with 100 mm of aerogel mats for the alternative with mineral wool, VIP, and aerogel, respectively.

Mineral wool insulation is produced in mats of stone wool fibres, which, depending on the application, have varying density from approximately 20 Kgm^{-3} to 180 Kgm^{-3} and above. Stone wool mats are made of natural stones, industrial waste from steel and cement production, and from stone wool waste. All components are melted in blast furnaces, impregnated with binders and oil, and finally blown out as fibres, compressed and packed [58, 59]. Since the density value of the mineral wool bats is a key factor for the CO_2 analysis, this has been chosen according to the needs that best fit the application in energy retrofitting. For this study the RockShell technology [60], which consists of self-standing Rockwool boards of 70 kgm^{-3} density and thermal conductivity of 0.034 $Wm^{-1}K^{-1}$, is used.

Vacuum insulation panels are at present time a promising solution for energy retrofitting. This is mostly due to the extremely low thermal conductivity condensed in a thin light-weight panel. A VIP panel consists of an airtight envelope containing an open-micro-pore core in which a low-pressure gas is trapped. At low pressure, gases decrease their thermal conductivity, which, at perfect vacuum reaches an infinite thermal resistance. A perfect vacuum is a only theoretical possibility, but a very low gas pressure positively affects the panel's thermal insulation properties, as described in Baetens et al. [61], and Jelle et al. [62]. In addition, the thermal conductivity of gases can also be reduced by reducing the movement of the gas molecules along the direction of the thermal flow, which limits the heat exchange through convection. To benefit from this principle the core material, in which the low-pressure-gas is trapped, needs to have a fine enough pore structure to avoid the elastic collision between two gas molecules.

This is ideally equal to 10 nm or below [61]. Fumed silica or silicon dioxide (SiO_x) is used for the core material because of its very low thermal conductivity. This varies as a function of the atmospheric pressure. This is between 0.003 $Wm^{-1}K^{-1}$ at 50 mbar and 0.020 $Wm^{-1}K^{-1}$ at 1 bar, where the thermal resistance of the silica core is approximately 30% higher than the one of polystyrene foam and glass fibres. Despite the high bulk density of the silica core, which is between 160 and 220 kgm^{-3}, its structure has a very high porosity (more than 90%), which makes the product extremely light-weight [61]. The air water vapour tightness of the core is secured by a multi-layered film, usually composed of aluminium foils, Polyethylene films, and polymer films, which completely wraps the silica core, as shown in Figure 13. The thermal conductivity of the composed panel varies from 0.004 $Wm^{-1}K^{-1}$ to 0.008 $Wm^{-1}K^{-1}$ due to ageing effects [61, 63]. 0.008 $Wm^{-1}K^{-1}$ is the value used for the energy calculation. The density of the panels is set to 190 kgm^{-3}, taken from [64].

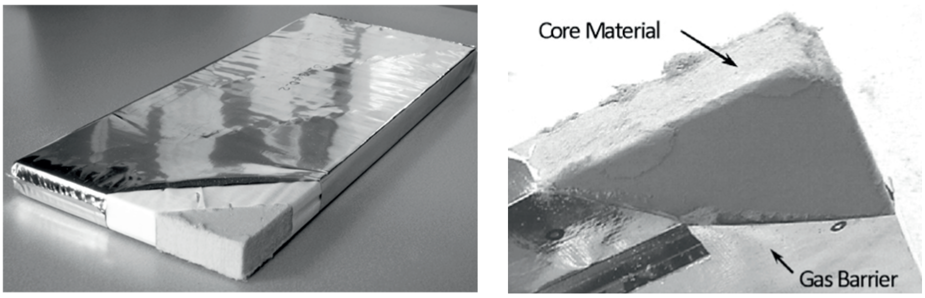


Figure 13. Two pictures of commercially available VIPs in which the different layers composing the panel are shown.

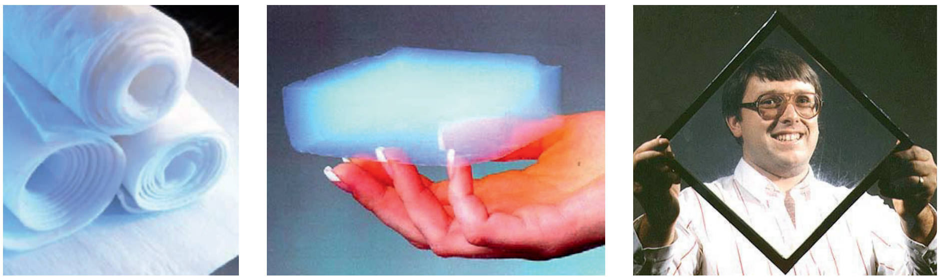


Figure 14. Three pictures of aerogel products. Left: aerogel mats for wall insulation. Centre and right: monolithic aerogel for windows insulation.

Silica-based aerogels have interesting physical properties, which make this material one of the best insulating materials that also is flexible in terms of how it can be used in the building sector, as shown in Figure 14. The density of the gel structure is 2200 kgm^{-3}, but, because of the high core porosity, commercially available aerogels for building application vary in density from 70 kgm^{-3} to 150 kgm^{-3}. The sponge-like structure makes aerogel withstand a compression force up to 3 bar, but it also has a very low tensile strength. This makes the material extremely fragile [65]. However, to strengthen its tensile resistance, the gel structure of commercially available products is adhered to a fibre matrix. Due to the porosity of aerogel structure, transfer of thermal energy through the core occurs in three ways: by gas convection, by conduction, and by radiation. The pore size and the resulting density of the core affect the thermal performance of the material which, as shown in [66], has its lowest thermal conductivity at 150 kgm^{-3}. Depending on the of pressure, temperature and core density, the thermal conductivity of aerogel varies between 4 and 15 $mWm^{-1}K^{-1}$ [65-68]. Specifically for this research, the Spaceloft aerogel by Aspen Aerogel is chosen as opaque insulation material. This has a thermal conductivity of 14 $mWm^{-1}K^{-1}$ [69].

SiO_2 aerogels, like the other metal oxides-based aerogels, also have interesting optical properties. Since the pores forming the gel networks are smaller than the visible light wavelength (380-740 nm), aerogels have high spectral normal and hemispherical transmittance values. This varies between 0.65 and 0.92 [67, 70, 71] It has a total transparency ratio between 0.78 and 0.96 [71, 72]. Thus, due to their optical and thermal properties, aerogels represent the most promising solution for achieving very low insulation values in transparent and translucent surfaces without compromising the daylighting conditions. As shown in Jensen et al. commercially available multi-glazed windows achieve lower U-values by diminishing their solar transmittance values (G-values). A multi-glazed window with low-energy coating and gas filling has an insulation value of 0.5 $Wm^{-2}K^{-1}$ and a G-value of 0.50. On the other hand, some studies show that a double glazing with aerogel filling with a similar U-value has a G-value of 0.75 [73]. Market-ready products are available by Kalwall and Okalux today. They have a U-value of 0.3 $Wm^{-2}K^{-1}$ but with a low G-value (0.2). Much research has gone into developing glazing solutions that can both have a high thermal resistance and optical properties comparable to standard glazing units. Jensen et al. [72-74] prototyped a double glazing window with 15-mm-thick monolithic aerogel insulation that has a centre U-value of 0.66 $Wm^{-2}K^{-1}$ and an average direct solar energy transmittance of 0.75, outperforming the solar energy transmittance of a standard triple glazing with argon filling. According to Shultz et al. [75, 76] a double-glazing unit with 20-mm-thick silica aerogel insulation evacuated at 10 hPa and equipped with a butyl sealant and polystyrene spacer would have a 0.50 $Wm^{-2}K^{-1}$ centre U-value and a 0.75 G-value. Similar results are presented by Duer and Svendsen [71] and Rubin and Lampert [70].

Two window technologies are considered in this study: a triple glazed window with argon filling and a double glazed window with monolithic aerogel filling. The first solution is a common technology used for energy retrofitting and has a U-value of 0.79 $Wm^{-2}K^{-1}$. It is composed of three 3-mm-thick low-energy glass panes and two 10-mm-thick argon layers. The second one is still at a prototype phase with a tested U-value of 0.50 $Wm^{-2}K^{-1}$. It is composed of two 3-mm-thick clear glass panes and one 20-mm-thick layer of monolithic aerogel [71, 77]. The solar heat gain coefficients are 0.73 and 0.40, for the aerogel and the argon respectively. The visible transmittances are 0.71 and 0.62, for the aerogel and the argon respectively.

Since aerogel-vacuum-insulated windows do not yet exist as commercial products, the data for modelling the aerogel glazing in this research are obtained by experimental analysis. Specifically, the normal and hemispherical light transmittance values derive from the spectral analysis of a 20-mm-thick sample of aerogel from the Swedish Airglass [71]. The thermal conductivity of the evacuated aerogel is also taken from Duer and Svendsen and is set to 11 $mWm^{-1}K^{-1}$ [71].

The roof and the basement walls and floor are also upgraded. However, for these parts of the building there is no change in the insulation layer. The roof construction consists of a timber frame on a concrete slab. This creates an air gap between the lower slab and the above covering of approximately 30 cm, which is filled with blow-in polystyrene insulation. The concrete walls delimiting the basement are insulated externally with 200-mm-thick expanded polystyrene slabs (EPS), and both the basement floor and ceiling are equipped with 100-mm-thick mineral wool slabs.

The new energy supply system installed in the building consists of three air-to-water heat pumps which substitute the electric-oil boiler and takes advantage of the already mounted radiators. The heat pumps operate in cascade and have a total heating capacity of 75000 kW and a rated COP of 3.2. The ventilation system consists of a central air handling unit connected to a heat recovery system with an efficiency of 83% [33].

2.7.2. Architectural approach: proposed alternatives

Here, the alternatives to the reference building mainly relate to the features of the building facades. The window-to-wall-ratio (WWR) is changed from approximately 24%, which is the current value of the *reference building* solution, to 33% and to 50%, as shown in Figure 15. These values represent the average WWR of both the East and West facades. Since it is a residential building, a higher value than 50% of the WWR is not used as it would reduce the available surfaces on which furniture and fittings can be placed.

In the retrofitting solutions with the aerogel glazing, not all the windows use this technology. This is because the monolithic aerogel is a very fragile material, and its use in an operable window leads to damages of its structure and to a reduction in its insulation value. Since some of the windows must be operable, it is decided to limit the amount of aerogel windows to only a part of the total glazing. The share of aerogel glazing is approximately 28% of the total window area for the 24% and the 33% WWRs, while it rises to 39% for the 50% WWR. This is summarized in Table II- d and Table II- e in Appendix II.

In the East and West facades, the external finishing is varied from the original used in the *reference building*, which has painted cement tiles. This is called the *CT* finishing type, as listed in Table II- f in Appendix II. The other finishing types consist of untreated wood cladding (named *UW*), copper impregnated wood cladding (named *CIW*), mineral-wool-insulated sandwich panels (named *SSP*), and polymer-cement tiles (named *PT*).

The external finishing of the North and South facades is made of a painted plaster coating, and the internal finishing for all the facades consists of painted gypsum plasterboards. The facades equipped with cement tiles and polymer cement tiles are coated with paint. The facades with copper impregnated wood cladding are coated with a layer of wood preservative. The facades with either the untreated wood cladding or the insulated sandwich panels do not have any coating. The insulated sandwich panels consist in a mineral-wool layer enclosed by two layers of zinc-coated steel sheets [78]. Considering that the thermal transmittance of these panels (0.039 $Wm^{-1}k^{-1}$) is higher than the thermal transmittance of mineral wool (0.034 $Wm^{-1}K^{-1}$), their thickness is set to 300 mm in order to equalize the insulation level of the façade with the 250-mm-thick mineral-wool layer (0.10 $Wm^{-2}K^{-1}$). Details of the construction of the facades with the different finishing types are in Table II- f in Appendix II.

The existing balconies, which are made of concrete slabs and prefabricated concrete panels for the balustrades, are removed and replaced. The new balconies have a steel structure which is completely detached from the floor slabs and self-supported by columns, and the original balustrades are replaced with glass panels. Two types of balconies are considered. The first solution is a standard balcony with a steel frame structure and glass balustrades. The second solution closes the volume between two balconies with glass panels to create sunspaces. The application of these solutions to the building facades results in three possible alternatives. The one called *B0* represents the facades as they are in the *reference building*, where steel and glass balconies are present on the West façade only. The *B1* is the alternative where steel and glass balconies are placed on both the East and West facades for the 33% and the 50% WWRs. In the *B2* alternative there are sunspaces on both the East and West facades for the 33% and the 50% WWRs, as shown in Figure 15. Table II- g in Appendix II lists the façade solutions with the different balcony alternatives. Finally, the technical and architectural alternatives are combined as listed in Table 3.

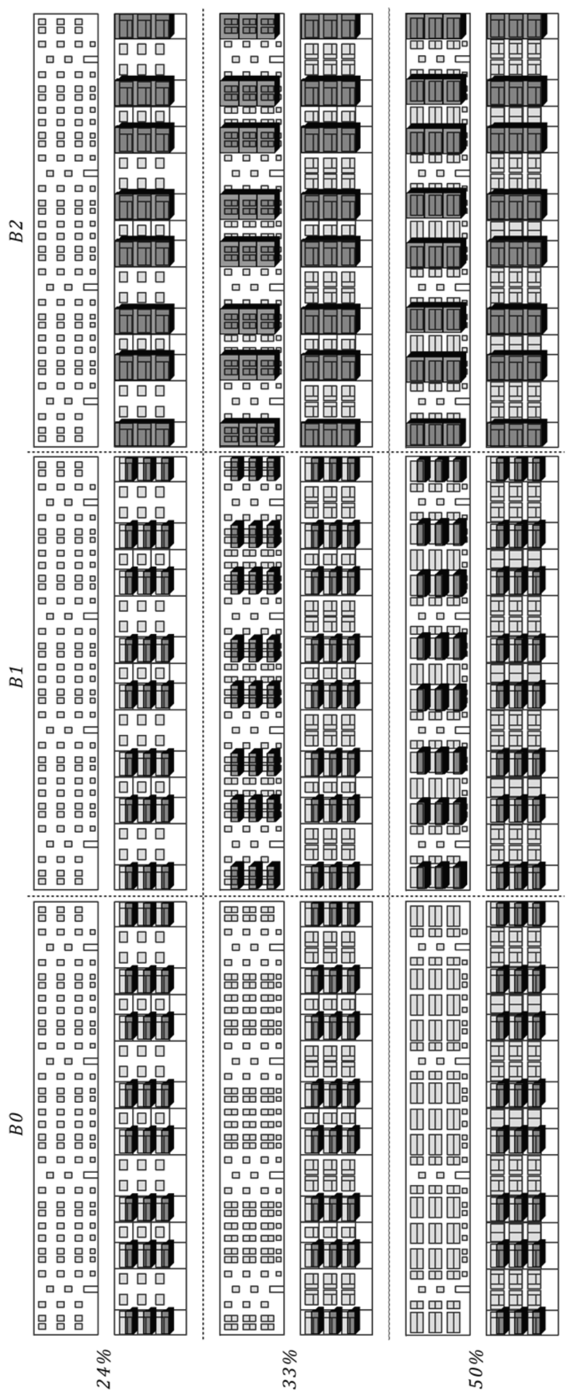


Figure 15. The façade solutions with the different alternatives for glazing ratio and balcony typologies. 24%, 33%, and 50% represent increasing window-to-wall ratios. B0, B1, and B2 represent the different balcony typologies.

		Technical solutions	Insulation type	Rockwool				Aerogel			VIP		
			Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions			Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type		Balcony type										
24%	CT		B0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	UW		B0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	UW		B1	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	UW		B2	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	CIW		B0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	SSP		B0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
	PT		B0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
33%	CT		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B1	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B2	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	CIW		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	SSP		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	PT		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
50%	CT		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B1	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	UW		B2	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	CIW		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	SSP		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO
	PT		B0	YES	YES	NO	NO	YES	NO	NO	YES	NO	NO

Table 3. The matrix of all the alternatives with the combinations of the technical and architectural solutions. Rockwool, aerogel, and VIP are the proposed insulations for the walls. 0.10, 0.15, and 0.18 are the proposed U-values of the external walls. AGN is triple glazing with argon, AGL is double glazing with aerogel. 24%, 33%, and 50% are the proposed glazing ratios of the facades. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios

2.8. Assumptions and limitations

Several authors [15, 47, 79] report values of energy use for demolition and construction activities on the building site. According to Adalberth [11] the energy use for construction and demolition activities is 1% of the total lifecycle energy for a 50-year lifetime. Similar values are reported by Blengini [15] and Gustavsson et al. [79]. Due to the small contribution of these figures and the lack of information regarding the installing and dismantling phases, the energy use of these phases has not been considered in the calculation.

The transportation distance between the building and the disposal site or the end-of-life (EOL) treatment plant is taken from Adalberth [47] and assumed to be 20 km. The EOL disposal scenarios are extracted from the *Nasjonal Handlingsplan for bygg-og anleggsavfall 2007-2012 (NHP2)*, which was issued in 2007 and includes a proposal regarding the handling and disposal of building waste in Norway [80]. The disposal scenarios for paint is sourced from [81], while the EOL scenarios for plastic materials and steel products are extracted from [17]. VIP, Aerogel and plaster are not part of the *NHP2*, so they are assumed to be 100% landfilled. The EOL disposal scenario for the materials in the *reference building* and in the retrofitting solutions are listed in Table III- a in Appendix III. All materials are 100% sourced from primary materials with the exception of EPS, of which 45% is sourced from recycled material. There are no environmental credits for energy recovery associated with incineration. No system expansion or substitution is credited to the recycling processes.

The transportation distances from the material production sites to the Myhrerenga Housing Cooperative are set according to the location of the closest production plants, and are itemized in Table III- a in Appendix III, where the means of transportation, which refer to a study from Blengini and Di Carlo [14], are also reported. The same table also lists the information regarding the material waste due to cutting and rendering at the building site, which is taken from Gustavsson et al. [79], Kellenberg et al. [45], Adalberth [47], and Blengini and Di Carlo [14].

Several authors, such as Adalberth [47], and Chiterlet and Defaux [49], consider 50 years as a normal lifetime for a residential building, while other sources span from 40 years [82], to 70 years [14, 81] and to 100 years, as in Gustavsson et al. [79]. Regarding this aspect, Haapio and Viitaniemi [83] studied the effects of different lifetime expectancies for the building components on the environmental impact of a residential buildings, extending their lifetimes from 60 years to 160 years. Their study shows that such differences cause the primary energy use of the operation and maintenance phases to increase by 1.8 times. Similarly, Gustavsson et al. [79] compare the effect of a doubled lifetime on the CO_2 emissions of a wooden frame residential building. These studies clarify how important the choice of the building lifetime is to the balance between the embodied energy and the energy use for operating the building. Since any lifecycle analysis of buildings is based on a predictive evaluation of the future lifetime of the object of study, it is clearly impossible to forecast an accurate value. However, regarding the specific case study in this research, some considerations can be drawn from the Norwegian building stock analysis by Bergsdal et al. [19] and by Sartori et al. [84]. Bergsdal et al. propose three scenarios of building demolition rates for the residential buildings in Norway from 1800 until 2100. The first two are time-fixed and define the building stock lifetime between 125 years (low demolition rate) and 75 years (high demolition rate). The third scenario is a dynamically descending time-curve, which define a range of lifetimes for the residential stock that varies between 150 years and 95 years. Similarly, Sartori et al. propose three lifetime scenarios for the residential buildings in Norway, 75 years, 100 years, and 125 years, respectively. Considering both these models, and considering that the Myhrerenga Housing Cooperative was built approximately 45 year ago, three different lifetimes for the retrofitting solutions are considered in this research: 25 years, 50 years, and 75 years. This matches the lifetimes proposed by Bergsdal et al. and Sartori et al.

The operation phase also covers the maintenance activities related to façade components. These are not always considered in lifecycle studies, but they are important to the final impact assessment. A study from Blom et al. [81] shows that the $CO_{2\text{-eq}}$ of $1m^2$ of façade of a residential apartment building varies by 25% if different maintenance scenarios are chosen. So, the expected service life of the building components is critical to the determination of an accurate environmental impact. The service lifetimes of building components are studied and reported in many sources [47, 81, 85]. However, such figures are strictly related to the building's geographical location, the local climatic conditions, and the manufacturers specification for the building elements. In such a perspective, SINTEF Byggforsk has prepared guidelines for the maintenance cycles for Norwegian building components, as reported in [86]. The length of time-intervals between each substitution/upgrading of building components depends on their technical quality and on the climatic and operational stress to which the building parts are subjected. Since windows are a critical building component, it was decided to study both short, medium and long substitution rates, as reported in table 4 of [86]. Since aerogel glazing is supposed to be more fragile than the triple glazing due to the vacuum within the two glass panes, a super-short substitution rate is proposed only for this window technology. The maintenance cycles for the relevant components and building parts are listed in Table III- b in Appendix III.

The energy use for transportation of workers from and to the building site during the maintenance activities has been also studied by Blom et al. [81], who state an average distance of 50 km, as given by maintenance companies. Their study reports that the impact of the transportation of workers is ranked third in importance, accounting for 22% of the total emissions. However, because information regarding the length and rate of each maintenance activity could not been obtained, the energy use due to the transportation of workers has not been included in the calculation.

Impact data for materials has been sourced from the Ecoinvent database. Many authors collect impact data from local sources and country-specific databases to reduce the uncertainty. However, such sources are not fully comprehensive, and their use reduces the grade of comparability to other studies. To overcome this issue, the Ecoinvent database is used for the impact assessment of the LCI data in order to give coherent and consistent results that can be compared to other studies based in European countries [87]. The materials whose environmental impact data has been extracted by other sources than the Ecoinvent database are: VIP and aerogel as insulation materials, untreated wood, copper impregnated wood, steel-laminated sandwich panels, and polymer-cement tiles as finishing materials.

The CO_2 emissions of VIP are taken from the model developed by Schonhardt et al. [64], and is equal to 8.06 $kgCO_{2\text{-}eq}kg^{-1}$. The VIP production process consists of several energy intensive steps: production of the fumed silica core, metallization of the film wrapping, and assembling of the panels. The first stage consists of the production of the silicon tetrachloride ($SiCl_4$) and silicon carbide (SiC), after which hydrogen (H_2) is obtained by methanolysis and employed in the flame hydrolysis of the $SiCl_4$, needed to produce the fumed silica core. The second stage consists of depositing a thin layer of aluminium (Al) on a polyethylene terephthalate (PET) film of 12μm thickness. The metallized film is the outer layer of the composite film wrapping, which is made of two 12-μm PET foils, one 18-μm-thick polypropylene (PP) film, and one 60-μm low-density polyethylene (LDPE) film, which is the innermost layer. All foils are simultaneously bonded together by spraying liquid polyurethane glue heated at 60°C. The final stage consists of mixing, pressing and drying the compound made of fumed silica, cellulose fibres and SiC. This is shaped to a panel form, wrapped in the multi-layered film and the air extracted from the envelope [64].

Aerogels, which were discovered and first synthetized by Kistler in the early 1930s [65], are extremely innovative materials that, among several applications in a variety of different fields, show very interesting insulation properties in both opaque and transparent building components. As described in Husing and Schubert [66], aerogels have the special characteristics of being highly porous materials. The porous structure, constituting the skeleton of the aerogel, is called *gel*. The *gel* is a three-dimensional sponge-like network of particles made by condensing particles that are dispersed in a liquid solution, called *sol*. To obtain the final product from this *sol-gel* compound, the liquid part is substituted with air through various processes. Depending on the process the gel structure can be altered and its volume reduced. In this case the resulting structure is called *xerogel*, and it can take the form of powder or be monolithic. When the gel porous network is left almost unaltered, the resulting product is called *aerogel*. Almost all metal or semimetal oxides, such as silica (SiO_2), aluminium oxide (Al_2O_3), titanium oxide (TiO_2) and zirconium oxide (ZrO_2) can contribute to a gel formation, which in such cases leads to inorganic aerogels. Among these, the SiO_2-gel is the one that has found the widest application. Also organic compounds, like polymerized organic monomers, can contribute to a gel formation, which is in this case consists of a mixture of resorcinol-formaldehyde and melamine-formaldehyde. Regardless of the initial mixture (organic or inorganic), the process of drying the wet sol-gel compound follows the principle of substituting the pore liquid with air through a controlled shrinkage of the gel network. These processes are called *supercritical drying, freeze-drying and drying at ambient pressure*. A thorough description of the processes of sol-gel formation and drying can be found in [66, 88, 89].

Currently, the information regarding the environmental impact data for aerogel production is only available at Aspen Aerogel and from a study by Dawson et al. [90]. They compared the embodied carbon emissions of the Spaceloft aerogel, as claimed by Aspen Aerogel, with the CO_2 emissions from the production of a lab sample in the facilities of the University of Bath. According to Dawson et al. the embodied energy and the $CO_{2\text{-eq}}$ burden associated with their sample are much higher than the Spaceloft production. However, as stated by Dawson et al., by widening the production at an industrial scale, by using more energy efficient equipment and recycling some of the chain sub-products, it is possible to lower the $CO_{2\text{-eq}}$ emissions to the value claimed by Aspen Aerogel, where a value of 4.2 $kgCO_{2\text{-eq}}kg^{-1}$ is reported.

The values of emissions per unit of mass for the production of untreated wood and copper impregnated wood are 0.0428 $kgCO_{2\text{-eq}}kg^{-1}$ [91] and 0.0663 $kgCO_{2\text{-eq}}kg^{-1}$ [92], respectively. The emissions of the production of polymer-cement tiles are 0.231 $kgCO_{2\text{-eq}}kg^{-1}$ [93], and of the mineral-wool-insulated sandwich panels are 0.91 $kgCO_{2\text{-eq}}kg^{-1}$ [94]. The environmental impact emissions of the cement tiles are 1.11 $kgCO_{2\text{-eq}}kg^{-1}$ and are sourced from the Ecoinvent database.

Conversion factors from electricity grid power (kWh) to $kgCO_{2\text{-eq}}$ are calculated for three different scenarios: European energy mix, Norwegian energy production only, and a projection of the future energy exchange within Europe developed by the Centre on Zero Emission Buildings (ZEB). The EU energy mix is calculated to be 0.361 $kgCO_{2\text{-eq}}kWh^{-1}$ and the Norwegian inland production 0.019 $kgCO_{2\text{-eq}}kWh^{-1}$ [95]. The "ZEB energy mix" is derived by projecting the EU energy imports-exports scenario that optimizes the use of renewable sources to achieve a carbon-neutral electricity grid by 2054. Assuming a 60-years lifetime of a building erected in 2010, the average CO_2 conversion factor becomes 0.132 $kgCO_{2\text{-eq}}kWh^{-1}$ [95]. This method proposes a dynamic calculation that predicts the future $kgCO_{2\text{-eq}}$-to-kWh conversion factor according to Equation *10*:

Equation 10 $$R_{el} = \frac{361}{2} \cdot \frac{t_n - t_0}{lifetime}$$

where t_n is the time at which the CO_2 emissions from the EU electricity mix equals zero. This is assumed to be in 2054. t_0 is the time at which the calculation is started (e.g. the starting point of the building lifetime), and this is assumed to be 2012 in this case. *Lifetime* is the length of time the building is operated, here as 25, 50 and 75 years. Since the conversion factor is dependent on the building lifetime, three values derive from the life spans used in this work: 0.303 $kgCO_{2\text{-eq}}kWh^{-1}$ for 25 years, 0.152 $kgCO_{2\text{-eq}}kWh^{-1}$ for 50 years, and 0.101 $kgCO_{2\text{-eq}}kWh^{-1}$ for 75 years.

3. Introduction to the results

Results of the calculation of the yearly building energy demand and the $CO_{2\text{-eq}}$ emissions from the comparison of the different technical and architectural variables applied to the Myhrerenga Housing Cooperative are presented in chapters 4, 5, 6, 7, and 8. Due to the large number of variables used, the results are divided in five chapters, of which the first three chapters present the results of the technical approach, and the last two present the results of the architectural approach. In the first chapter the proposed insulation materials (mineral wool, aerogel, and vacuum insulation panels) are compared. The second chapter shows the results from the comparison of the different glazing ratios: 24%, 33%, and 50%. In the third chapter, the use of the aerogel windows is assessed against the standard triple-pane-window with argon. Both window technologies are examined by varying the glazing ratio (24%, 33%, and 50%). The fourth chapter shows the results from the comparison of different finishing of the East and West facades. These finishing types are: cement tiles, untreated wood, copper impregnated wood, steel-coated and mineral-wool-insulated sandwich panels, cement-polymer tiles. The fifth chapter shows the results from the comparison of varying balcony quantities and types. These are: standard balcony on West façade, standard balcony on both East and West facades, and sunspace on both East and West facades. The balcony solutions are examined by varying the East and West facade glazing ratios (24%, 33%, and 50%).

4. Comparison of different insulation materials

Here the results from the comparison of the use of different insulation materials are presented. The results from the analysis of the different retrofitting scenarios are presented as normalized to 1 m^2 of heated building area per year. The first set of data shows the results of the building energy demand and the greenhouse gas emissions from the comparison of the use of mineral wool, aerogel, and VIP as insulation materials. The second set of data presents the results of the building energy demand and the greenhouse gas emissions from the comparison of different insulation thicknesses applied to the aforementioned insulation materials. Finally, the last set of data shows the results of the building energy demand and the greenhouse gas emissions from the comparison of different glazing ratios of the facades insulated with mineral wool, aerogel, and VIP.

Each set of data is examined by varying the building lifetime and the kWh-to-CO_2 conversion factor. These are: 25-year, 50-year, and 75-year building lifetime, and the conversion factor developed at the Research Centre on Zero Emission Buildings (ZEB), the EU average conversion factor, and the Norwegian energy mix at inland production. Lastly, the compositions of the greenhouse gas emissions of each of the retrofitting option are compared for the three building lifetimes.

4.1. Objective

The objective of the work is to compare and assess the environmental impact of different insulation materials applied in the energy retrofitting of a housing complex, the Myhrerenga Borettslag, located in Oslo, Norway. A reference solution, which represents the actual accomplished renovation work of the building [33], is compared to three options with improved thermal resistance of the external walls using different insulation materials. The insulation level of the facades in the reference solution is 0.12 $Wm^{-2}K^{-1}$, and the insulation material used is mineral wool. The insulation materials used in the alternative retrofitting upgrades are mineral wool, vacuum insulation panels (VIP) and aerogel, and the U-values of the external facades of these solutions is set to 0.10 $Wm^{-2}K^{-1}$. To better evaluate the share of embodied emissions of the proposed insulation alternatives, the kWh-to-CO_2 conversion factor and the building lifetime are varied.

The first sensitivity analysis is carried out to better understand to what extent it is environmentally wise to apply massive insulation layers in energy upgrades of residential buildings. In order to do so, the thickness of the insulation material of the three retrofitting options (mineral wool, aerogel, and VIP) is varied to meet the insulation levels set in the NS 3700:2010 [29] for the energy retrofitting of residential buildings. These levels are set for the external facades to an U-value of 0.18 $Wm^{-2}K^{-1}$ for low-energy houses, 0.15 $Wm^{-2}K^{-1}$ for passive houses, and 0.10 $Wm^{-2}K^{-1}$ respectively. The environmental drawbacks of using the super-insulating options are compared with the lighter alternatives by analysing the $CO_{2\text{-eq}}$ emissions for each solution.

The second sensitivity analysis is carried out to evaluate to what extent higher energy losses, due to a higher glazing ratio of the building facades, are counterbalanced by lower embodied greenhouse gas emissions due to a smaller amount of insulation in the external facades. The three insulation materials (mineral wool aerogel, and VIP) with a U-value of the facades of 0.10 $Wm^{-2}K^{-1}$ are evaluated for glazing ratios of 24%, 33%, and 50%. To better evaluate the environmental benefits of smaller quantities of insulation, all three kWh-to-CO_2 conversion factors are applied. To evaluate the share of the insulation material in the composition of the building CO_2 emissions, the three lifetimes scenarios are applied.

Details of the external facades in the retrofitting scenarios are presented in Table II- b, Table II- c, Table II- d, and Table II- e in Appendix II. Details of the renovation activities for the basement, roof, windows, balconies, and other parts of the building are presented there. Walls to non-conditioned zones (such as the stairwells) are either insulated with 140 mm of Rockwool slabs, 40 mm VIP panels or 100 mm Aerogel mats for the insulation alternatives named *Rockwool*, *VIP*, and *Aerogel*, respectively. For all the insulation alternatives the following apply: the basement ceiling is insulated with 100 mm Rockwool slabs, existing windows are substituted with triple glazing with Argon filling (U-value 0.79 $Wm^{-2}K^{-1}$), existing prefabricated concrete balconies are substituted with new steel structures which are completely detached from the floor slabs, and their original cement balustrades are substituted with glass panels, the roof is insulated with approximately 30 cm of blow-in polystyrene, the concrete walls delimiting the basement are insulated externally with a 200-mm-thick expanded polystyrene slab (EPS), and the basement floor is equipped with 100 mm Rockwool slabs.

4.2. Results: energy retrofitting alternatives

Figure 16 shows the energy demand of the retrofitting packages with mineral wool, aerogel, and VIP insulation, and the reference building. It should be noted that the U-value of the external facades of the proposed retrofitting upgrades is 0.10 $Wm^{-2}K^{-1}$ and that the U-value of the external facades of the reference building is 0.12 $Wm^{-2}K^{-1}$, i.e. not a large difference.

The shares of single end-uses are presented, but the heating and the DHW system are aggregated as they are served by the same air-to-water heat pump. As seen in Figure 16, the alternatives with mineral wool, aerogel, and VIP have a yearly energy use for space heating and DHW of approximately 53 $kWhm^{-2}y^{-1}$ while the reference building is 2 $kWhm^{-2}y^{-1}$ higher due to the thinner insulation layer, with a slightly lower insulation value, as detailed in Table II- b in Appendix II.

The $CO_{2\text{-eq}}$ emissions of the four retrofitting scenarios using the ZEB energy mixes and the 25-year, 50-year, and 75-year building lifetimes are presented in Figure 17. In the 25-year lifetime scenario, the lifecycle embodied emissions of the building components change the even distribution of energy uses in Figure 16. The contribution of the $CO_{2\text{-eq}}$ emissions from material production, maintenance cycles and waste treatment account for 13% and 20% of the total, for the reference building and the *VIP* option, respectively. The total emissions of alternative with VIP (31.8 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$) are 7% higher than those of the reference building (29.7 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$), while the emissions of the *Rockwool* alternative (29.4 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$) are 1% lower than those of the reference building. The alternative *Aerogel* has 1 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ lower emission than the *VIP* alternative due to the lower emission impact of this material and its total emissions are 4% higher than those of the reference building.

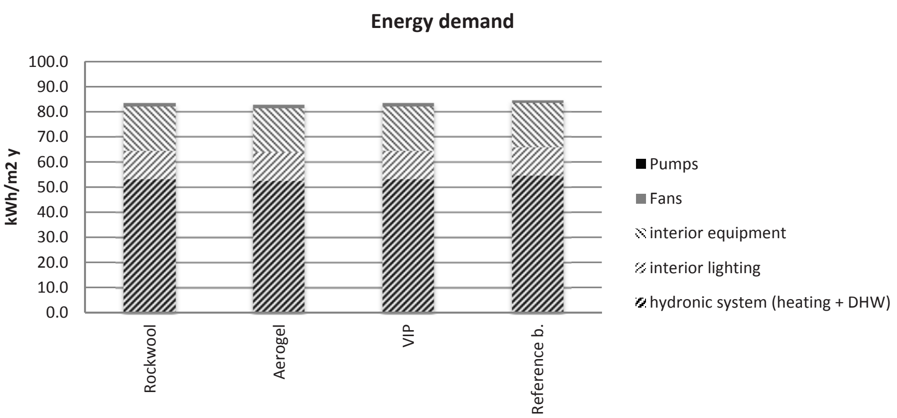


Figure 16. Composition of the yearly energy demand of the four retrofitting alternatives. Values are normalized to 1 m^2 of building heated area.

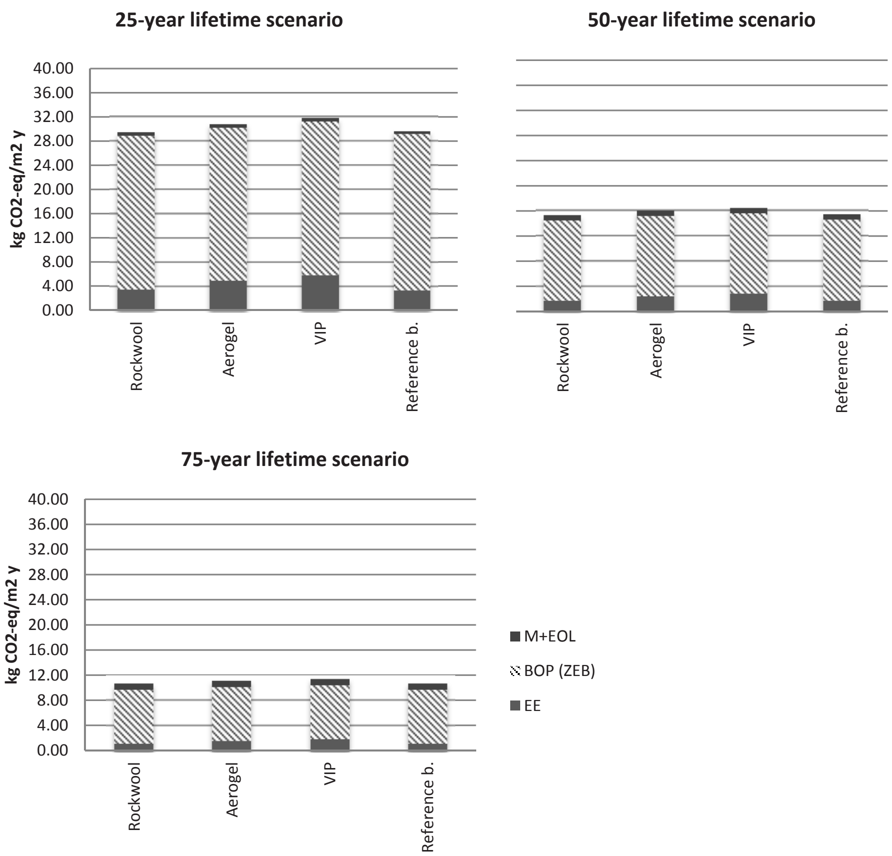


Figure 17. CO_2 emissions for retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

When introducing the 50-year and the 75-year lifetime scenarios, the relative contribution of the embodied emissions (*EE* and *M+EOL*) increases. This is 17% and 23% for the alternative *Rockwool* for the 50-year and the 75-year lifetime scenario, respectively. The same contribution is 20% and 26% for the alternative *VIP*, for the same lifetime scenarios as above. This is due to the fact that the ZEB electricity-to-emissions conversion factor varies with time and renders a greener energy grid for longer lifetimes. In addition, the total embodied emissions are spread over a longer period, causing the difference in absolute emissions between the retrofitting options to be lower in the 75-year scenario. However, their relative difference does not change.

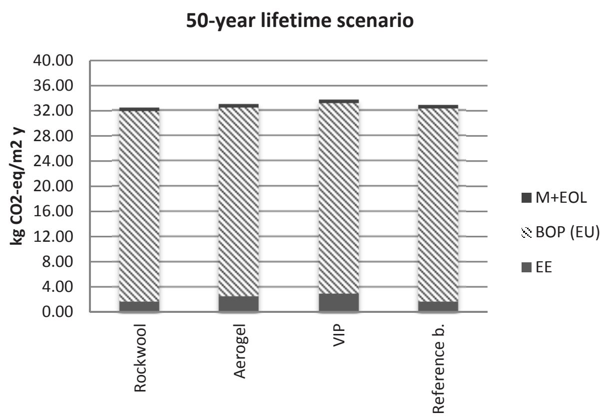


Figure 18. CO_2 emissions for retrofitting alternatives for the 50-year lifetime scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year.

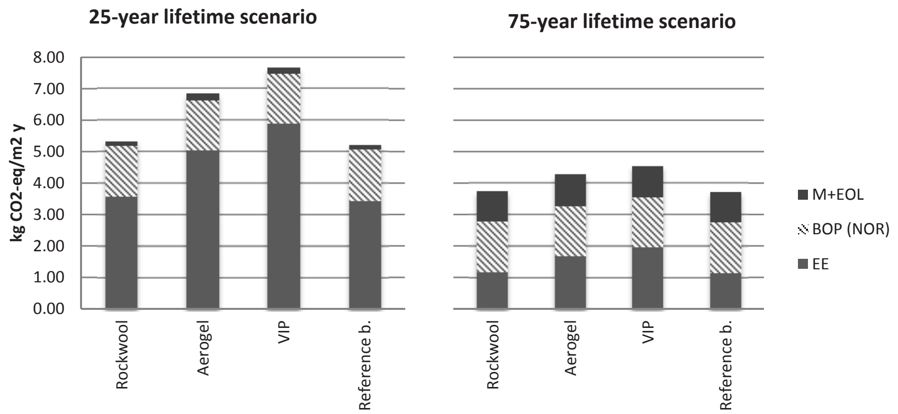


Figure 19. CO_2 emissions for retrofitting alternatives for the 25-year and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the Norwegian average energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year.

Figure 18 shows the $CO_{2\text{-eq}}$ emissions for the four retrofitting alternatives with the European average energy mix (*BOP EU*) and the 50-year lifetime scenario. The EU energy mix has a higher impact per kWh of produced electricity than the ZEB mix, and it is constant over time. For both these reasons, the share of embodied emissions (*EE* and *M+EOL*) is very small, but its variation with the building lifetime is much wider than in the ZEB mix. This is 17% and 9% for the VIP alternative in the 25-year and the 75-year lifetime scenario, respectively. Similarly, the contribution of the embodied emissions for *Rockwool* is almost halved (11% and 7%) for the same lifetimes (the figures for the 25-year and the 75-year lifetime scenarios are not presented here). For this reason, the maximum relative difference in lifecycle emissions between the energy upgrades varies from 2% in the 75-year scenario to 6% in the 25-year scenario. The average of the emissions in the 50-year lifetime is 33 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$, and it varies by ±1 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ between the other two lifetime scenarios.

The $CO_{2\text{-}eq}$ emissions of the four retrofitting alternatives for the Norwegian energy mix and the 25-year and the 75-year building lifetimes are presented in Figure 19. The Norwegian inland production energy mix has the lowest emissions per kWh of produced electricity. For this reason, the relative contribution of the emissions embodied in building material (*EE* and *M+EOL*) is the greatest. This varies between a minimum of 57% for the reference building and the 75-year lifetime, to a maximum of 79% for the VIP option and the 25-year lifetime. As a consequence, the relative difference between the retrofitting options is maximized. In the 25-year scenario, *Rockwool* and *VIP* are 2% and 47% higher than the reference building, respectively. In the 75-year building lifetime, this difference is reduced to 1% and 22% for the same retrofitting options. This is due to the fact that in the shortest lifetime scenario the initial embodied emissions (*EE*) have the highest share (77% in *VIP*) and thus enhance the different environmental impacts of the production phase between the insulation materials. The embodied emissions of 1 kg of VIP are almost eight times higher than those of 1 kg of mineral wool. On the other hand, in the 75-year scenario, the embodied emissions (*EE*) are spread over a longer period, while the share of the maintenance cycle and the end-of-life increases (22% on average for the *M+EOL* phase). Due to the above, the total emissions of the retrofitting alternative in the 75-year scenario drop by 1.6 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for *Rockwool* and 3.1 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for *VIP.* These represent a difference in the total emissions between the 25-year and the 75-year lifetimes of 30% for the alternative with mineral wool, and 40% for the alternative with VIP.

As presented in Figure 20, the main contributors to the environmental impact in all retrofitting scenarios consist of paint and finishes, concrete tiling, asphalt shingles, and insulation materials (EPS, Rockwool, VIP and aerogel). The paint, which is applied to both indoor and outdoor surfaces, including window frames, is alkyd paint diluted with 60% water with CO_2 emissions of 2.74 $kgCO_{2\text{-}eq}kg^{-1}$. Despite its initial small quantity, its frequent maintenance cycle (a new coating every 10 years) and its high emissions due to waste-treatment (2.38 $kgCO_{2\text{-}eq}kg^{-1}$) makes it an important contributor to the total environmental impact in the 50-year and 75-year lifetime scenarios.

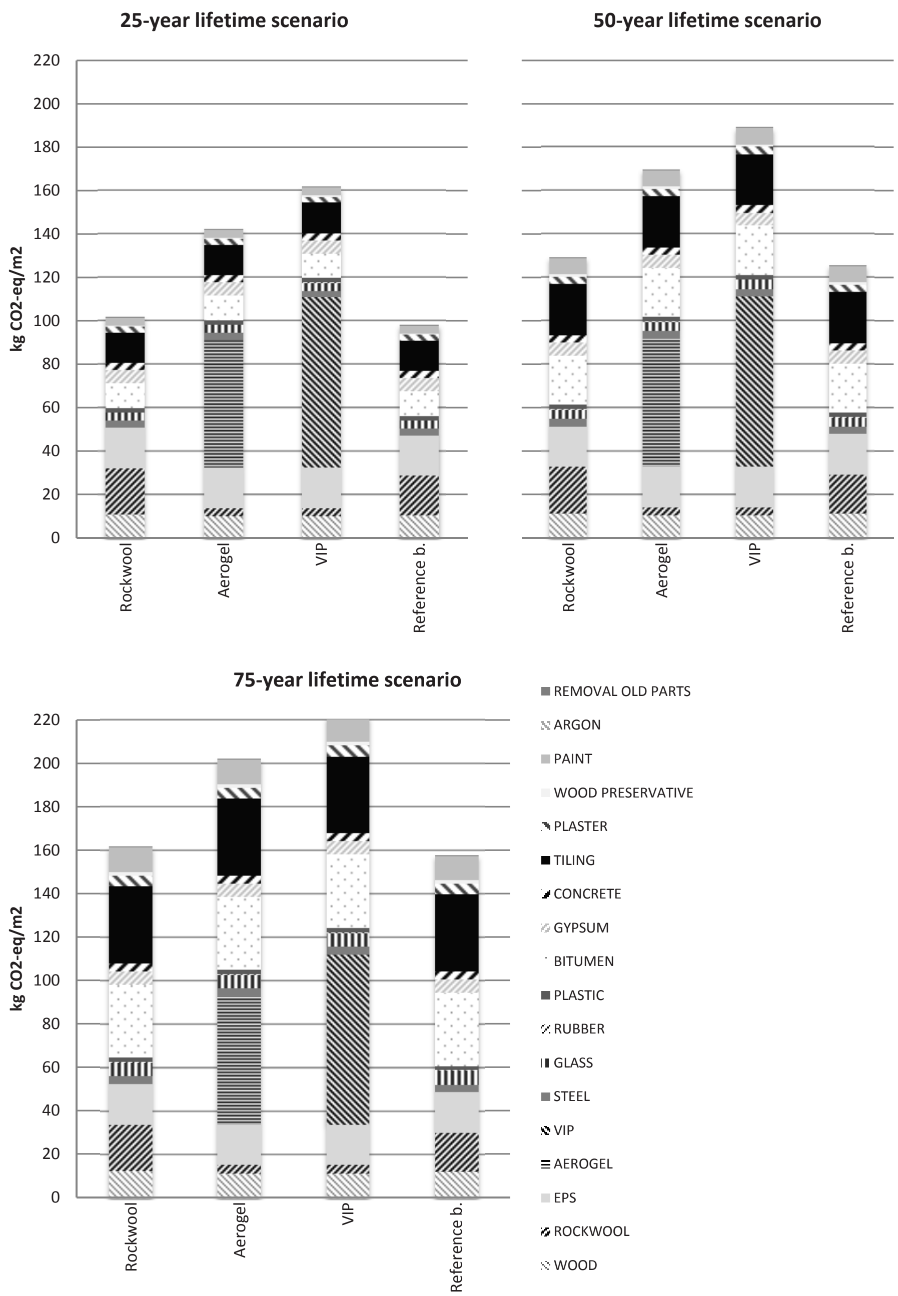


Figure 20. Composition of CO_2 emissions for the materials used in the four retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. All values are normalized to 1 m² of heated building area.

The main reason for the high contribution of concrete cladding is due to its high mass, which alone is approximately 14% of the total mass composition in each of the renovation alternatives. Bitumen is mainly used as asphalt shingles, laid to provide a waterproof layer to the flat rooftop, and its substantial contribution to the overall $CO_{2\text{-eq}}$ emissions is due to the waste treatment process, which has 4-times higher emissions than the production process of the material itself. With a complete substitution of the asphalt layer every 25 years, bitumen represents the 2nd ranked impact contributor for the reference building in the 50-year and 75-year lifetime scenarios.

Insulation materials represent the other large family of contributors, with a share of 30% and 53% of the total embodied emissions, for the reference building and the *VIP* alternative, respectively. This is for the 50-year lifetime scenario. Comparing the reference building and the *Rockwool* alternative, the 2%-reduction in emissions due to the lower energy demand for building operation is counterbalanced by a 2% increase in embodied emissions due to the thicker insulation layer. The 50-mm thicker mineral wool layer used in the *Rockwool* alternative causes a 15% higher impact from the Rockwool alone. Mainly because of its high mass (ranked 4th in both *Rockwool* and *reference building* alternatives), Rockwool contributes alone between 15% and 18% of the total embodied emissions in the 50-year lifetime scenario.

The $CO_{2\text{-eq}}$ emissions of EPS, which is mainly used as roof and basement wall insulation account between 9% and 18% of the total embodied emissions in all alternatives. Since the CO_2 emissions for the production of EPS is higher (2.59 $kgCO_{2\text{-eq}}kg^{-1}$) that that of mineral wool, the share of emissions attributed to EPS is comparable to the one of mineral wool even if the mass of EPS used is lower. In the retrofitting alternatives with aerogel and VIP for the 50-year lifetime scenario, the insulation materials are clearly credited with the highest contribution to the total environmental impact. Aerogel and VIP account for 35% and 40% of the total embodied emissions, respectively. Despite the fact that aerogel and VIP have 29% and 49% less mass than the mineral wool in the *Rockwool* alternative, their much higher embodied emissions from production increases the total embodied emissions by 20% and 24%, respectively.

It is important to notice that for both aerogel and VIP no information is available regarding the emissions from the waste treatment process, which therefore has been assumed to be the same as landfilling of inert construction materials. It can be assumed that other end-of-life scenarios are likely to alter the final lifecycle emissions of the above insulation materials.

The emission figures for transportation of materials from the production plant to the building site and to the waste treatment plant are aggregated in Figure 20. Transportation accounts for from 2% of the total embodied emissions for the concrete cladding to 22% for the Scandinavian softwood in the 50-year lifetime scenario. The greater distance from which aerogel and VIP are delivered increases the impact of transportation for these materials and ranges from 2.3% of the total for Rockwool to 7.6% for aerogel. It is important to remember that these figures relate to the share of the embodied emissions of the single component, and not to the total embodied emissions of the retrofitting alternative. Considering the impact of transportation of components in the total embodied emissions of any of the four alternatives, this accounts for maximum 5% of the total.

Since the "ZEB energy mix" is based on future projections of EU energy exchanges, halving and extending the building lifetime greatly affects the emissions from to building operation. For the 25-year scenario there is not a large difference between using the ZEB energy mix and the EU energy mix (Figure 17 and Figure 18). On the other hand, extending the lifetime to 75 years makes the building benefit from the close-to-zero conversion factor. In the "ZEB mix" the share of emissions of the production and end-of-life phases (*EE* and *M+EOL*) of the *reference building* changes very little for the three lifetime scenarios (from 13% to 20%), while in the EU energy mix the share of the emissions of the *EE* and *M+EOL* phases account for 6% and 16% for the 75 and the 25-year scenarios, respectively. The same share for the NOR energy mix is 55% and 70% for the 75 and the 25-year scenarios, respectively. The maintenance and end-of-life phases (*M+EOL*) gain more weight the more the building lifetime is extended, especially in the NOR energy mix. In the *reference building*, it goes up from a 3% share to 26% of the total, when using a 75-year rather than a 25-year lifetime. Clearly, the materials for which the lifecycle emissions are mostly affected by the maintenance cycle have higher fluctuations when varying the lifetime, as in the case for paint. For the 25-year scenario, insulation materials dominate the composition of emissions of the retrofitting alternatives. In these, single VIP and aerogel components account for 47% and 40% of the total $CO_{2\text{-eq}}$ emissions, respectively (Figure 20). The share of the emissions of mineral wool for the retrofitting option *Rockwool* is four times higher than that of the *reference building*. On the other hand, in the 75-year scenario, the differences between different insulation alternatives are very small, and the share of the total emissions due to insulation materials, including EPS, is between 23% and 45%, as shown in Figure 20.

4.3. Sensitivity analysis: variation of insulation thickness

In this part the three different façade retrofitting alternatives are evaluated for three thicknesses of insulation each. The thicknesses of the insulation in the alternatives are: 250 mm, 140 mm, and 100 mm for mineral wool, 100 mm, 60 mm, and 45 mm for aerogel, and 60 mm, 35 mm, and 25 mm for VIP. These thicknesses gives a U-value of the external facades of 0.10 $Wm^{-2}K^{-1}$, 0.15 $Wm^{-2}K^{-1}$, and 0.18 $Wm^{-2}K^{-1}$, respectively and regardless of the insulation type used. The mineral wool thickness in the reference building is 200 mm and the external façade U-value is 0.12 $Wm^{-2}K^{-1}$. Details of the external facades in the retrofitting alternatives are presented in Table II- c in Appendix II.

Figure 21 shows the energy demand of the proposed upgrading options, in which the shares of single end-uses are presented. The heating and the DHW system are aggregated as they are served by the same air-to-water heat pump. As expected, the heating energy demand increases when the insulation thickness is reduced, regardless of insulation type. On average, the difference between the least and the best insulated alternatives is approximately 9 $kWhm^{-2}y^{-1}$, which represents approximately 10% of the total energy use. The reference building uses 84.8 $kWhm^{-2}y^{-1}$. This is only 1 $kWhm^{-2}y^{-1}$ higher than the options with walls U-values of 0.10 $Wm^{-2}K^{-1}$.

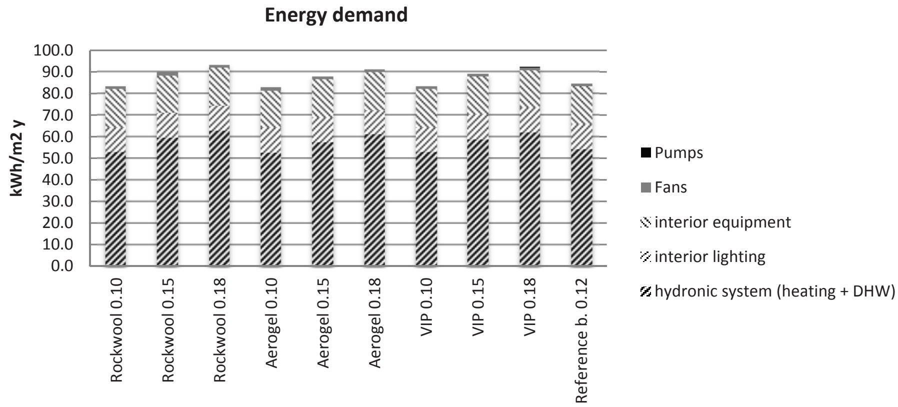


Figure 21. Composition of the yearly energy demand of the nine retrofitting alternatives and the reference building. Values are normalized to 1 m^2 of building heated area. The number after each insulation name represents the corresponding U-value of the facades.

The $CO_{2\text{-eq}}$ emissions of the same ten retrofitting alternatives using the ZEB energy mix are presented in Figure 22. Including the embodied emissions of the façade components throughout their life span flattens the differences seen in energy use. In the three lifetime scenarios the increasing embodied emissions due to the greater thicknesses of the insulation layer counterbalances the reduced emissions due to the lower energy demand. It is worth noticing that this trend is more evident for the options with VIP insulation than for the ones with mineral wool. This is because the VIP panels are highly emission-intensive in production, and a subtle change of thickness has a great influence on the final environmental impact. In this respect, aerogel lies in between the two.

Since the kWh-to-$kgCO_{2\text{-eq}}$ conversion factor of the ZEB energy mix follows a time-varying curve, the influence of the energy use for operation on the total environmental impact lessens with time. In addition, the emissions due to the production phase are also reduced at longer lifetimes because the same amount is spread over a longer timeframe. As a consequence, the variation in lifecycle emissions due to the different thicknesses of the insulation layer remains constant for all alternatives, regardless of the building lifetime. The difference is approximately 8% between the different alternatives with mineral wool, and 4% and 3% between the alternatives with aerogel and VIP, respectively. However, the total lifecycle emissions for all the alternatives drastically decrease over time. In the 25-year scenario, where the energy-to-emissions conversion factor is far from the point at which the energy grid is projected to be carbon neutral (0.303 kg$CO_{2\text{-eq}}$kWh^{-1}), the total emissions are 29.5 kg$CO_{2\text{-eq}}$m^{-2}y^{-1} for the *Rockwool 0.10* and 32.4 kg$CO_{2\text{-eq}}$m^{-2}y^{-1} for the *VIP 0.18*. Moving ahead in time the energy conversion factor renders a greener energy grid (0.101 kg$CO_{2\text{-eq}}$kWh^{-1} for the 75-year lifetime). Therefore, the total lifecycle emissions are reduced by almost three times. The $CO_{2\text{-eq}}$ embodied emissions of the options with mineral wool, including the production and the end-of-life phases, contribute 11% in the *Rockwool 0.18* alternative in the 25-year lifetime scenario and 20% in the *Rockwool 0.10* alternative in the 75-year scenario.

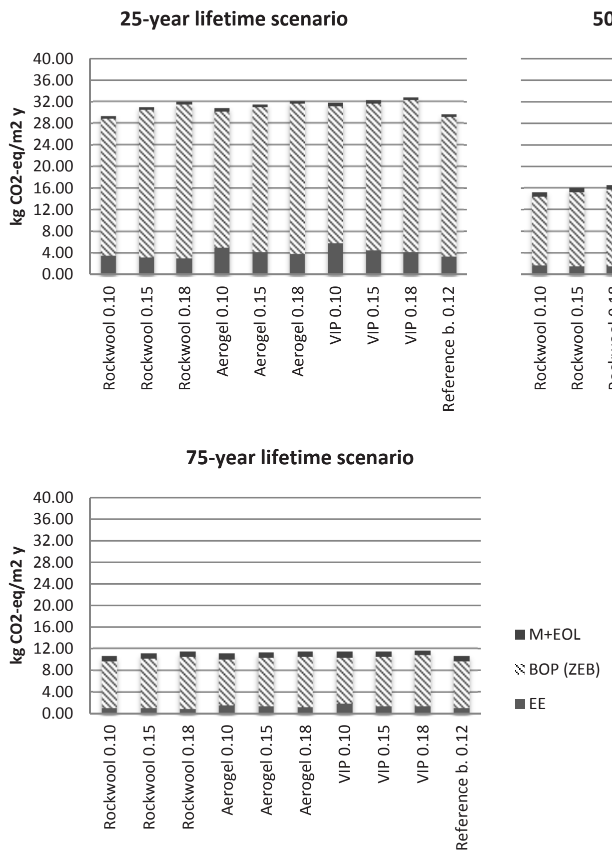


Figure 22. CO_2 emissions for retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding U-value of the facades. All values are normalized to 1 m² of heated building area for 1 year.

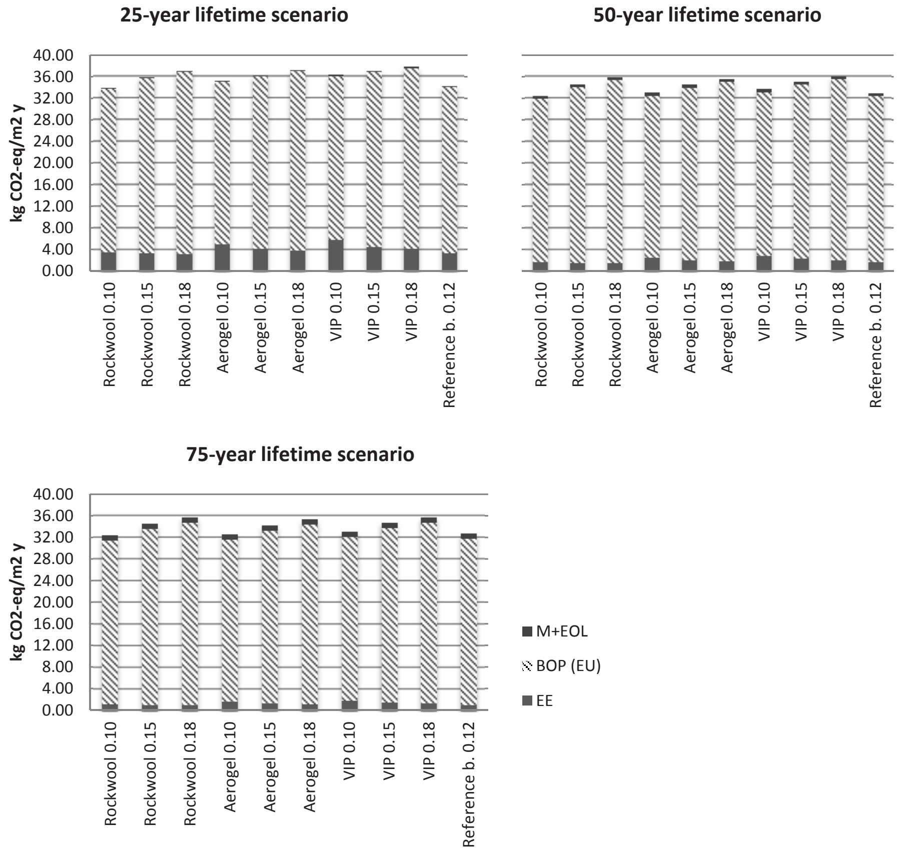


Figure 23. CO_2 emissions for retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding U-value of the facades. All values are normalized to 1 m² of heated building area for 1 year.

The contribution of the embodied emissions in the materials and end-of-life phases is 14% and 20% for the *VIP 0.18* in the 25-year and 75-year lifetime scenarios respectively. This increases to 20% and 26% for the *VIP 0.10* alternative, in the 25-year and 75-year lifetime scenarios respectively. The variation in the contribution of the material production phase over the three lifetime scenarios has a maximum variation limited to 1% for any of the insulation alternatives. This is due to the time-dependency of the kWh-to-kg$CO_{2\text{-eq}}$ conversion factor, which reduces the emissions of the energy use for operation with time. On the other hand, the $CO_{2\text{-eq}}$ emissions due to the maintenance and end-of-life phase (*M+EOL*) increase with longer building lifetimes, because of the increased number of maintenance cycles. The contribution of the *M+EOL* phases to the total impact varies from 2% in the shortest lifetime scenario to 10% in the longest for all the insulation alternatives. In the 75-year lifetime scenario the impact of the *M+EOL* phases is approximately one fifth less than that of the material production phase. On the other hand, in the 25-year lifetime scenario the impact of the production phase is between 7 and 10 times higher than that of the maintenance and end-of-life phases.

Figure 23 shows that in the scenario with the European average energy-to-$CO_{2\text{-eq}}$ conversion factor the energy use for operation is the big player in determining the lifecycle emissions for all the insulation alternatives. Regardless of the building lifetime, the emissions are in the range from 32 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ to 37 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ for all the alternatives. However the European energy mix is assumed to be constant over time, thus showing a greater variation in lifecycle emissions due to the different thicknesses of insulation at longer lifetimes than for the ZEB energy mix. In the 25-year scenario, the *Rockwool 0.10* alternative has 91.5% of the emissions of the *Rockwool 0.18* alternative. This difference is increased by just 1% (to 90.5%) in the 75-year lifetime scenario. The difference in emissions between the *VIP 0.10* and the *VIP 0.18* alternatives is 4% for the 25-year and 7% for the 75-year lifetime scenarios, respectively. Such variations between the insulation alternatives are explained by the fact that the $CO_{2\text{-eq}}$ emissions of the production phase are less per unit of surface in the longer lifetime scenario where, as a consequence, the benefit from a higher level of insulation gains more weight. Similarly for the ZEB energy mix, the alternatives with mineral wool are the ones in which the best insulated option reduce lifecycle emissions the most (approximately 9% less), regardless of lifetime. As a general trend, according to Figure 22 and Figure 23, thicker insulation layers result in lower lifecycle emissions.

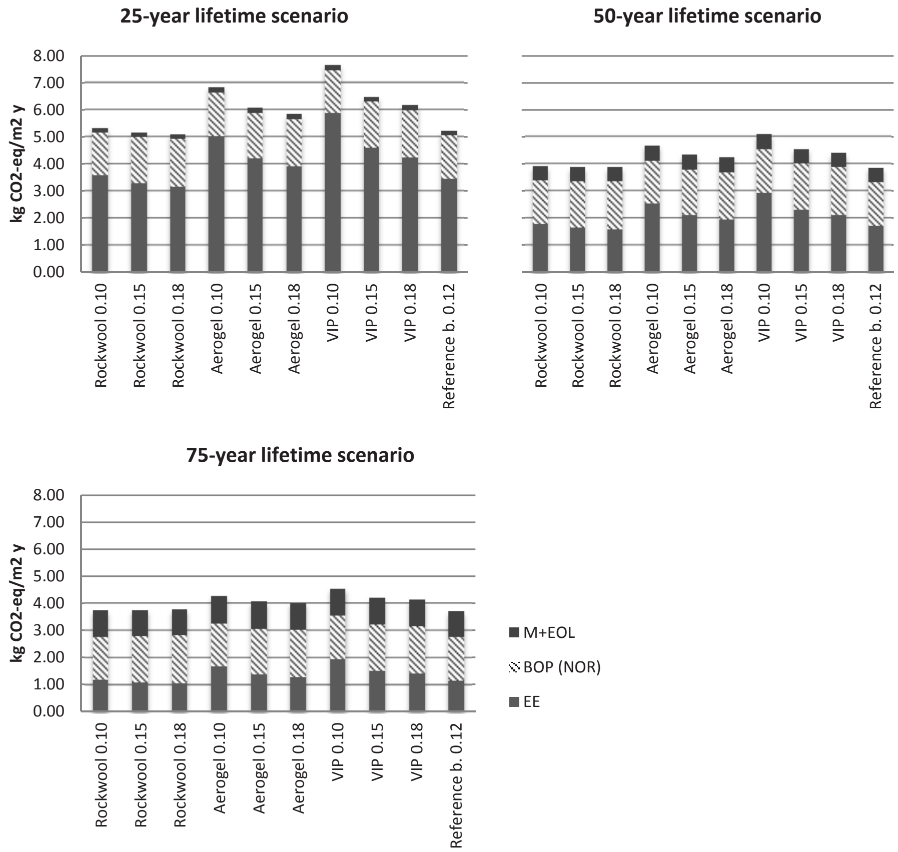


Figure 24. CO_2 emissions for retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding U-value of the facades. All values are normalized to 1 m² of heated building area for 1 year.

A completely different picture is presented in Figure 24, where the $CO_{2\text{-eq}}$ emissions of the alternatives with the scenario of the Norwegian inland energy production are presented. Since this conversion factor implies a very green power grid (0.019 $kgCO_{2\text{-eq}}kWh^{-1}$), the resulting emissions are strongly influenced by the difference in embodied emissions due to the variation in insulation thickness. This is due to the fact that the embodied emissions, counting the production and end-of-life phases, contribute from 54% up to 79% of the total. In such a perspective, the options with higher embodied emissions are less environmentally attractive.

In the 25-year lifetime scenario the alternative with an external wall with mineral wool and a U-value of 0.10 $Wm^{-2}K^{-1}$ has 5% higher emissions than the alternative with mineral wool and a U-value of 0.18 $Wm^{-2}K^{-1}$. The difference between *VIP 0.10* and *VIP 0.18* for the same building lifetime is 20%. This is due to the very high share of emissions in the production phase, which is 60% for *Rockwool 0.18* and 75% for *VIP 0.10*. On the other hand, in the shortest lifetime scenario the contribution of $CO_{2\text{-eq}}$ emissions of the *M+EOL* phases accounts for only 3% of the total.

As in the previous case, the options with VIP panels and aerogel have a more pronounced difference between the highest and the lowest insulation levels, whereas the solution with mineral wool has a flatter distribution. By increasing the building lifetime the emissions of the production phases decrease while the emissions of the end-of-life phase increases. Since the end-of-life scenarios of the mineral wool, VIP and aerogel have been set as landfilling of inert materials (which results in the same values for each of the alternatives), the variation between the different insulation levels are minimized when the lifetime of the building is set to 75 years. In this scenario the amount of emissions due to the end-of-life phase is approximately 25% of the total, while for the production phase they vary between 30% and 41% of the total amount. For this reason the differences between the least and the best insulated options for each material are reduced to 1% for the alternative with mineral wool and to 9% for the option with VIP. However, in the 75-year lifetime scenario, the option with the wall U-values of 0.18 $Wm^{-2}K^{-1}$ still has the least emissions per unit of surface for both VIP and aerogel, while the mineral wool alternative has the same value as the alternatives with the U-value of 0.10 $Wm^{-2}K^{-1}$.

Figure 25 shows the values normalized per unit of floor area of the emissions of the least and best insulated solutions for each retrofitting alternative. These charts show only the embodied emissions (production and end-of-life phases) for each solution. The alternatives with a thinner insulation layer have a lower environmental impact in all lifetime scenarios. However, as already seen in the previous charts, the difference due to the variation in insulation thickness increases for the more emission-intensive materials, such as aerogel and VIP. In the 25-year scenario, this is 11% for the alternatives with mineral wool. The alternatives with aerogel and VIP go to 22% and 27%, respectively.

However, it is worth noticing that the lifetimes of the insulation materials of the three alternatives are set to be equal to the building lifetime for all the lifetime scenarios. For this reason, in the 75-year scenario the materials with shorter maintenance cycles, such as the paint, the asphalt shingles on the roof, and the cement tiling on the facades, have higher contributions to the emissions. This causes the relative difference in environmental impact between the insulation alternatives to shrink.

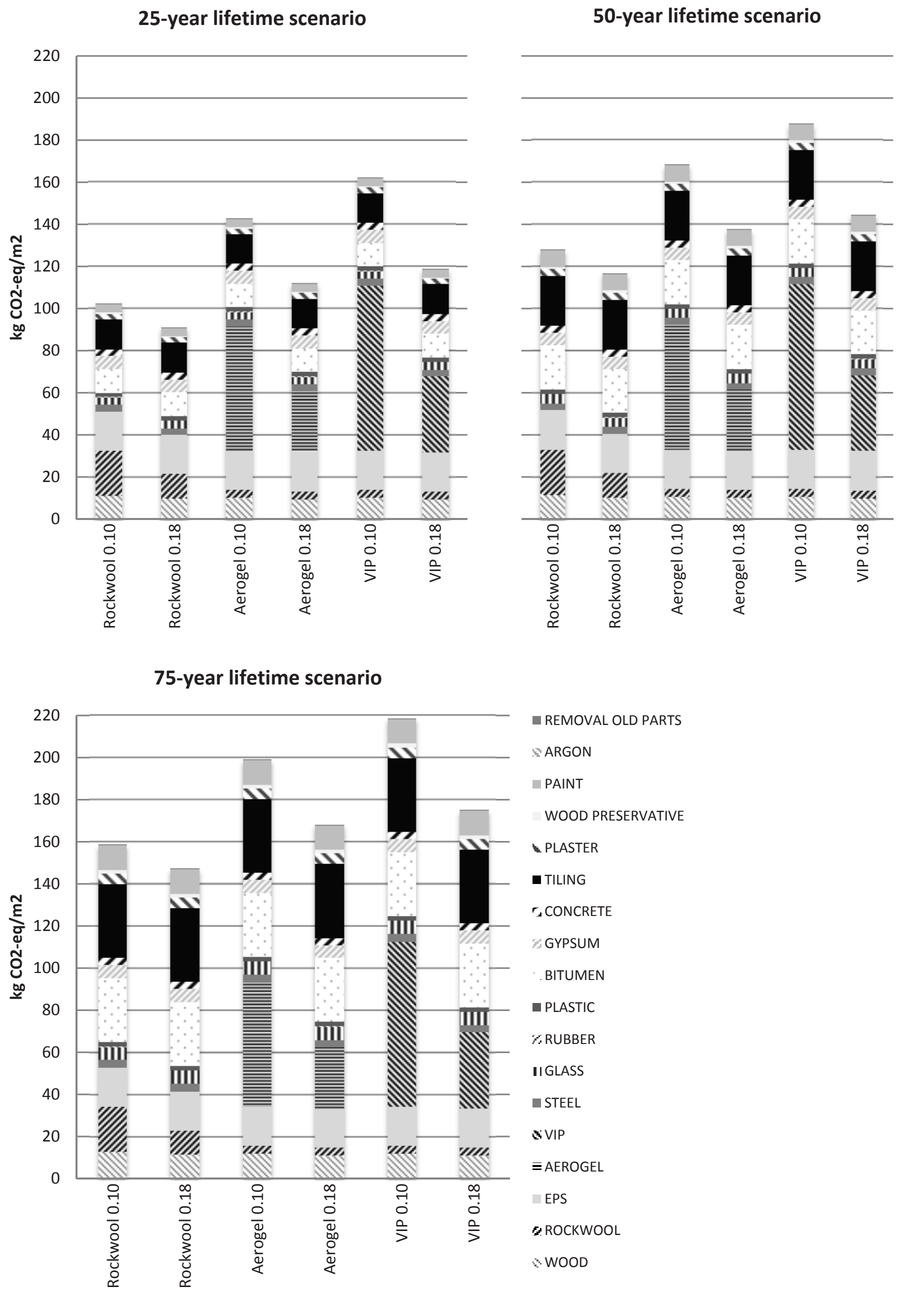


Figure 25. Composition of CO_2 emissions for the materials used in the retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The number after each insulation name represents the corresponding U-value of the facades. All values are normalized to 1 m^2 of heated building area.

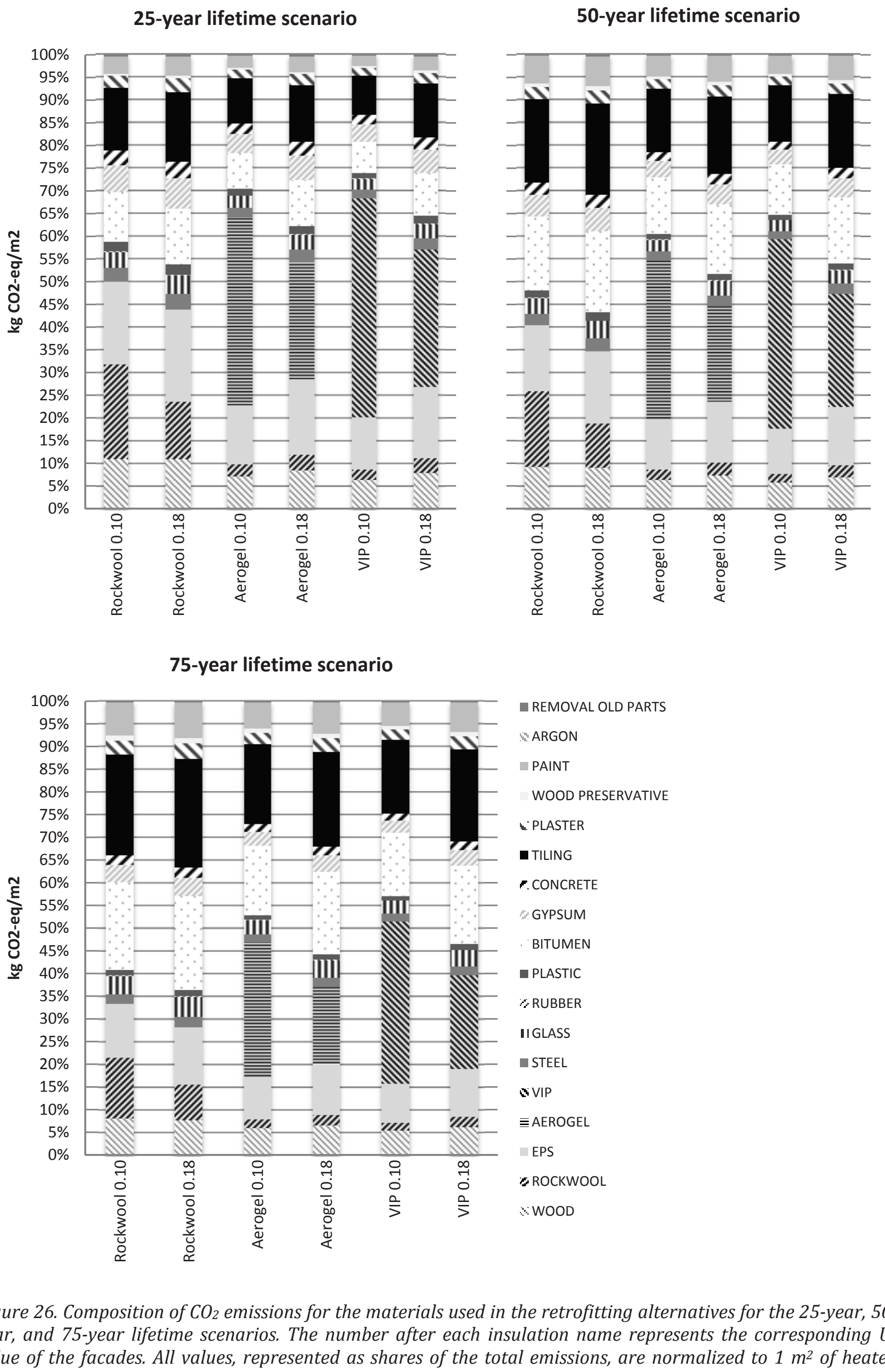


Figure 26. Composition of CO_2 emissions for the materials used in the retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The number after each insulation name represents the corresponding U-value of the facades. All values, represented as shares of the total emissions, are normalized to 1 m² of heated building area.

In the 75-year scenario the difference in lifecycle emissions between the *Rockwool 0.18* and the *Rockwool 0.10* alternatives is 7%. When comparing the differences in the U-values for the alternatives with aerogel and VIP, this difference goes up to 15% and 20%, respectively. The cumulated $CO_{2\text{-eq}}$ emissions due to the substitution of building materials for each alternative increase by 60 $kgCO_{2\text{-eq}}m^{-2}$ when the building lifetime is set to 75 years.

In Figure 26 the cumulative $CO_{2\text{-eq}}$ emissions of each building component are presented as shares of the total. From these charts it can be seen that the weight in terms of environmental impact of the insulation materials diminishes when increasing the building lifetime. In the shortest lifetime scenario (25 years) mineral wool accounts for between 13% and 21% of the total, while aerogel and VIP account for between 26-42% and 30-49%, respectively. The contributions of *paint*, *tiling*, and *bitumen* (which represent the paint and the cement tiling on the facades, and the asphalt shingles on the roof), account for 17% in *VIP 0.10* and 33% in *Rockwool 0.18*. EPS, which is used as insulation of the basement walls, represents the second highest impact in five cases out of six. In the longest lifetime scenario the sum of the $CO_{2\text{-eq}}$ emissions of *paint*, *tiling*, and *bitumen* varies between 40% and 53% of the total. The share of total emissions attributed to insulation materials is reduced to 7% for *Rockwool 0.18* and 12% for *Rockwool 0.10*. Similarly, the contributions of aerogel and VIP for the lowest and the highest insulated alternatives are between 16% and 28% and between 21% and 36%, respectively. In the retrofitting alternatives with mineral wool the greatest contributor is the cement tiling, followed by the asphalt shingles. The environmental impact of the paint layer is equal to the impact of the rock wool insulation in the *Rockwool 0.18* solution. In the options with aerogel and VIP with the wall U-value of 0.10 $Wm^{-2}K^{-1}$, the emissions from the façade insulation materials are still the greatest contributors. However, in the least insulated alternatives, the environmental impact of the cement tiling and the VIP are equal, and the contribution of the aerogel is ranked third, after *tiling* and *bitumen*.

4.4. Sensitivity analysis: variation of glazing ratio

In this part the three different insulation materials in the external façades are compared with three different glazing ratios for facades (24%, 33%, and 50%). The alternatives are named *Aerogel 24%*, *Rockwool 24%, VIP 24%, Aerogel 33%*, *Rockwool 33%, VIP 33%*, and *Aerogel 50%*, *Rockwool 50%, VIP 50%*. Details of the facades in the retrofitting scenarios are presented in Table II- e, in Appendix II.

The aim of this work is to evaluate to which extent higher energy losses, due to a higher glazing ratio of the building facades, are counterbalanced by lower embodied greenhouse gas emissions, due to a smaller amount of insulation in the external facades. The first set of data shows the energy demand of the proposed retrofitting options and the share for different end uses for these glazing alternatives. The results of the analysis of the retrofitting alternatives are grouped for each energy mix: ZEB, EU average, and Norwegian production only, respectively. Within each group, the contributions to total emissions for the three proposed lifetimes are compared. In-depth descriptions of the share of the embodied emissions of the different materials composing some of the insulation alternatives are then detailed.

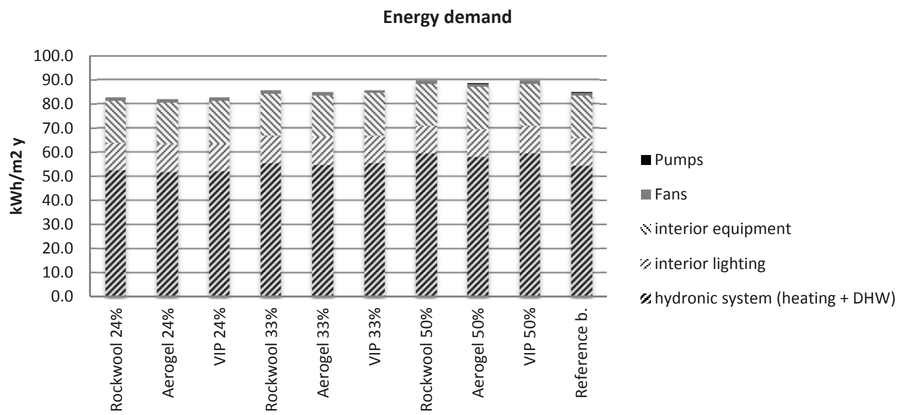


Figure 27. Composition of the yearly energy demand of the nine retrofitting alternatives and the reference building. Values are normalized to 1 m² of building heated area.

Figure 27 shows the composition of the yearly energy demand of the proposed upgrading options, in which the shares of single end-uses are presented. The heating and the DHW system are aggregated as they are served by the same air-to-water heat pump. As expected, the heating energy demand increases when the insulation thickness is reduced and the glazing ratio is increased, regardless of the insulation type. The reference building with a U-value of the external walls of 0.12 $Wm^{-2}K^{-1}$ has a yearly energy demand of 84.8 $kWhm^{-2}y^{-1}$. The solutions *Aerogel 24%*, *Rockwool 24%,* and *VIP 24%*, with a U-value of 0.10 $Wm^{-2}K^{-1}$, indicates a yearly energy saving of 3% (82.5 $kWhm^{-2}y^{-1}$ on average). The solutions *Aerogel 33%*, *Rockwool 33%,* and *VIP 33%*, have a yearly energy demand similar to the one of the reference building (85.5 $kWhm^{-2}y^{-1}$ on average). The same solutions with the 50% glazing ratio have an energy demand which is approximately 5% higher than the one of the reference building (89.0 $kWhm^{-2}y^{-1}$ on average). In terms of energy demand, a larger glazing ratio (33%) counterbalances the energy savings attributed to a thicker insulation layer (0.10 $Wm^{-2}K^{-1}$). When increasing the glazing ratio to 50%, the influence of the energy losses due to the windows overcomes the benefits of a lower U-value of the external facades, regardless of the insulation material.

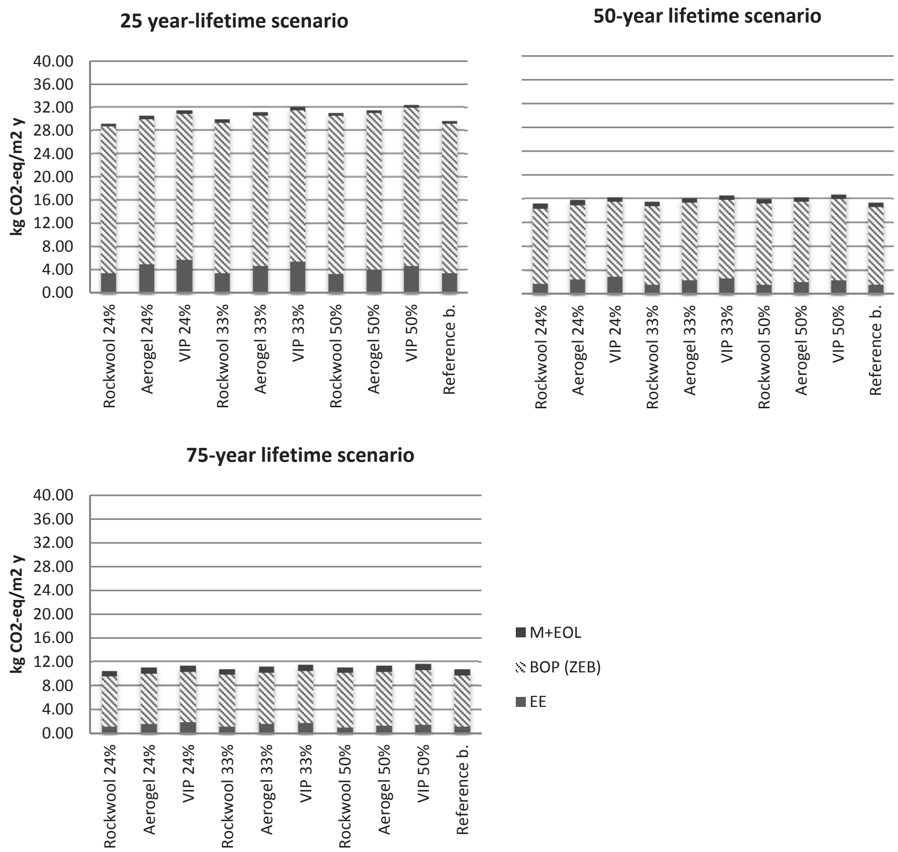


Figure 28. CO_2 emissions for retrofitting alternatives for the 25-year, 50-year, and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding glazing ratio of the facades. All values are normalized to 1 m^2 of heated building area for 1 year.

Figure 28 shows the greenhouse gas emissions of the same retrofitting alternatives using the ZEB energy mix and the 25-year, 50-year, and 75-year lifetime scenarios. In the 25-year lifetime scenario, the influence of the initial embodied emissions is 12% for the reference building and 19% for the *VIP 24%* alternative. It is worth noticing that the relative contribution of the initial embodied emissions decreases with larger glazing ratios. This is 12% and 11% of the total emissions for R*ockwool 24%* and *Rockwool 50%*, respectively, and 19% and 15% of the total for *VIP 24%* and *VIP 50%*, respectively. This is due to the fact that the emissions per unit of surface of the opaque part of the façade are higher than those of the glazed part. The relative contribution of emissions due to the substitution of the building components and their end-of-life treatment is relatively constant and similar for all the retrofitting options. It represents less than 1% of the total emissions. This is due to the fact that the insulation layer has the same service life as the building, and that the end-of-life treatment (material landfilling) is the same for all the insulation options. Considering the lifecycle emissions, the alternatives with a 24% glazing ratio show much smaller or no savings. Relative to the *reference building* (29.7 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$), *Rockwool 24%* has 1.6% lower emissions, *Rockwool 33%* 0.9% higher emissions, and *Rockwool 50%* 4.6% higher emissions. These increase by 6.4% for *VIP 24%*, 8.4% for *VIP 33%*, and 9.4% for *VIP 50%*.

In the 50-year and in 75-year lifetime scenarios, the emissions attributed to the building operation (*BOP ZEB*) and the initial embodied emissions decrease, while the emissions due to the maintenance and end-of-life phase increase. This is because the electricity-to-emissions ZEB conversion factor varies with time and the embodied emissions are spread over a longer period of time. On the other hand, due to the longer building lifetime, a higher number of maintenance cycles causes higher emissions. For these reasons the ratio of the embodied emissions (*EE* and *M+EOL*) to the total does not differ much with different lifetime scenarios, and, as a consequence, the relative difference between the retrofitting options remains as in the 25-year lifetime scenario. However, the total emissions decrease consistently with longer building lifetimes, and in the 75-year lifetime these are approximately a third of the total emissions of the 25-year lifetime scenario.

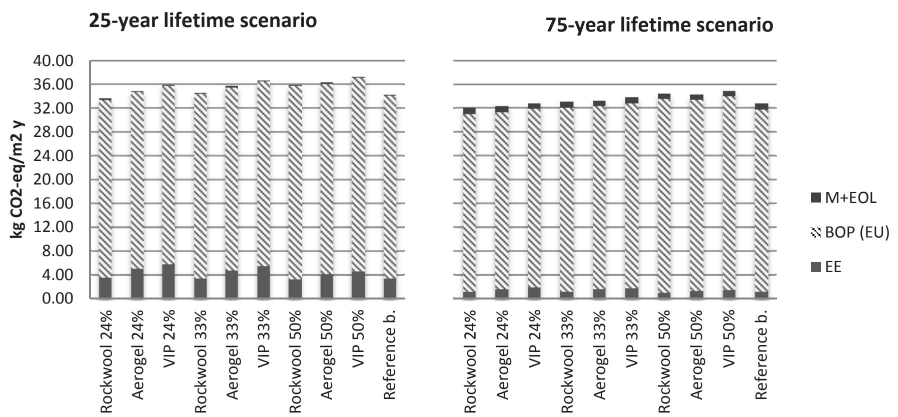


Figure 29. CO_2 emissions for retrofitting alternatives for the 25-year and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding glazing ratio of the facades. All values are normalized to 1 m^2 of heated building area for 1 year.

Figure 29 compares the emissions of the 25-year and the 75-year lifetime scenarios with the European average energy mix (*BOP EU*). The EU energy mix is highly carbon intensive (0.361 $kgCO_{2\text{-}eq}kWh^{-1}$) and, as a consequence, the total greenhouse gas emissions are strongly influenced by the building energy demand. In the 25-year lifetime scenario, the initial embodied emissions account for 9% for *Rockwool 50%* and 16% for *VIP 24%*. The maintenance and the end-of-life phases accounts for only 0.5% on average for all the retrofitting options. For this reason, there is up to a 9% difference between the reference building and the *VIP 50%*

option. Relative to the reference building, the alternatives *Rockwool 24%*, *Rockwool 33%*, and *Rockwool 50%* have 98.3%, 101.0%, and 104.9% emissions, respectively. The alternatives *VIP 24%*, *VIP 33%*, and *VIP 50%* are 105.0%, 107.3%, and 109.0%, respectively. The alternatives with aerogel have values that are in between the two. These values are similar to the ones in the 25-year lifetime scenario with the ZEB energy mix. However, the total emissions of the options with the EU energy mix are on average 5 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ higher than the solutions with the ZEB conversion factor and the same lifetime scenario.

In the 75-year lifetime scenario, the initial embodied emissions are three times lower, and the greenhouse gas emissions of the maintenance and end-of-life phases are six times higher than in the 25-year scenario. As a consequence, the relative difference between the retrofitting options is lower than in the shortest lifetime scenario. Relative to the reference building, the alternatives with mineral wool and glazing ratio of 24%, 33%, and 50%, have 97.9%, 101.0%, and 105.3% emissions, respectively. The alternatives with aerogel with the same glazing ratios as above have 98.9%, 101.8%, and 104.8% emissions, respectively. The alternatives with VIP with the same glazing ratios as above are 100.3%, 103.4%, and 106.7%, respectively. Interestingly, this is the only case where there are two alternatives that have a constant reduction in emissions (*Rockwool 24%* and *Aerogel 24%*) and three alternatives in which the total emissions are less than 2% higher than for the reference building (*VIP 24%*, *Rockwool 33%*, and *Aerogel 33%*). The average of the total emissions is 33.4 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$, which are 2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ lower than the average of the solutions in the 25-year lifetime scenario. This is because the share of emissions due to the material production phase is slightly higher than the maintenance and end-of-life phases (*M+EOL*). It should be remembered that the service life of the insulation layer is the same as of the building (no substitution) and that it is disposed for landfilling (0.00056 $kgCO_{2\text{-}eq}kg^{-1}$), regardless of the kind of insulation used.

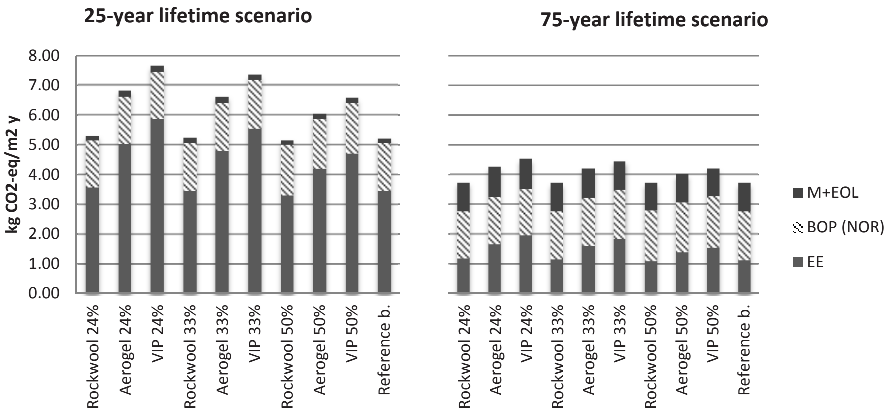


Figure 30. CO_2 emissions for retrofitting alternatives for the 25-year and 75-year lifetime scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). The number after each insulation name represents the corresponding glazing ratio of the facades. All values are normalized to 1 m^2 of heated building area for 1 year.

Figure 30 shows the greenhouse gas emission of the retrofitting solutions with the Norwegian energy mix (*BOP NOR*) and the 25-year and the 75-year building lifetimes. Because the emissions per kWh of produced electricity is very small, the total environmental impact of the retrofits is less than a fifth of that in the EU energy mix for the same lifetime scenarios. As a consequence, the share of the embodied emissions (*EE* and *M+EOL*) is 60% for the 75-year and 73% for the 25-year building lifetimes. In the 25-year lifetime scenario, the initial embodied emissions account for at least 64% of the total, while the maintenance and end-of-life phases do not exceed 3% of the total. For this reason, the quantity and kind of insulation material used in the facades define the distribution of the total emissions. Relative to the reference building, the alternatives *Rockwool 24%*, *Rockwool 33%* have 1.9% and 0.3% higher emissions, respectively, while *Rockwool 50%* has 1.1% lower emissions. The alternatives *VIP 24%*, *VIP 33%*, and *VIP 50%* have 46.5%, 40.9%, and 26.0% higher emissions, respectively. The alternatives with a larger glazing ratio have lower emissions than the alternatives with 24% glazing. This is different from in the previous cases and is because the emissions attributed to 1m^2 of opaque surface of any external facade are higher than the emissions of a unit of transparent surface of the same façade. The variation is more evident in the alternatives insulated with VIP (of which the emissions for production are 8.06 $kgCO_{2\text{-eq}}kg^{-1}$), than in the ones with mineral wool (of which the emissions for production are 1.13 $kgCO_{2\text{-eq}}kg^{-1}$). Differently from the above, the alternatives with the walls insulated with mineral wool have their total emissions similar to those of the reference building, due to the fact the share of the embodied emissions of mineral wool is lower than that of VIP and aerogel. As a consequence, the variation of the amount of used insulation does not change much the result.

In the 75-year lifetime scenario, the share of the environmental impact of the material production phase is only half of that in the 25-year lifetime scenario. On the other hand, the share of the maintenance and end-of-life phases is eight times higher than in the 25-year lifetime. For this reason, the emissions attributed to the above phases are similar, and the relative difference between the retrofitting alternatives is smaller than in the 25-year lifetime scenario. The reference building and the alternatives with mineral wool have the same emissions. The alternatives with aerogel increase by 14.5% for the 24% glazing ratio, and 8.0% for 50% glazing ratio. The alternatives with VIP increase by 21.7% for the 24% glazing ratio, and 12.9% for the 50% glazing ratio. Moreover, because the initial embodied emissions are spread on a longer lifetime, the total emissions are reduced by an average of 2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$.

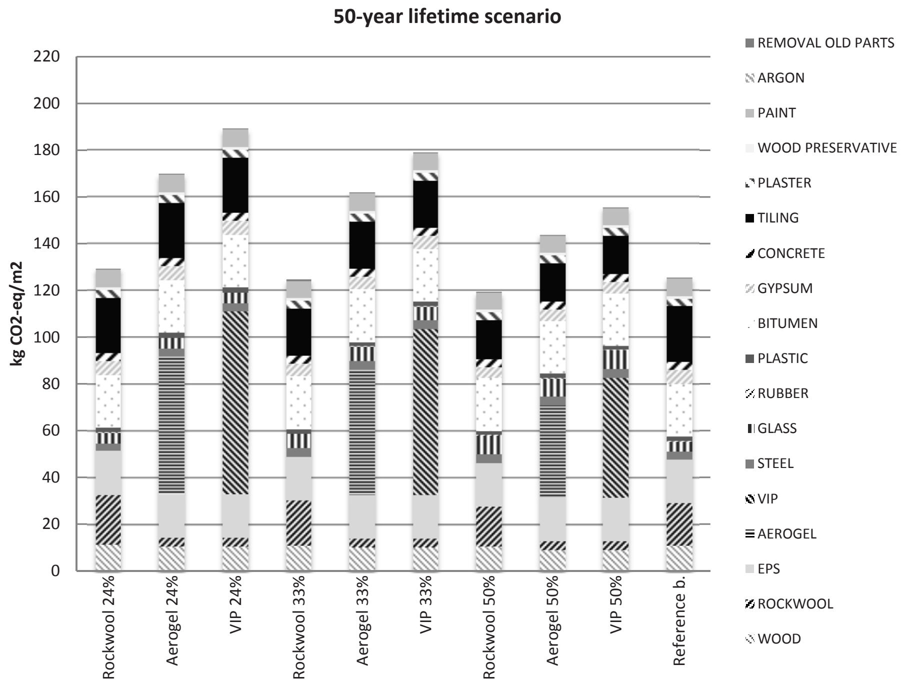


Figure 31. Composition of CO_2 emissions for the materials used in the retrofitting alternatives for the 50-year lifetime scenario. The number after each insulation name represents the corresponding glazing ratio of the facades. All values, represented as shares of the total emissions, are normalized to 1 m^2 of heated building area.

Figure 31 shows the composition of the greenhouse gas emissions of the retrofitting alternatives for the 50-year lifetime scenario. Since the emissions for the building operation are not included in this chart, the differences in emissions of the insulation materials installed in the external facades are substantial. Due to the higher greenhouse gas emission per unit of mass of VIP (8.06 $kgCO_{2\text{-}eq}kg^{-1}$), the shares of VIP are 41% for the alternative with 24% glazing ratio and 33% for the alternative with 50% glazing ratio. The emissions of aerogel (4.20 $kgCO_{2\text{-}eq}kg^{-1}$) are almost half of that of VIP, but due to its higher thermal transmittance (14 $mWm^{-1}K^{-1}$ for aerogel and 8 $mWm^{-1}K^{-1}$ for VIP) a greater mass is needed to achieve the same insulation value of the walls with VIP. For this reason, the share of the emissions due to aerogel is 35% in *Aerogel 24%* and 27% in *Aerogel 50%*. On the other hand, mineral wool shows a better balance between its environmental impact (1.13 $kgCO_{2\text{-}eq}kg^{-1}$) and its thermal transmittance (34 $mWm^{-1}K^{-1}$), and, as a consequence, the share of emissions decreases to 17% in the alternatives with 24% glazing ratio, and 14% in the alternatives with 50% glazing ratio.

It is worth noticing that the alternatives with higher glazing ratios benefit from a lower share of cement tile finishing, as this is replaced by windows. The façade finishing accounts for up to 18.2% in *Rockwool 24%,* and it decreases to 13.8% in *Rockwool 50%*. As a consequence, there is a general reduction of embodied emissions due to the increasing glazing ratio, in addition to the reduction attributed to the insulation materials.

4.5. Limitations

The uncertainty and the choice of data used in this work might influence the results presented. Specifically, the information regarding the maintenance cycle, and the emissions of aerogel and VIP, might be critical to the results.

Maintenance cycles of building components and materials have been chosen according to the report *Intervaller for vedlikehold og utskifting av bygningsdeler*, where the medium rate of substitution of components has been chosen. It must be noted that according to [86] the substitution rate derives from the technical quality of the component and the climatic stress to which the same element is subjected. Since this information is not available, it was decided to choose a medium substitution rate. This is equivalent to assigning a low climatic stress to low-quality components or a high stress to good and very good components. However, since some materials, such as paints, have very short lifetimes, the difference between medium and high substitution rates is 100%, while between medium and low is 50%. Clearly, choosing a shorter lifetime for such materials definitely affects both the total emission impact and the share they have in the building composition, especially for the extended lifetime scenario.

The emissions due to transporting workers to the building site during the installation/dismantling phases of components has not been included in the calculation due to lack of data. This aspect has been studied by Blom et al. [81], who report that the impact of the transportation of workers can be up to 22% of the total emissions. Clearly, in addition to a higher substitution rate, this factor can be critical for determining the total emissions. However, since this work is mostly focused on comparing different insulation materials, for which the service life is equal to the building lifetime, this aspect is not very relevant.

Finally, as explained in section 2.8, the information regarding the CO_2 emissions for aerogel and VIP are very scarce in literature and, as a consequence, the results are subject to a high uncertainty level. In addition, the service life of these materials has been set equal to the building lifetime, which is not realistic as both aerogel and VIPs are not likely to maintain their pristine performance for 75 years. This choice was due as detailed information regarding the service life of aerogel and VIP couldn't be found in literature. However, it is worth remembering that the thermal conductivity of VIP is set to 0.008 $Wm^{-1}K^{-1}$, which is the value attributed to the "aged" panels.

4.6. Conclusions

The CO_2 emissions of three building renovation alternatives equipped with either Rockwool, VIP or aerogel have been compared with a reference retrofitting solution of a residential block in Oslo. The analysis shows that the use of more carbon intensive insulation materials, such as VIP and aerogel, has the effect of increasing the total lifecycle emissions. The differences in lifecycle emissions between the use of mineral wool and VIP or aerogel are stronger in the alternatives with the shortest lifetime scenario. This is because the share of the initial embodied emissions is very high when the building lifetime is short.

Varying the electricity-to-emissions conversion factor strongly influences the share of the embodied emissions in the different alternatives. A high carbon intensive conversion factor, such as the EU average factor, tends to reduce the differences between the emissions due to the use of alternative insulation materials. A low carbon intensive conversion factor increases the share of the embodied emissions and, as a consequence, it enhances the differences in lifecycle emissions between the alternative insulation materials. If it is assumed that the European energy grid will use more renewable energy sources, the use of highly carbon intensive insulation materials, such as VIP and aerogel, is not a competitive choice in future buildings.

In addition, the variation of the conversion factors also has a strong influence on the results when the thickness of the insulation is varied. The EU conversion factor favors the alternatives with a thicker insulation layer, regardless of the insulation material used, because the share of the emissions due to the building space heating is very high. On the other hand, a greener conversion factor (NOR) presents a reversed picture. In this case, the share of the embodied emissions is very high, and especially in a short lifetime scenario, this favors the use of a thin insulation layer. By extending the building lifetime, the share of the embodied emissions decrease and, as a consequence, the use of any of the alternative insulation materials becomes less relevant.

Higher glazing ratios have higher energy losses for space heating. With a conversion factor that attributes a high share of emissions to the energy use for operation of the building, the alternative with a low glazing ratio is the best option. On the other hand, when the conversion factor credits a high share to the embodied emissions, the alternative with a high glazing ratio gives the lowest lifecycle emissions, regardless of which insulation material is used. The differences in lifecycle emissions between the alternatives with different glazing ratios are high for a carbon-intensive insulation material, such as VIP.

In conclusion, the use of a carbon-intensive insulation material generally increases the total emissions, but it is not possible to determine to what it is extent due to the influence of the conversion factor. If it is assumed that the future European energy grid will tend to emit low amounts of CO_2 per kWh of produced electricity, the use of materials with high embodied emissions is not a good choice.

However, limitations to the CO_2 emissions source data for VIP and aerogel require further investigation to better understand if the presented values are subject to wider variations, as may be expected.

5. Comparison of window-to-wall ratios

In this chapter the results from the comparison of the use of different window-to-wall ratios are presented. The first set of data shows the results of calculations of building energy demand using a 24%, 33%, and 50% glazing ratio. The second set of data shows the emissions for these the retrofits. The third set of data shows the emissions of the different glazing ratios when varying the building lifetime. The final set of data shows the emissions of the three retrofitting alternatives when varying the cycle of substitution of the building components. Each set is calculated for each of the three kWh-to-CO_2 conversion factors.

5.1. Objective

The objective of the work is to compare and assess the emissions of different façade glazing ratios applied in the energy retrofitting of an apartment building. A reference solution, which represents the actual accomplished renovation work [33], is compared to three alternatives with improved thermal resistance of the external walls and increasing window-to-wall ratios. The insulation level of the facades in the reference solution is 0.12 $Wm^{-2}K^{-1}$, the insulation material used is mineral wool, and the average glazing ratio for the East and West facades is 24%. The U-value of the external facades of the retrofitting alternatives is set to 0.10 $Wm^{-2}K^{-1}$, the insulation material used is mineral wool, and the glazing ratios are 24%, 33%, and 50%. The windows are triple glazed with Argon filling (U-value 0.79 $Wm^{-2}K^{-1}$). To better evaluate the share of embodied emissions of the proposed alternatives, the kWh-to-CO_2 conversion factor and the building lifetime are varied. The reference lifetime for the reference building and the retrofitting alternatives is set to 50 years. The maintenance cycle for the building components derives from [86] and it is set to a medium rate of substitution. Details of the maintenance cycles for the different building components are found in Table III- b in Appendix III.

The first sensitivity analysis is aimed at evaluating to what extent the embodied emissions of the building components are counterbalanced by the emissions from the building operation. The variation of the building lifetime influences the total emissions of the building, which include the embodied emissions due to the production and first installation of the components (*EE* phase) and the embodied emissions due to the replacement and disposal of the components (*M+EOL* phase). The service life of the glazing is different than that of the other components of the façade. As a consequence, by using different building lifetimes and varying the glazing ratio, it is possible to understand to which extent the embodied emissions of the glazed part of the facade influence the total amount. The emissions due to the building operation are calculated by applying three electricity-to-emissions conversion factors, as explained above.

The second sensitivity analysis addresses the variation of the maintenance schedule. Since windows undergo a faster substitution rate than the other components of the façade, such as the insulation layer, the variation of their maintenance cycle helps to understand the share to the total emissions of the glazed components. It is expected that the lifecycle emissions of the retrofits with a high glazing ratio will be largely affected by the maintenance cycle. The medium maintenance cycle is substituted with a short and a long cycle, as seen in Table III-b in Appendix III. Since the differences in the total emissions due to the different maintenance schedules are connected to the building lifetime, the 25-year and the 75-year lifetimes are used in this analysis. The 50-year lifetime is not analysed because it would not add any significant information. The kWh-to-CO_2 conversion factor is varied, as mentioned above, in order to understand the influence of the emissions of the building operation in the total emissions. It is expected that the choice of glazing ratio will be largely influenced by the electricity-to-emissions conversion factor used. A "green" factor is expected to favour the choice of retrofitting alternatives with low embodied emissions, while an emissions-demanding factor will favour the alternatives with low energy use (e.g. low glazing ratio). The composition of the total emissions for the different glazing ratios are analysed by applying the short and the long maintenance scenarios, and the 25-year and the 75-year building lifetimes.

Details of the external facades of the retrofitting alternatives are presented in Table II- b, and Table II- d in Appendix II.

5.2. Energy retrofitting alternatives

Figure 32 shows the yearly energy demand for the end-uses of the reference building and the retrofitting alternatives with different glazing ratios. The heating and the DHW system are aggregated as they are served by the same air-to-water heat pump. Since the glazed part of the facades has a lower insulation value than the opaque part, the heating energy demand increases when the glazing ratio is increased.

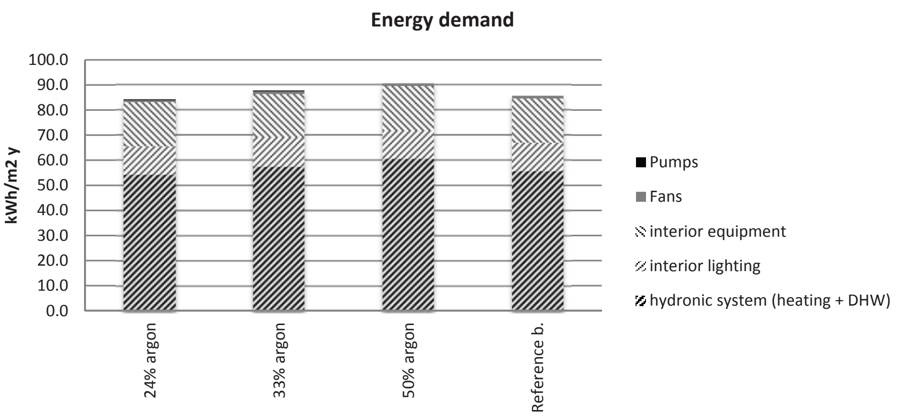


Figure 32. Composition of the yearly energy demand of the three retrofitting alternatives with different glazing ratios and the reference building solution. Values are normalized to 1 m² of building heated area.

The reference building, which is less insulated than the retrofitting alternatives (U-value of the external walls of 0.12 $Wm^{-2}K^{-1}$), has approximately 1 $kWhm^{-2}y^{-1}$ higher energy use than the upgraded version with the same glazing ratio, (the *24% argon* alternative). Its energy use is 84.1 $kWhm^{-2}y^{-1}$. The alternatives with 33% and 50% glazing ratios have an energy demand of 87.6 $kWhm^{-2}y^{-1}$ and 80.6 $kWhm^{-2}y^{-1}$, respectively. Relative to the reference building, the *24% argon* alternative has 1.9% lower emissions, while the *50% argon* alternative has 5.7% higher emissions. This means that by increasing the glazing ratio from 24% to 50% the yearly energy demand increases by 7% and more for the same insulation level of the external facades (0.10 $Wm^{-2}K^{-1}$). In addition, the difference in energy demand between the *24% argon* and *33% argon* alternatives is higher (by approximately 2%) than the difference in energy demand between the reference building and the *24% argon* alternative.

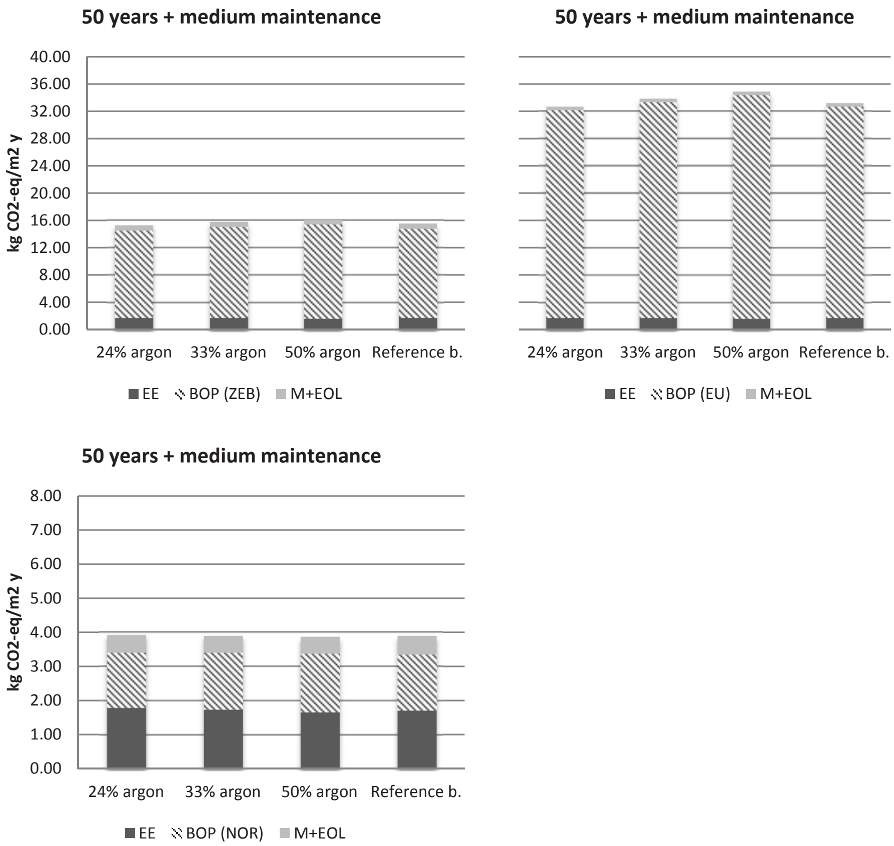


Figure 33. CO_2 emissions for retrofitting alternatives with different glazing ratios for the 50-year lifetime and medium maintenance scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

The emissions of the three retrofitting alternatives and the reference building for the 50-year lifetime scenario and the medium maintenance schedule are presented in Figure 33. Since the emissions from the building energy use are calculated using three different kWh-to-kg$CO_{2\text{-eq}}$ emission factors, this considerably influences the final results.

The average total emissions of the alternatives are 15.7 kg$CO_{2\text{-eq}}$$m^{-2}y^{-1}$ when calculated with the ZEB energy mix, 33.7 kg$CO_{2\text{-eq}}$$m^{-2}y^{-1}$ with the EU energy mix, and 3.9 kg$CO_{2\text{-eq}}$$m^{-2}y^{-1}$ with the Norwegian energy mix. The relative contribution of the embodied emissions (*EE* and *M+EOL*) in the three cases varies accordingly, and it is on average 6.7% with the EU mix, 15.9% with the ZEB mix, and 57.5% with the NOR mix. For these reasons, the results of the total emissions of the retrofitting alternatives using the NOR energy mix are distributed in a reverse way compared to the results using the EU mix. Relative to the lifecycle emissions of the reference building, the emissions of the upgraded alternatives calculated with the European average conversion factor with 24%, 33%, and 50% glazing ratios have 98.5%, 102.0%, and 105.0% emissions, respectively. These follow the distribution given by the energy demand, presented in Figure 32. On the other hand, the lifecycle emissions of these retrofitting alternatives calculated with the Norwegian conversion factor have 101.1%, 100.6%, and 99.6% emissions, respectively. Using the ZEB conversion factor, the difference between the reference building and the *50% argon* alternative is limited to 4%. This shows that for different conversion factors the optimal choice will be different. This is due to the balance between the embodied emissions and the emissions for the building energy use, which changes with the conversion factor.

5.3. Sensitivity analysis: variation of building lifetime

Figure 34 shows the emissions of these retrofitting alternatives when varying the building lifetime. When using the ZEB mix, the difference in total emissions of each of the alternatives between the 25-year and the 75-year lifetimes is almost threefold. The average total emissions for the 25-year lifetime are 30.3 kg$CO_{2\text{-eq}}$$m^{-2}y^{-1}$, and they decrease to 10.9 kg$CO_{2\text{-eq}}$$m^{-2}y^{-1}$ in the 75-year lifetime. This is due to the fact that the calculation of the ZEB conversion factor is time-dependent and results is lower kg of emissions per kWh of produced electricity for longer lifetimes. However, at the same time the embodied emissions (*EE* and *M+EOL*) also decrease because they are distributed over a longer period of time. As a consequence, the average relative contribution of the emissions due to the building operation of all the alternatives varies only between 87.0% and 80.8% for the shortest and the longest lifetime, respectively. Similarly, the difference in emissions due to the building operation between the reference building and the *50% argon* alternative is 4.3% in the 25-year lifetime, and 3.7% in the 75-year lifetime. In this respect, when using the ZEB mix the difference in lifecycle emissions decreases when the building lifetime increases.

When using the EU conversion factor, the average relative contribution of the emissions due building operation is 89.7% for the 25-year lifetime and 93.8% for the 75-year lifetime. In this case, the emissions due to building operation in the reference building and in the *50% argon* alternative account for the same share in the two lifetime scenarios. Thus, the EU conversion factors always favours the solution with the lowest glazing ratio and the highest insulation level, regardless of the building lifetime.

As seen in Figure 33, the use of the Norwegian conversion factor reverses the distribution of the results. In the 25-year lifetime scenario, the contribution of the embodied emissions (*EE* and *M+EOL*) is predominant (68.6% on average) in all the retrofitting alternatives. Of this share, the part attributed to the emissions due to the first installation of the building components (*EE*) is the majority (65.5% on average) in all the alternatives. As a consequence, the alternatives with a higher glazing ratio are better. In the 25-year lifetime the average total emissions of all the alternatives is 5.3 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$. Relative to the lifecycle emissions of the reference building, the *24% argon* alternative have 2.1% higher emissions and the *50% argon* alternative 1.1% lower emissions.

On the other hand, in the 75-year lifetime, the average total emissions of all the alternatives decrease to 3.7 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ because the relative contribution of the replacement of the building components and their disposal increases at a rate which is lower than the decreasing value of the initial embodied emissions. The average contribution of the embodied emissions of all the alternatives is 55.8% in the 75-year lifetime. This is almost 13% lower than in the 25-year lifetime (68.6%). Thus, in the 75-year lifetime the share of the emissions due to the building operation counterbalances the share of the emissions from the *EE* and *M+EOL* phases and results in a distribution of the results of all the retrofitting alternatives which is almost equal (0.8% maximum difference).

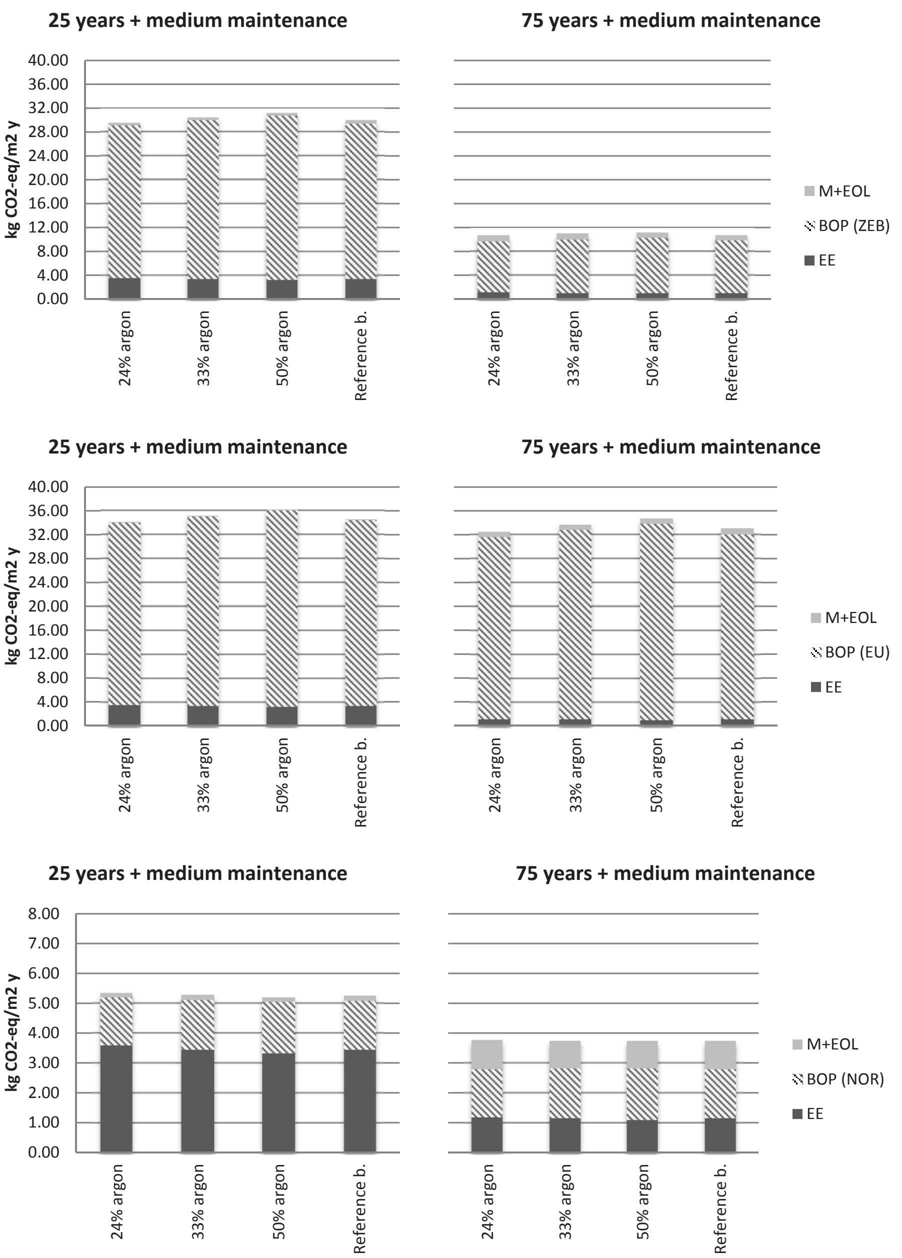


Figure 34. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and medium maintenance scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year.

5.4. Sensitivity analysis: variation of maintenance cycle

The insulation materials (mineral wool and EPS), the wood carpentry and boards, and the internal gypsum boards do not undergo any substitution (Table III- b in Appendix III) and their absolute contributions remain constant, regardless of the building lifetime. On the other hand, the glazing and the finishing are subject to be replaced. When varying the glazing ratio, the proportion between the glazed and the opaque parts of the façade changes. As a consequence, the facades lifecycle emissions change. By varying the maintenance cycle of the façade components, it is possible to understand to what extent the building components which have higher replacement rates, contribute to the total emissions. It is expected that the variation of the maintenance cycle will have a higher influence on the lifecycle emissions in the alternatives with a high glazing ratio.

Figure 35 presents the emissions of the retrofitting alternatives for the 25-year and the 75-year lifetime scenarios, the short and the long maintenance schedules, and the ZEB energy mix. As seen in Figure 34, with the ZEB mix the emissions due to the building operation decrease drastically with the longest lifetime, in all the retrofitting alternatives. The same is the case for the initial embodied emission (*EE* phase), which are spread over a longer period of time. For this reason, the ratio between the total embodied emissions and the emissions for building operation is not very different for different building lifetimes.

With the short maintenance, the *M+EOL* phase has an average share of 3.1% for all the retrofitting alternatives for the 25-year lifetime. This rises to 14.1% for the 75-year lifetime. In the 25-year lifetime the *M+EOL* phase accounts for 0.98 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ (3.3%) for the *24% argon* alternative, and 0.92 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ (2.9%) for the *50% argon* alternative. In the 75-year lifetime these values increase to 1.65 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ (14.5%) and 1.61 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ (13.5%), for the same retrofitting options. These results show that when using the short maintenance cycle the replacement and disposal of the glazing components have lower emissions per unit of surface than the replacement and disposal of the opaque part of the façade, in both the building lifetimes. However, the share of the embodied emissions, including the material production (*EE*) and the maintenance and end-of-life (*M+EOL*), does not significantly influence the distribution of the total results, which are ruled by the emissions due to the building operation for all the alternatives and in both the building lifetimes.

With the long maintenance schedule, the average share of emissions of the *M+EOL* phase of all the retrofitting alternatives is 1.4% for the 25-year lifetime, and is 5.9% for the 75-year lifetime. The average share of the embodied emissions (*EE* and *M+EOL*) for all the alternatives varies between 11.4% for the 25-year lifetime and 10.9% for the 75-year lifetime, leaving the building operation phase (*BOP*) the key role in determining the total emissions. This shows that the variation of the maintenance cycle does not significantly influence the emissions of the alternatives with a higher glazing ratio, regardless of the building lifetime. The most significant difference in the emissions is given by the increase in glazing ratio, regardless of the building lifetime and the maintenance cycle used.

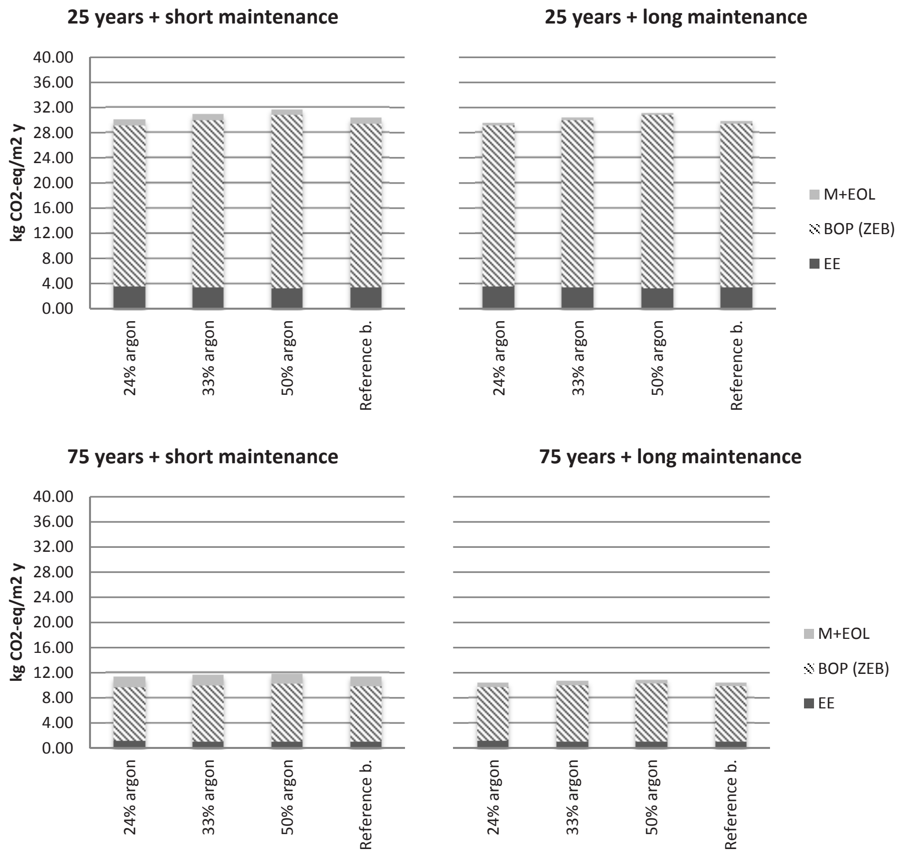


Figure 35. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

With the EU energy mix, the influence of the maintenance and disposal phase is even smaller than in the alternatives with the ZEB energy mix, as shown in Figure 36. The average value of all the alternatives for the *M+EOL* phase varies between 0.4% in the 25-year scenario and long maintenance cycle, and 4.8% in the 75-year lifetime and short maintenance cycle. As a consequence, the total average emissions for all the retrofitting alternatives are between 33.2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 75-year lifetime and long maintenance schedule, and 35.2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 25-year lifetime and short maintenance schedule. By using the EU conversion factor the contribution of the *M+EOL* phase is too small to significantly influence the difference in total emissions among the different retrofitting alternatives, which are ruled by the emissions due to the building operation. As a consequence, the variation of the maintenance cycle has very little influence on the lifecycle emissions, regardless of the glazing ratio and the building lifetime used.

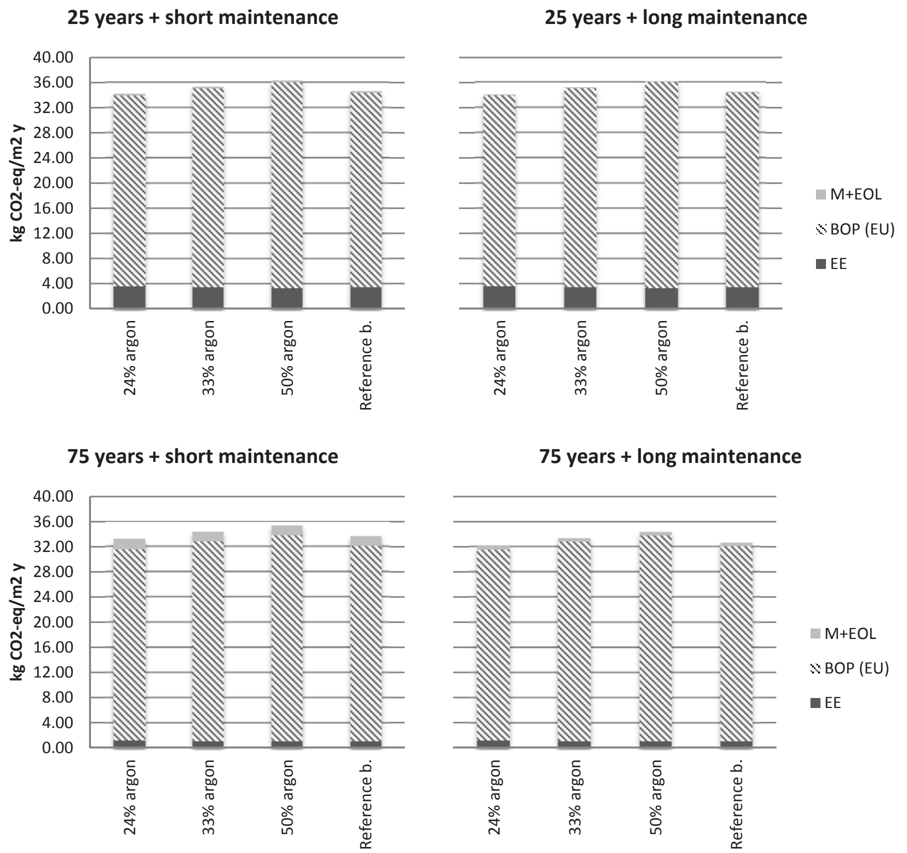


Figure 36. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

On the other hand, using the Norwegian conversion factor maximizes the contribution of the embodied emissions of the building components (*EE* and *M+EOL*) and, consequently, its variation due to the different maintenance cycles, as shown in Figure 37. Considering the 25-year building lifetime, the highest share of emissions is due to the first installation of the new building components (*EE*), regardless of the maintenance schedule. The average emissions of the *EE* phase for all the retrofitting alternatives are 63.6% of the total for the short maintenance cycle and 65.8% for the long maintenance cycle. Because of the short building lifetime, the emissions due to the replacement of the components are very small and, as a consequence, the distribution of the total emissions among the different retrofitting alternatives does not change with the variation of the maintenance scenario. The average total emissions for all the alternatives are 5.4 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ and 5.2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$, for the short and the long maintenance cycle, respectively. Relative to emissions of the reference building, the emissions of the *24% argon* alternative has the highest value (102%), and the *50% argon* alternative the lowest (99%), regardless of the maintenance scenario. In the 75-year lifetime, the emissions due to the replacement and disposal of the building components increase considerably, because the long lifetime allows more cycles of replacements.

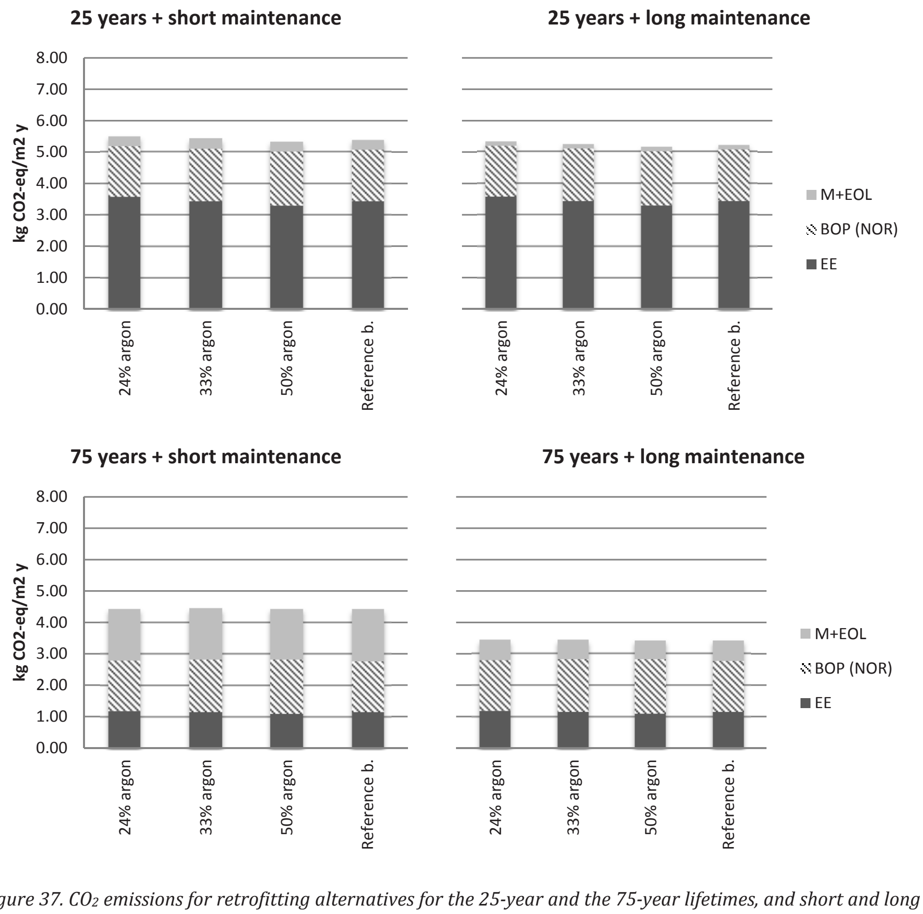


Figure 37. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

Considering the short maintenance cycle in all the alternatives, the average share of the *M+EOL* phase is 36.8%, the average share of the building operation phase

(*BOP*) is 37.3%, and the average share of the initial embodied emissions (*EE*) is 25.6%. The emissions due to the *EE* and the *M+EOL* phases of the *24% argon* are 3% higher than those of the *50% argon* alternatives. This difference counterbalances the higher emissions of the building operation phase of the 50% glazing alternative, thus resulting in an equal value of the total emissions (4.4 $kgCO_{2-eq}m^{-2}y^{-1}$) in all the alternatives. In the long maintenance scenario, the average share of emissions of the replacement and disposal phase of all the alternatives decreases to 18.3%, while the average share of the initial embodied emissions increases to 33.5%. However, in terms of absolute values, the relative difference of the embodied emissions (*EE* and *M+EOL*) between the alternatives with the lowest and the highest glazing ratios remain almost constant. For this reason, the total emissions for the long maintenance schedule are almost the same for all the alternatives, as in the previous case. However, it differs from the case with the short maintenance schedule in that the average total emissions of all the alternatives decrease to 3.4 $kgCO_{2-eq}m^{-2}y^{-1}$, as a consequence of the reduced value of the emissions of the replacement of the building components phase. This shows that the variation of the maintenance cycle has very little influence on the lifecycle emissions of the alternatives with different glazing ratios, regardless of the building lifetime used.

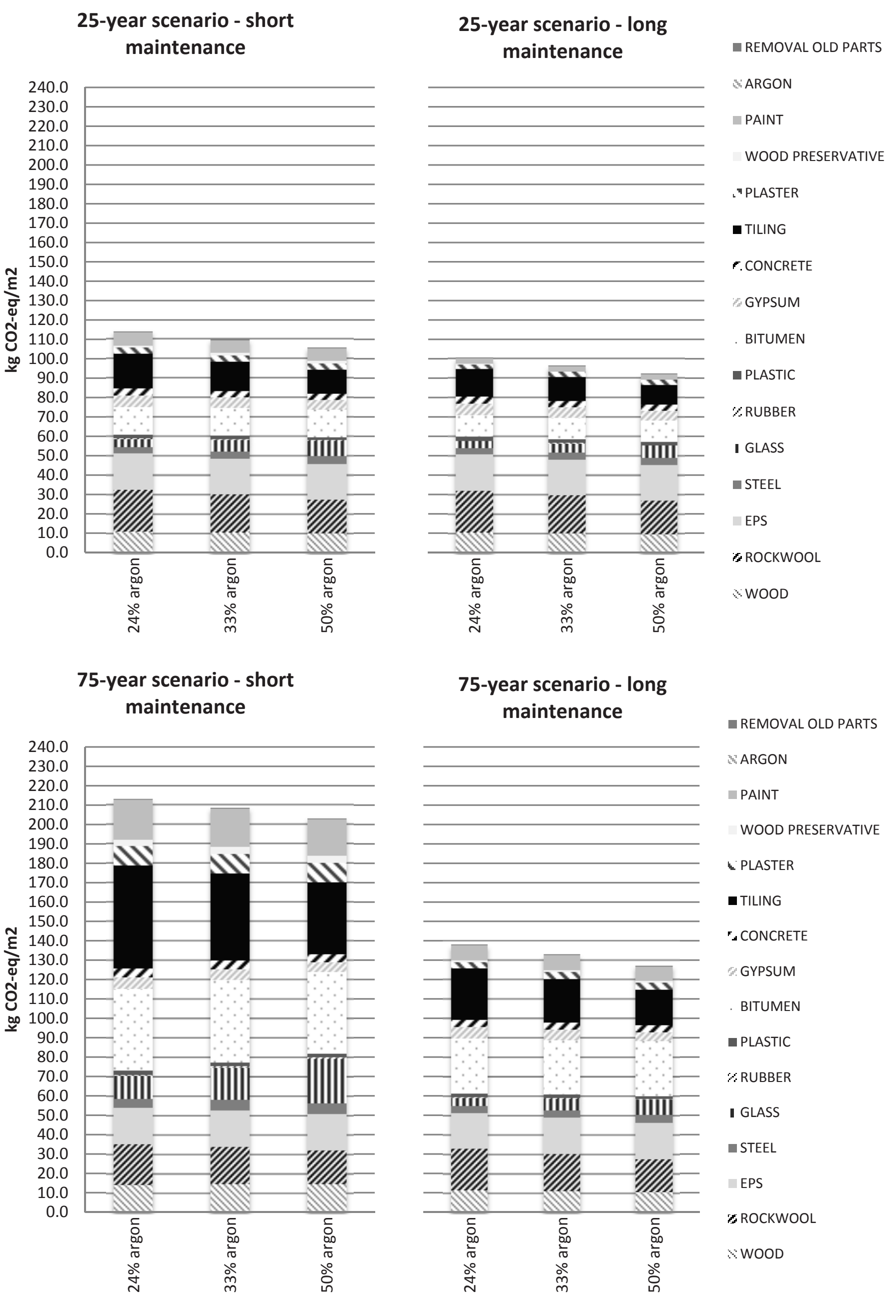


Figure 38. Composition of CO_2 emissions for the materials used in the retrofitting alternatives for the 25-year and 75-year lifetimes, and short and long maintenance scenarios. All values are normalized to 1 m^2 of heated building area.

Figure 38 shows the composition of the greenhouse gas emissions of the retrofitting alternatives with the three glazing ratios for the 25-year and the 75-year building lifetimes, and the short and the long maintenance schedules. The figure shows the embodied emissions only (*EE* and *M+EOL*) of the three alternatives. It shows that he values decrease with increasing glazing ratios, regardless of the lifetime and the maintenance schedule. In the 25-year lifetime, the variation of the maintenance cycle does not significantly influence the total emissions. The total emissions of the *24% argon* alternative are 13% higher with the short maintenance cycle than with the long maintenance. Similarly, the *50% argon* alternative with the short maintenance cycle has emissions that are 14% higher than its corresponding alternative with the long maintenance. The total emissions of the alternative with 24% glazing are 114.0 $kgCO_{2\text{-}eq}m^{-2}$ and 100.6 $kgCO_{2\text{-}eq}m^{-2}$ for the short and the long maintenance schedules, respectively. Similarly, the emissions of the alternative with 50% glazing are 105.7 $kgCO_{2\text{-}eq}m^{-2}$ and 92.4 $kgCO_{2\text{-}eq}m^{-2}$ for the short and long maintenance schedule, respectively. The components that show the highest difference due to the variation of the maintenance schedule between the alternatives with the same glazing ratio are wood preservative (3.0 times higher) and paint (2.6 times higher), followed by glass, rubber sealing, bitumen for the roof waterproofing, plaster, and cement tiling for the façade finishing (between 1.2 and 1.3 times higher). However, in terms of absolute contributions, only the variation of *bitumen* and *tiling* influences the results significantly. In all the alternatives and maintenance schedules mineral wool and EPS are the first and the second contributors to the total emissions, respectively. Cement tiling is the third contributor, while the contribution of glass is very small in all cases. For this reason, the increasing amount of emissions from glass is not enough to outweigh the emissions savings from the smaller masses of mineral wool and cement tiling. This explains the lower emissions of the alternatives with the highest glazing ratio, which are lower than the embodied emissions of the 24% glazing alternative by approximately 8%, regardless of the maintenance schedule.

In the 75-year lifetime scenario, the difference in the total emissions of corresponding retrofitting alternatives with short and long maintenance cycles is more pronounced. The total embodied emissions of the alternatives with the short maintenance cycle are approximately 1.5 times higher than the emissions of the corresponding alternatives with the long maintenance cycle. The total embodied emissions for the alternatives with 24% and 50% glazing are 138.1 $kgCO_{2\text{-}eq}m^{-2}$ and 127.3 $kgCO_{2\text{-}eq}m^{-2}$, with the long maintenance cycle, and 213.0 $kgCO_{2\text{-}eq}m^{-2}$ and 203.2 $kgCO_{2\text{-}eq}m^{-2}$, with the short maintenance cycle, respectively.

The greatest variation in embodied emissions of the building components between the alternatives with the same glazing ratio but with different maintenance cycles is given by wood preservative and plaster (3.0 times), followed by glass, paint and rubber (2.6 times), tiling (2.0 times), bitumen (1.5 times), and finally concrete, steel, and wood (1.25 times).

The embodied emissions of glass increase more in the alternative with a high glazing ratio when the maintenance cycle shifts from long to short. For this reason, the difference in embodied emissions between the alternatives with 24% and 50% glazing ratios decreases from 8% to 5%, when the maintenance cycle is changed from long to short. In the short maintenance scenario, the two most important contributors to the total emissions in any of the retrofitting alternatives are the cement tiling and bitumen (between 20% and 25% of the total, depending on the glazing ratio), followed by mineral wool and paint (between 8% and 10%, depending on the glazing ratio). In the long maintenance scenario, the most important contributor in any of the retrofitting alternatives is *bitumen* (20%-22%), followed by *tiling* (15%-19%), and mineral wool (13%-16%). It is worth noticing that any alternative with a lifetime of 75 year and a short maintenance cycle has total embodied emissions which are 1.9 times higher than the emissions of the corresponding alternative with a 25 years lifetime and the same maintenance cycle. This difference decreases to 1.3 times when the long maintenance cycle is used. This means that better quality components or a longer replacement rate of these can equalize the embodied emissions of a building with a lifetime that is three times higher.

5.5. Discussion and conclusions

This work presents the results of the greenhouse gas analysis of three retrofitting alternatives with increasing façade glazing ratios. The alternatives are compared to the currently accomplished renovation of the same building, which is used as a reference. The analysis of the energy demand shows that by increasing the glazing ratio of the facades the building energy use increases accordingly, as expected, up to a maximum of a 7% increase. However, it is worth remembering that, due to the geometry of the building, only the East and West facades are equipped with windows. A variation of the orientation of the building has not been shown, and, according to the work by Persson et al. [96], this might introduce a significant change of the results in the present work.

The greenhouse gas analysis has been carried out in three steps. First, comparing the retrofitting alternatives by varying the electricity-to-emissions conversion factors. Second, comparing the alternatives by introducing the variation of the building lifetime as a new variable. Third, comparing the alternatives by adding to the above the variation of the maintenance schedule of the building components as a further variable. The first analysis shows that the variation of the conversion factors for the energy mix is the key element in determining which alternative has the lowest total emissions. When the European average energy mix or the "ZEB energy mix" is used, the emissions due to the energy use for building operation are predominant. For this reason, the alternatives with higher energy uses have higher total emissions. However, the inclusion of the embodied emissions in the calculation reduces the difference between the alternative with the highest glazing ratio and the alternative with the lowest glazing ratio to 5%. On the other hand, when using the conversion factor for the Norwegian production of electricity the embodied emissions of the building components are predominant in any of the retrofitting alternatives. In this case the total emissions of the alternative with the highest glazing ratio is 2% lower than the alternative with the lowest glazing ratio. This is because with an increasing window area the emissions of the insulation layer and the façade finishing decrease accordingly. It is therefore difficult to determine which alternative has the highest emission savings. Also, the use of different conversion factors causes the total emissions to vary considerably, regardless of the retrofitting alternative. These differences are up to 8.6 times when comparing corresponding retrofitting alternatives with the European average conversion factor and the Norwegian conversion factor.

The introduction of the variation of building lifetime is aimed at evaluating to what extent the embodied emissions of the building components are counterbalanced by the emissions due to building operation. This first sensitivity analysis shows that the influence of the variation of the building lifetime on the share of the embodied emissions is strongly dependent on the conversion factor used. With the European conversion factor there is no significant change, and the emissions due to the building operation are predominant in both the 25-year and the 75-year scenarios, as before. With the ZEB conversion factor, the picture is more complicated. Since with this conversion factor the calculation of the emissions per each kWh of produced electricity is dependent on the building lifetime, the results show that with longer lifetimes the difference in total emissions between the alternative with the highest glazing ratio and the alternative with the lowest glazing ratio tends to decrease. Moreover, due to the use of this factor, which changes with time, the emissions for the 25-year lifetime are almost three times higher that the emissions for the 75-year lifetime, for any of the retrofitting alternatives. With the Norwegian conversion factor, the distribution of the results depends on the building lifetime. In the shortest lifetime, the total emissions of the alternative with the lowest glazing ratio are 3% higher than the emissions of the alternative with the highest glazing ratio. Comparing the same alternatives for the 75-year lifetime, these differences are eliminated. This is due to the fact that in the 75-year lifetime the emissions due to the replacement of the windows in the 50% glazing alternative counterbalances the embodied emissions of the insulation material and the façade finishing of the 24% glazing alternative. In conclusion, the results of this part of the work show that the variation of the building lifetime has an effect on determining which of the retrofitting alternatives is most attractive and that this depends on the conversion factor used. Longer lifetimes do no influence the results when using the European conversion factor, as seen before. However, they tend to favour the alternative with the highest glazing ratio when the ZEB conversion factor is used, and the alternative with the lowest glazing ratio when the Norwegian conversion factor is used.

The last sensitivity analysis introduces the variation of the maintenance schedule in order to see to what extent this influences the results. Using the European or the ZEB conversion factor, the variation of the maintenance schedule does not affect the distribution of the results, because of the predominance of the emissions due to building operation in any of the retrofitting alternatives. Using the Norwegian conversion factor, the results also remains constant for all the retrofitting alternatives even if two different maintenance cycles are used. This is due to the fact that the maintenance schedule influences the absolute emissions due to the substitution of the materials and the end-of-life phase, but its variation does not significantly change the relative differences between any two of the retrofitting alternatives. As a matter of fact, the variation of the maintenance schedule has very little influence on the alternatives for the 25-year lifetime, but it increases the total emissions by 22% for any of the corresponding alternatives for the 75-year lifetime. In this respect, when extending the building lifetime from 25 years to 75 years, the increase in total emissions for any of the alternatives with the same glazing ratio is limited to a 10% difference when the European or the ZEB conversion factor is used. In conclusion, this last sensitivity analysis shows that the variation of the maintenance schedule has a significant effect only on the total emissions of the alternatives with the Norwegian energy mix and the 75-year lifetime.

There are some aspects of this work that have not been considered in the calculation but that are worth noticing. The emissions due to transporting workers to the building site during the installation/dismantling phases of components has not been included in the calculation due to lack of data. This aspect has been studied by [Blom et al. 2010], who report that the emissions of the transportation of workers can be up to 22% of the total emissions. Clearly, in addition to a higher substitution rate, this factor can be critical for determining the distribution of the results of the retrofitting alternatives. The emissions per unit of mass of all the construction materials used in this research reflect the current European industrial production chain. Using different electricity-to-emissions conversion factors of the power grid results in different embodied emissions for the building materials. If a greener power grid is foreseeable in the future, the weight of the emissions of the material production phase is expected to be reduced accordingly. However, the entangled flows of the current industrial processes go beyond the geographical borders of Europe and, for this reason, make it a difficult task to quantify the extent of future emission abatement. In conclusion, it is difficult to determine a clear path of choices among the proposed retrofitting alternatives since the use of different conversion factors produces opposite results. However, if it assumed that the future European energy mix is moving towards a considerable use of renewable energy sources, this would lead to a reduction in the differences in emissions of the use of alternative glazing ratio on the building facades.

6. Comparison of two windows technologies

The results from the comparison of the use of two windows technologies (triple glazing with argon and double glazing with aerogel) are presented in this chapter. The results from the analysis of the different retrofitting alternatives are normalized to 1 m^2 of heated building area per year. The first set of data shows the results of the building energy demand from the comparison of the use of the two glazing technologies with the 24%, 33%, and 50% glazing ratios. The second set of data shows the greenhouse gas emissions of these alternatives. The third set of data shows the greenhouse gas emissions for the different alternatives when varying the building lifetime. The final set of data shows the greenhouse gas emissions for the alternatives when varying the cycle of substitution of the building components. Each set of data is examined by varying the kWh-to-CO_2 conversion factor.

6.1. Objective

The objective of the work is to compare and assess the lifecycle emissions from the use of two different glazing technologies applied to a façade with different glazing ratios. The retrofitting alternatives are tested on the Myhrerenga housing complex, and compared to the reference solution, which represents the actual accomplished renovation work of the building. [33]. The retrofitting alternatives are equipped with improved thermal resistance of the external walls and increasing window-to-wall ratios. The insulation level of the facades in the reference solution is 0.12 $Wm^{-2}K^{-1}$, the insulation material used is mineral wool, the average glazing ratio for the East and West facades is 24%, and the installed windows are triple glazed with argon filling (U-value 0.79 $Wm^{-2}K^{-1}$). The U-value of the opaque facades of the alternatives is set to 0.10 $Wm^{-2}K^{-1}$, the insulation material used is mineral wool, the glazing ratios are 24%, 33%, and 50%, and the installed glazing technologies are a window with triple glass-panes and argon filling and a fixed glazing with double-glass-panes and monolithic aerogel filling (U-value 0.50 $Wm^{-2}K^{-1}$). The share of the aerogel glazing varies and is set to 28% for the 24% and the 33% glazing ratios, and to 39% for the 50% glazing ratio. This leaves enough operable window area to allow natural ventilation of the building. Details of the glazing technologies are found in Table II- d in Appendix II.

Since the use of these two glazing technologies results in different energy use for building operation, it is interesting to study the influence of the emissions due to the building operation and how it varies with different electricity-to-conversion factors. It is expected that when using a conversion factor that credits large amounts of emissions for each kWh of produced electricity, the choice of the glazing technology would be important. The reference kWh-to-CO_2 conversion factor of the power grid is based on the model developed at the Research Centre on Zero Emission Buildings (ZEB), and this is compared to the EU average value and the Norwegian energy mix at inland production. The reference lifetime for the reference building and the retrofitting alternatives is set to 50 years. The maintenance cycle for the building components is taken from [86] and is set to a medium rate of substitution. Details of the maintenance cycles for the different building components can be found in Table III- b in Appendix III.

The first sensitivity analysis is aimed at comparing the embodied emissions of the two glazing technologies applied to facades with different glazing ratios and to evaluate the efficacy of the use of aerogel glazing for different building lifetimes. The variation of the building lifetime influences the total emissions of the building because the embodied emissions from the installation of the components and their replacement cycle vary accordingly. By lengthening the building lifetime to 75 years or shortening it to 25 years, one can see what the share of the embodied emissions is in the total emissions and how it varies. The emissions due to the building operation are calculated by applying three electricity-to-emissions conversion factors, as explained above.

The second sensitivity analysis addresses the variation of the maintenance schedule. The glazing components undergo a faster replacement rate than the other parts of the façade, such as the insulation layer and the finishing. In addition, a fixed glazing insulated with aerogel has higher embodied emissions than a window with argon filling, but it has a better insulation value. For these reasons, the use of this technology has both the positive effect of reducing the emissions due to a lower building energy use and the negative effect of increasing the embodied emissions due to the aerogel insulation. Therefore, the variation of the maintenance cycle of the building components helps to understand the limit for when the use of aerogel glazing is positive. The medium maintenance cycle is replaced with a short and a long cycle applied to the retrofitting alternatives with the two glazing technologies and with the different glazing ratios. In addition, to simulate the expected high failure rate of aerogel glazing, its replacement rate is set as double that of the windows with argon filling. Since the variation in total emissions due to the different maintenance cycles is related to the building lifetime, the 25-year and the 75-year lifetimes are used in this analysis. Details of the maintenance cycles of the different glazing technologies are found in Table III- b in Appendix III. The 50-year lifetime is not analysed because it would not add any significant information. Similarly to the analyses in the previous chapters, the kWh-to-CO_2 conversion factor is also varied in order to understand the extent of the influence of the emissions for building operations.

Details of the external facades of the retrofitting alternatives are presented in Table II- b, and Table II- d in Appendix II.

6.2. Results from the energy and the greenhouse gas analyses

Figure 39 shows the energy demand of the retrofitting alternatives with the aerogel glazing and with the windows with argon filling. The building energy use shows a diverging trend in which the alternatives with the triple-glazing with argon have increasing values and the alternatives with the double-glazing with aerogel have stable values. That is, the use of aerogel windows reduces the energy use for space heating compared to the other the alternatives that have the same glazing ratio. Relative to the total energy demand of the reference building, the energy demand of retrofitting alternatives with aerogel glazing is 94.1% for the *24% aerogel* retrofit and 94.7% for the *50% aerogel* retrofit. These percentages correspond to a total energy use of 80.6 kWhm^{-2}y^{-1} for the *24% aerogel*, 81.3 kWhm^{-2}y^{-1} for the *33% aerogel*, and 81.2 kWhm^{-2}y^{-1} for the *50% aerogel* alternative. This illustrates that to maintain the same energy use for space heating in the alternatives with increasing glazing ratios, it is necessary to increase the share of aerogel glazing. It is worth remembering that the share of aerogel glazing is 28% for the retrofits with both 24% and 33% glazing ratios, while it is 39% for the retrofit with a 50% glazing ratio. As a consequence, the savings in the energy use for space heating of the retrofits with aerogel glazing increase with increasing window-to-wall ratios. It is 6.5% for the 24% aerogel glazing alternative, 11.0% for the 33% aerogel glazing alternative, and 15.5% for the 50% aerogel glazing alternative. The savings in total energy use are 4.2%, 7.2%, and 10.4% for the retrofits with a 24% , 33%, and 50% glazing ratio, respectively.

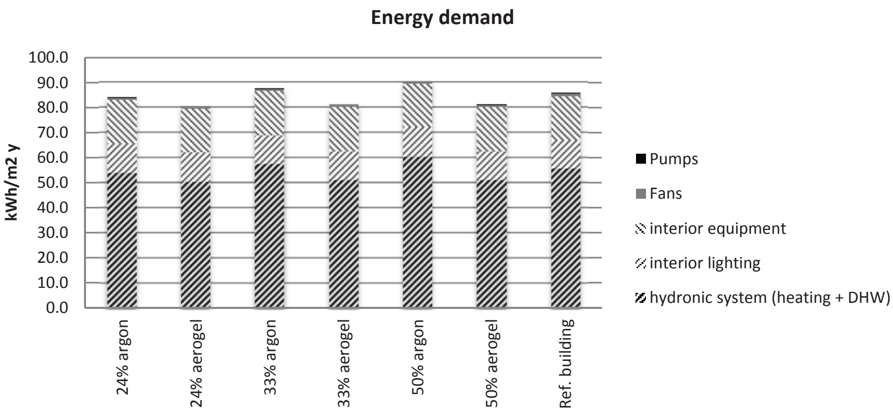


Figure 39. Composition of the yearly energy demand of the different retrofitting alternatives and the reference building solution. Values are normalized to 1 m² of building heated area.

Figure 40 shows the results of the emissions of the retrofitting alternatives for the 50-year lifetime, medium maintenance, analysed with the ZEB, European, and Norwegian electricity-to-emissions conversion factors. As seen in Figure 40, the alternatives with aerogel always have lower emissions per unit of surface than the corresponding alternative with the triple-glazing windows. When using the ZEB conversion factor, the use of aerogel glazing results in constant total emissions of 14.9 kg$CO_{2\text{-eq}}$m^{-2}y^{-1}, regardless of the glazing ratio. The retrofits with windows with argon filling have total emissions which vary between a minimum of 15.3 kg$CO_{2\text{-eq}}$m^{-2}y^{-1} for the *24% argon* alternative and a maximum of 16.1 kg$CO_{2\text{-eq}}$m^{-2}y^{-1} for the *50% argon* alternative. These results confirm the trend given by the analysis of the energy demand, in which the increase in energy use for space heating due to the increasing glazing ratio of the retrofits with the triple-glazing technology makes the alternatives with the glazing with aerogel a better choice. This is due to the fact that the share of emissions from the building operation is at least 82% of the total in all of the retrofitting alternative when using the ZEB conversion factor.

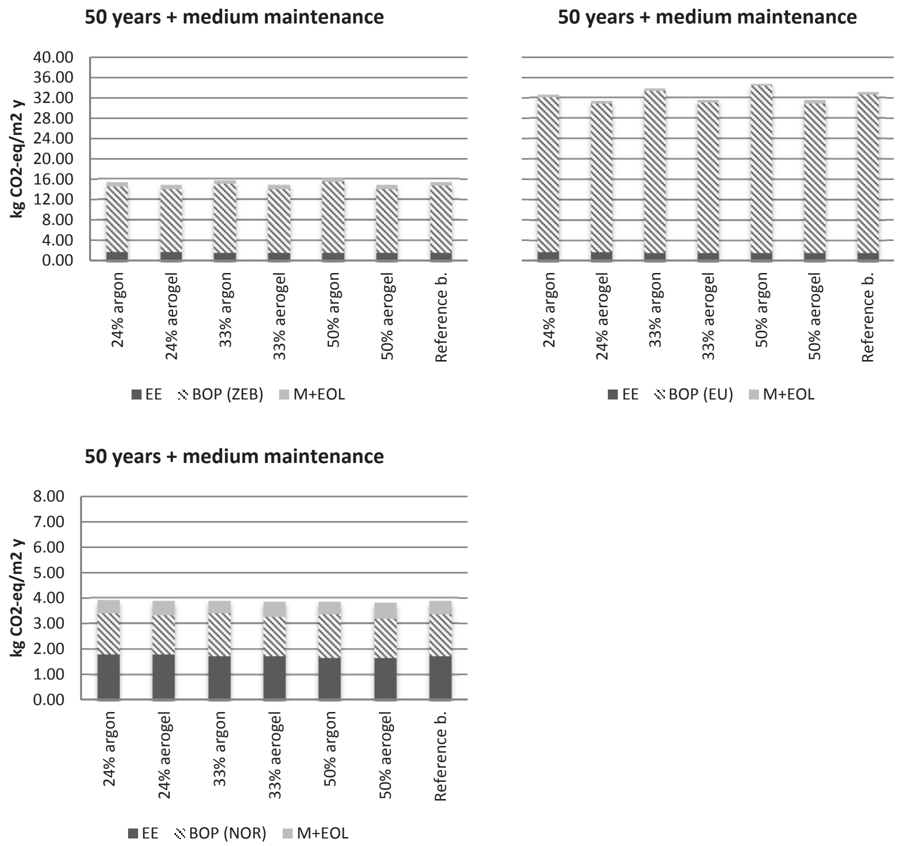


Figure 40. CO_2 emissions for retrofitting alternatives for the 50-year lifetime and medium maintenance scenario using different CO_2 factors. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

However, in terms of embodied emissions (*EE* and *M+EOL*) the alternatives with aerogel have higher values than the alternatives with argon, regardless of the glazing ratio. The difference is 0.8% for the alternatives with 24% glazing and 2.5% for the alternatives with 50% glazing. As a consequence, the savings in total emissions between the alternatives with aerogel glazing and argon windows are 3.2% for the 24% glazing ratio, 5.3% for the 33% glazing ratio, and 7.7% for the 50% glazing ratio.

The use of the average European conversion factor increases the emissions from the building energy use and, as a consequence, gives a distribution of results similar to the one in Figure 39. The share of the emissions from building operation is at least 93% of the total, and the difference in emissions between the use of the two glazing technologies are 3.8% for the 24% glazing alternative and 9.8% for the 50% glazing alternative. The total lifecycle emissions of the alternatives with aerogel are 31.6 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$, regardless of the glazing ratio. Relative to the total emissions of the reference building, the lifecycle emissions of any of the alternatives with aerogel are approximately 95%. These are 10% lower than the total emissions of the *50% argon* retrofit. It is worth noticing that substituting the ZEB conversion factor with the EU conversion factor increases the emissions of the building operation phase (*BOP*) by 2.3 times. As a result, the average total emissions for all the retrofitting alternatives is 32.8 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$.

When using the Norwegian conversion factor, the share of the emissions from building operation decreases to 41% on average. As a consequence, the distribution of the results does not follow a diverging trend, as seen in the previous cases, but it slopes slightly downwards with increasing glazing ratios, regardless of the glazing technology used. The alternatives with aerogel still represent some savings, but the difference between any of the alternatives with the same glazing ratio but with different glazing technologies diminishes. It is 0.9% for both the alternatives with 24% and 33% glazing ratios, and 1.4% for the alternatives with a 50% glazing ratio. Moreover, the difference between the reference building and the other alternatives also diminishes. Relative to the reference building as, the lifecycle emissions of the *24% argon* retrofit is 101.1%, of the *24% aerogel* retrofit 100.1%, of the *50% argon* retrofit 99.6%, and of the *50% aerogel* retrofit 98.2%. As a consequence, when using the Norwegian conversion factor, all alternatives have very similar results (3.9 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$, on average.

6.3. Sensitivity analysis: variation of building lifetime

Figure 41 shows the emissions of the retrofitting alternatives with the 25-year and the 75-year building lifetimes and the medium maintenance cycle. When using the ZEB conversion factor, the average total emissions of all the alternatives decreases from 29.6 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ for the 25-year lifetime to 10.7 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ for the 75-year lifetime. This is due to the fact that the ZEB conversion factor is calculated with the building lifetime as a variable and, as a consequence, produces "greener" results when the building lifetime is extended. On the other hand, the embodied emissions of any of the alternatives also decrease with longer lifetimes and, consequently, the share of the emissions from the building operation (*BOP*) does not differ very much between the two lifetimes. The average is 86.7% for all the alternatives for the 25-year lifetime and 79.9% for all the alternatives for the 75-year lifetime. It is worth noticing that the increased embodied emissions due to the use of aerogel does not counterbalance the savings in lifecycle emissions due to the lower energy use for operation. For this reason, the difference in lifecycle emissions between the use of aerogel glazing and argon windows tends to diminish with longer lifetimes, as the share of the emissions from the building operation decreases as well. The difference in total emissions between the alternative with the windows with argon and the one with the glazing with aerogel with a 24% glazing ratio is 3.5% for the 25-year lifetime and 2.9% for the 75-year lifetime. It is 9.7% for the 50% glazing alternatives for the 25-year lifetime and 6.9% for the 50% glazing alternatives for the 75-year lifetime. It can therefore be expected that when using the ZEB conversion factor and lifetimes even longer than 75 years, the savings given by the use of aerogel as insulation for glazing tends towards zero.

When using the European average conversion factor the influence of the emissions due to the building operation phase is very large. It is at least 89% of the total for the 25-year lifetime and 93% for the 75-year lifetime. As a consequence, the share of the embodied emissions (*EE* and *M+EOL*) varies very little between the two building lifetimes, and the distribution of the results is very similar to the one presented in Figure 40. The savings in emissions from the use of aerogel is 5.8% in the alternative with the 24% glazing ratio and 9.8% in the alternative with the 50% glazing ratio, regardless of the building lifetime. In addition, the variation of the building lifetime does not significantly influence the total emissions of any of the retrofitting alternatives. Considering the average total emissions of all the retrofits, these are 34.1 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 25-year lifetime and 32.6 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 75-year lifetime.

With the Norwegian conversion factor, the share of the embodied emissions (*EE* and *M+EOL*) is very large, and, as a consequence, it is greatly influenced by the building lifetime. In the 25-year lifetime, the average share of the embodied emissions (*EE* and *M+EOL*) is 69.3%, while it is 57.1% in the 75-year lifetime. In addition, the share due to the replacement of building components and their disposal (*M+EOL*) is 3.3% of the average total emissions in the 25-year lifetime and 26.3% in the 75-year lifetime.

Since the replacement rate for the glazing with aerogel is double that of the replacement rate for the windows with argon, the savings in the alternatives with aerogel do no exceed 2.4% for the 50% glazing retrofit in the 25-year lifetime. In the 75-year lifetime the savings in emissions due to the use of aerogel is very close to zero for any of the alternatives. This implies that for a lifetime longer than 75 years, the total emissions of the alternatives with aerogel tend to be larger than the total emissions of the alternatives with the triple-glazing with argon. It is worth noticing that the average total emissions of all the alternatives is 5.2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 25-year lifetime and 3.7 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the 75-year lifetime. This difference (approximately 29%) is due to the fact that by extending the lifetime the increasing emissions due to the phase of replacement and end-of-life, the building materials (*M+EOL*) do not counterbalance the decreasing emissions due to the initial embodied emissions (*EE*) of the building materials. For this reason, with the Norwegian conversion factor and the medium maintenance cycle, extending the building lifetime produces considerable savings in total emissions, regardless of the retrofitting alternative.

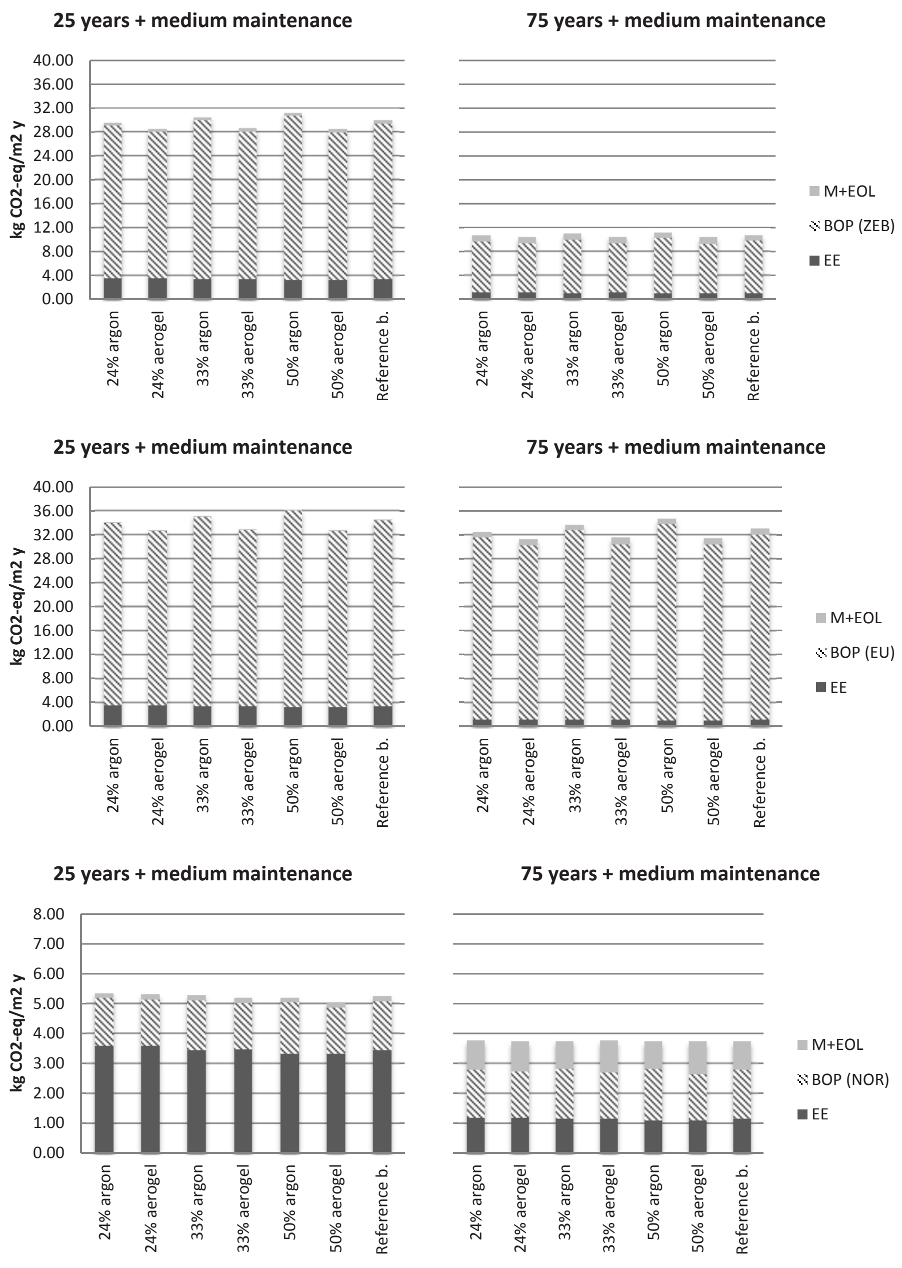


Figure 41. CO_2 emissions for retrofitting alternatives for 25-year and the 75-year lifetimes and medium maintenance scenario for the different CO_2 factors. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year.

6.4. Sensitivity analysis: variation of maintenance cycle

Figure 42 shows the emissions of the retrofitting alternatives with the ZEB conversion factor for the 25-year and the 75-year lifetimes and the short and long maintenance cycles. For the alternatives with the shortest lifetime, the variation of the substitution rate of the materials does not significantly alter the results. The emissions from the phase of replacement and disposal of the building components (*M+EOL*) on the average for all the alternatives are 3.5% of the total for the short maintenance cycle and 1.5% of the total for the long maintenance cycle. As a consequence, the average total emissions of all the alternatives vary from 30.1 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the short cycle to 29.5 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the long cycle. This is due to the fact that the share of the emissions from building operation (*BOP*) is between a minimum of 84% for the *24% aerogel* retrofit with the short maintenance cycle and 88.1% for the *50% argon* retrofit with the long maintenance cycle. For this reason, the variation of the maintenance cycle does not change the distribution of total emissions of any the alternatives when using the ZEB factor.

For the 75-year lifetime, the share of the emissions from the *M+EOL* phase gains more weight. This is on average 15.2% for all the alternatives with the short maintenance cycle and 6.4% for all the alternatives with the long maintenance cycle. However, the variation of the maintenance cycle still has some influence on the relative savings between the alternatives with the same glazing ratio but with different glazing types. The difference in emissions is 4.9% between the *50% argon* and *50% aerogel* alternatives for the short cycle, and 7.6% between the same alternatives for the long cycle. These differences diminish to 2.3% between the *24% argon* and the *24% aerogel* alternatives for the short maintenance cycle, and to 3.1% between the same alternatives for the long maintenance cycle. The diminishing savings when using aerogel insulation in the glazing are due to the increasing replacement rate for this glazing type, which has a replacement rate that is twice that of the windows with argon filling. The variation of the maintenance cycle has also very little effect on the average total emissions of all the alternatives. These are 11.4 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the short cycle and 10.3 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the long cycle.

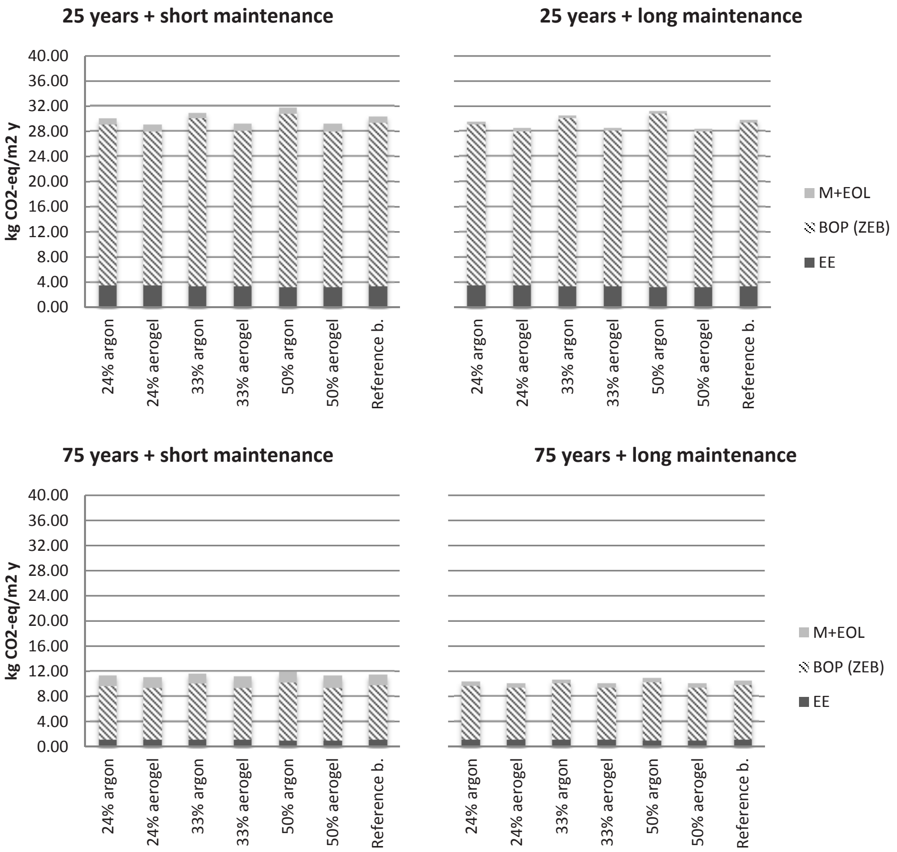


Figure 42. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year.

Figure 43 shows the emissions of the retrofitting alternatives calculated with the EU conversion factor for the 25-year and the 75-year lifetimes and the short and the long maintenance cycles. As shown in the bar charts, the contribution of the replacement and disposal phase of the building material (*M+EOL*) is so small for the 25-year lifetime (between 1.0% and 0.5% for the short and the long maintenance cycles) that there is no significant variation in the results. The emissions from building operation are the key factor and favour the alternatives with aerogel in both cases. The resulting savings are up to 9.2% for the *50% aerogel* retrofit and the *50% argon* retrofit. When using the 75-year lifetime, the contribution of the *M+EOL* phase increases up to 3% on average for the alternatives with the long maintenance cycle and to 5.2% on average for the alternatives with the short maintenance cycle. In this last case, the influence of the emissions from building operation (*BOP*) is still very high (at least 90% of the total) and, thus, the alternatives with the double-glazing with aerogel show savings that are up to 8.5% between the *50% aerogel* and the *50% argon* alternatives. In all cases, the average total emissions of all the alternatives does not vary significantly and is a minimum of 32.6 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the alternatives with the 75-year lifetime and the short maintenance cycle, and a maximum of 34.3 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the alternatives with the 25-year lifetime and the long maintenance cycle.

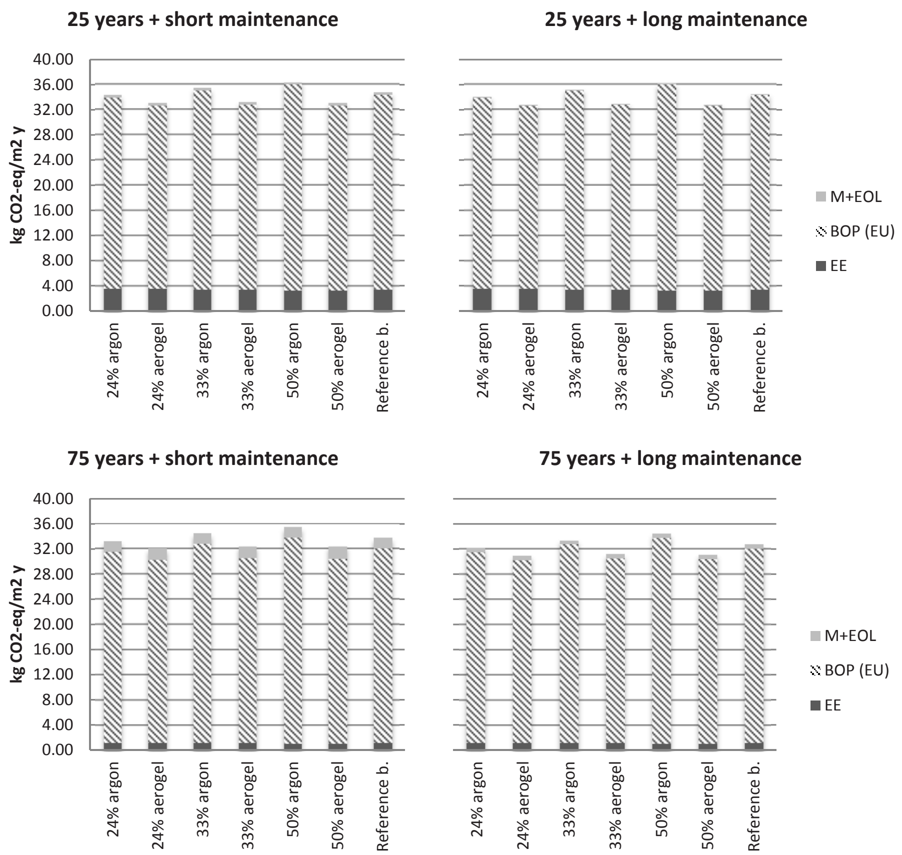


Figure 43. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

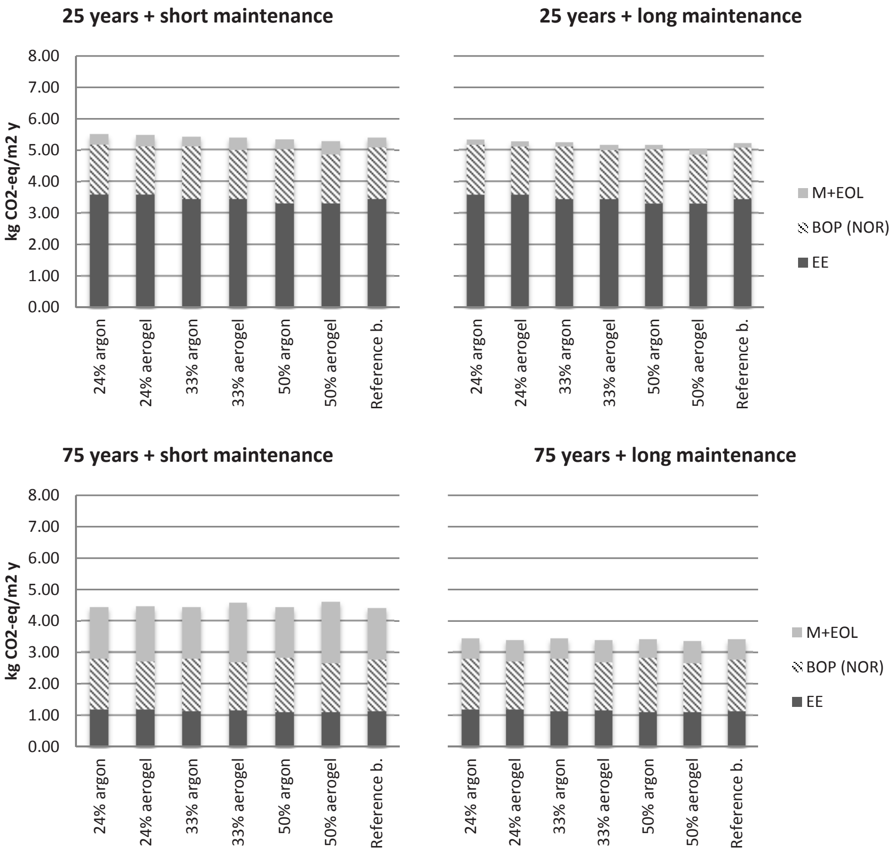


Figure 44. CO_2 emissions for retrofitting alternatives for the 25-year and the 75-year lifetimes, and short and long maintenance scenarios. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year

Figure 44 shows the total emissions of all the alternatives with the Norwegian energy mix, the 25-year and the 75-year lifetimes, and the short and the long maintenance cycles. For the 25-year lifetime, the share of the emissions of the phases of substitution and disposal of the building material is very small. For all the retrofitting alternatives it is on average 2.8% and 6.5% for the long and the short maintenance cycles, respectively. In addition, as previously seen, the share of emissions due to the building operation phase is approximately 30% of the total for any of the alternatives, regardless of the maintenance cycle. For these reasons, the savings in emissions when using the glazing with aerogel are very small and do not exceed 2.7%, which is the difference between the *50% aerogel* and the *50% argon* alternative with the long maintenance cycle.

By extending the building lifetime to 75 years, the variation of the maintenance cycle has a much stronger influence on the results. The use of a long replacement rate for the building materials does not result in a significant variation in total emissions, as seen in the 25-year lifetime with the long maintenance cycle. The greatest difference between the alternatives with corresponding glazing ratios and different glazing types is 1.7%. This difference is between the *50% aerogel* and the *50% argon* alternatives with the long maintenance cycle. This picture is, however, completely reversed when applying the short maintenance cycle. The alternatives with glazing with aerogel always have higher total emissions than their corresponding alternatives with triple-glazing with argon. This difference is 0.5% between the alternatives with a 24% glazing ratio and increases to 4.2% between the retrofits with a 50% glazing ratio. This is due to the fact that the share of emissions of the phases of substitution and disposal of the building materials is 33.7% on average for all the alternatives for the long maintenance cycle and 38.5% on average for all the alternatives for the short maintenance cycle.

In addition, the replacement rate of the glazing with aerogel is twice the replacement rate of the triple-glazing with argon and, as a consequence, the embodied emissions of the glazing component outweigh the savings from the energy use for operation in the long lifetime. It is worth noticing that for the 25-year lifetime the average total emissions of all the alternatives is 5.2 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the long maintenance cycle and 5.4 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the short cycle. Their relative difference is less than 4%. On the other hand, for the 75-year lifetime the average total emissions of all the alternatives are 3.4 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the long cycle, and 4.5 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the short cycle. Their relative difference is approximately 24%. It shows that with the Norwegian conversion factor the variation of the maintenance cycle is critical only for the retrofits with the longest lifetime. More specifically, with the long cycle the *50% aerogel* alternative is slowly becoming less competitive than the *50% argon* alternative when the building lifetime is extended. This trend is magnified when the short cycle is applied. In this case the alternatives with the glazing with aerogel have more emissions than their counterparts with the windows with argon.

Figure 45 shows the composition of the embodied emissions (*EE* and *M+EOL* phases) of the all the alternatives with the 25-year and the 75-year building lifetime and the short and the long maintenance cycles. By excluding the energy savings of the use of the glazing with aerogel, this figure shows the difference in embodied emissions between the corresponding alternatives with and without aerogel. For the 25-year lifetime and the short maintenance cycle, the difference in embodied emissions is less than 2% between the *24% argon* and the *24% aerogel* alternatives, and it is 8.6% between the two alternatives with the 50% glazing ratio. This difference is due to the increasing emissions for wood (in the windows frame), for glass (due to the higher substitution rate of aerogel glazing), and for aerogel. Considering the variation of emissions between the two alternatives with the highest glazing ratio, the cumulative emissions for wood, glass, aerogel, and argon are 27.5 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% aerogel* alternative and 18.4 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% argon* alternative (in which aerogel does not account for any emissions).

Aerogel only accounts for 3.4 $kgCO_{2\text{-}eq}m^{-2}$, which is close to 3% of the total emissions.

For the long maintenance cycle, the difference in total emissions between the alternatives with the highest glazing ratio diminishes to 2.5%. The cumulative emissions of wood, glass, aerogel and argon are 16.4 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% argon* alternative and 18.8 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% aerogel* alternative. The cumulative share of these materials in total emissions are 23.9% and 17.4% for the *50% aerogel* and the *50% argon* alternative for the short maintenance cycle and 19.8% and 17.8% for the long maintenance cycle. This means that with the short lifetime the emissions of the glazing part of the façade are not enough to significantly change the results when increasing the replacement rate for the materials. With the 75-year lifetime, the variation of the maintenance cycle has a much stronger influence on the results. With the short cycle the *24% aerogel* alternative has 3.1% more embodied emissions than its counterpart with the alternative with windows with argon. This difference rises to 13.4% when comparing the alternatives with the 50% glazing ratio. The cumulative emissions of wood, glass, aerogel and argon are 37.5 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% argon* retrofit and 64.8 $kgCO_{2\text{-}eq}m^{-2}$ for the *50% aerogel* alternative. These values represent 18.5% and 28.1% of the total emissions, for the argon and the aerogel alternatives respectively.

For the long maintenance cycle the same shares are reduced to 14.7% and 20.4%, for the *50% argon* and the *50% aerogel* alternatives respectively. In the 25-year lifetime the difference between the two maintenance cycles is less than 4% for the *50% aerogel* alternative and less than 1% for the *50% argon* alternative. In the 75-year lifetime this difference is almost 8% for the aerogel alternative and almost 4% for the argon alternative. The total emissions of the alternative with the highest glazing ratio and the glazing with aerogel are 230.5 $kgCO_{2\text{-}eq}m^{-2}$ for the 75-year lifetime and the short maintenance. They decrease to 136.4 $kgCO_{2\text{-}eq}m^{-2}$ for the 75-year lifetime and the long cycle. On the other hand, the total emissions of the same alternative for the 25-year lifetime are 114.8 $kgCO_{2\text{-}eq}m^{-2}$ and 94.8 $kgCO_{2\text{-}eq}m^{-2}$, for the short and the long maintenance cycle respectively. This means that for the same alternative the variation in total emissions due to the different maintenance cycles is approximately 21% for the short building lifetime and almost 70% for the long building lifetime. It is worth noticing that the variation of the maintenance cycle has a different effect depending on whether the alternatives with the windows with argon or the alternatives with the glazing with aerogel are considered. In the alternatives with windows with argon the total embodied emissions always decrease when increasing the glazing ratio, regardless of the building lifetime and the maintenance cycle applied. On the other hand, the total embodied emissions of the alternatives with aerogel are stable for the 25-year lifetime and the short maintenance cycle, decrease for the 25-year and the 75-year lifetimes and the long maintenance cycle, and increase for the 75-year lifetime and the short maintenance schedule.

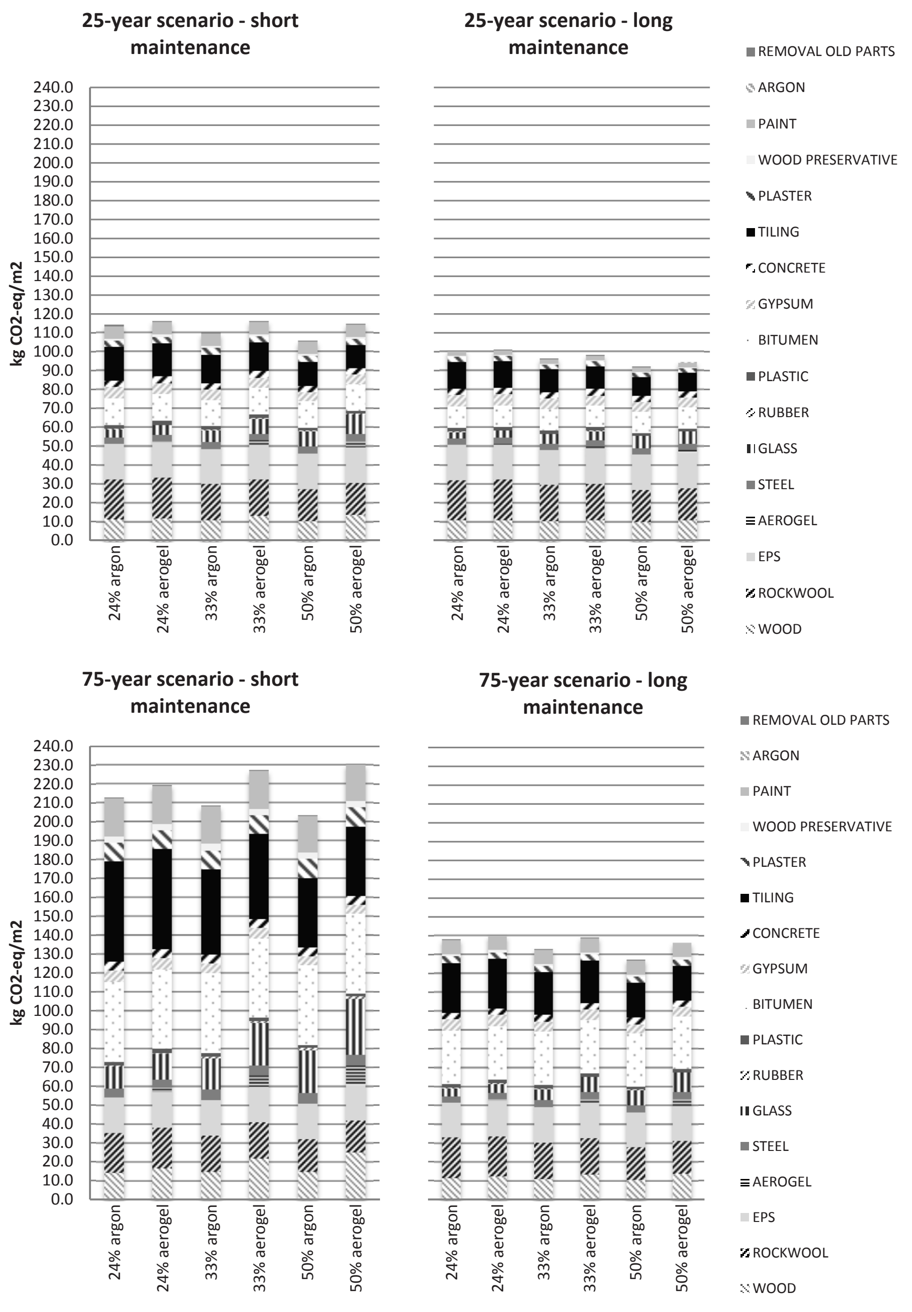
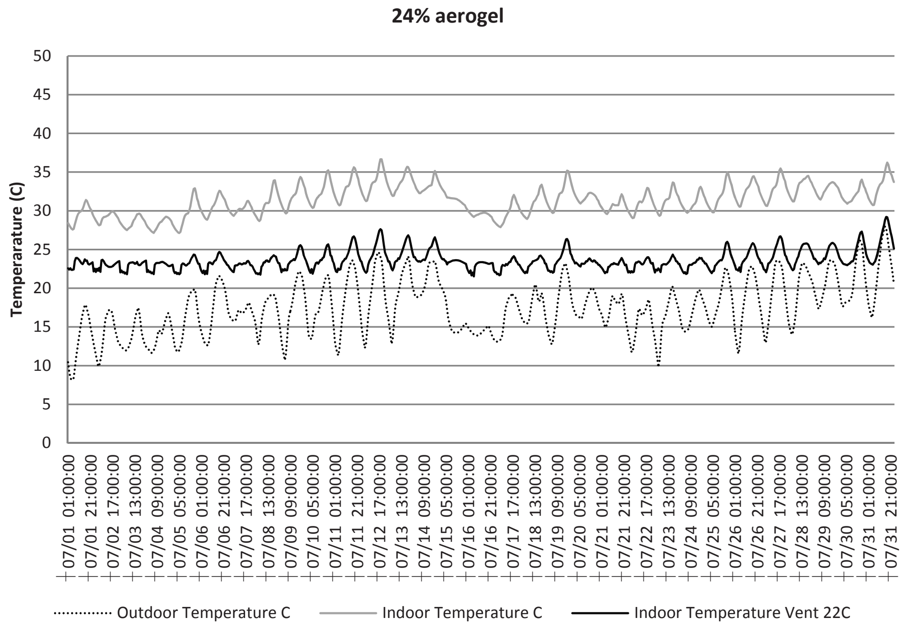


Figure 45. Composition of CO_2 emissions for the materials used in the retrofitting alternatives for the 25-year and 75-year lifetimes, and short and long maintenance scenarios. All values are normalized to 1 m² of heated building area.

6.5. Use of natural ventilation

The last analysis presents the results of calculations of the use of natural ventilation in one of the apartments for the *24% aerogel* and the *50% aerogel* alternatives. These were done in order to evaluate to what extent natural ventilation is sufficient for avoiding overheating of the apartments and to eliminate the need for energy for cooling. The analysis has been limited to the apartment located on the first floor on the south side of the building, because this apartment has the highest monthly average indoor temperature for July. The comparison is limited to two alternatives with aerogel windows only, as they represent the worst cases in terms of overheating potential due to the high insulation value of this glazing technology. In Figure 46 the indoor temperature variations with and without natural ventilation are compared. The results show how the increase in glazing ratio, from 24% to 50%, critically increases the apartment overheating. In the *24% aerogel* alternative the indoor temperature varies between 28 C and 36 C when no natural ventilation is used. In the *50% aerogel* alternative, the temperature rises from a minimum of 31 C up to 47 C. The natural ventilation is activated by opening the area constituted by the triple-glazing with argon windows. This area varies for the two retrofitting alternatives from 1.7 m^2 for *24% aerogel* to 3.8 m^2 for *50% aerogel*. The mechanical ventilation system remains in operation when the windows are open. In the alternative with the lowest glazing ratio, the use of natural ventilation lowers the indoor temperature and is below 25 degrees most of the time. When the outdoor temperature is above 22 C, the indoor temperature rises accordingly. The amount of time the indoor temperature is above 25 C is limited to 104 hours (14%) and 14 peak-days in the *24% aerogel* alternative. Due to the larger glazing area in the *50% aerogel* alternative the daily peak temperature is above the 25 C limit for 22 days out of 31. This corresponds to 216 hours (29%). It is worth considering that there is no movable or fixed shading system on the glazed area of either the retrofit alternatives, except for the abutting floor of the balcony on the West side of the apartment on the second floor.



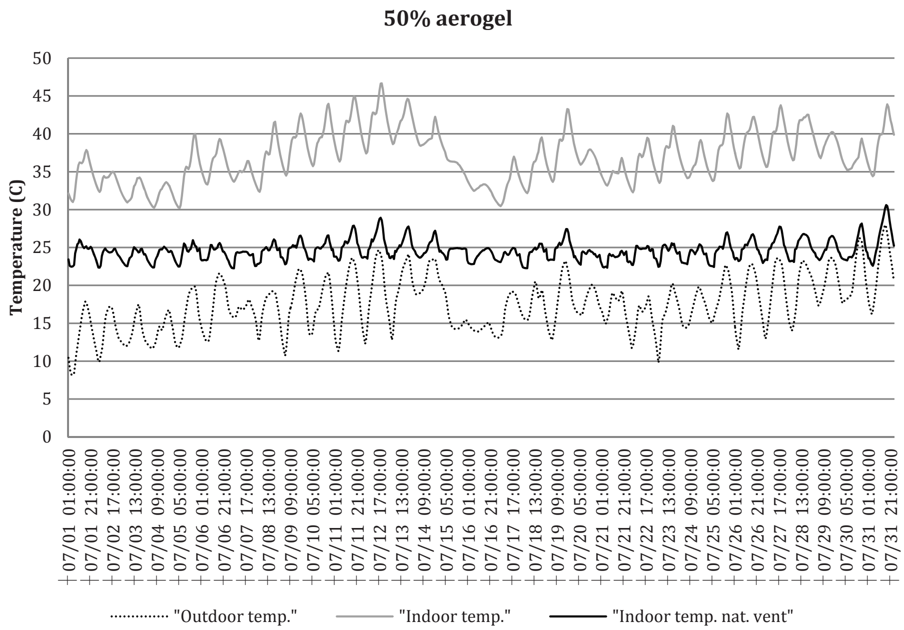


Figure 46. Variation of the indoor temperature due to the use of natural ventilation. Natural ventilation is used when the indoor temperature is above 22 C. Analysis performed for one apartment with the 24% aerogel and the 50% aerogel retrofitting alternatives.

6.6. Discussion and conclusions

This work presents the results of the greenhouse gas analysis of two glazing technologies (triple-glazing with argon and double-glazing with aerogel) applied to the external facades of a residential block in Oslo, the Myhrerenga Borettslag. The glazing ratio of the façades is varied from 24% to 33% and 50%. The resulting retrofitting alternatives are compared to the currently accomplished renovation of the Myhrerenga Borettslag, used as a reference. The analysis of the energy demand shows that by partially substituting the argon-insulated windows with the aerogel-insulated glazing the energy demand for space heating is reduced. These savings are 6.5% for the 24% aerogel glazing alternative, 11.0% for the 33% aerogel glazing alternative, and 15.5% for the 50% aerogel glazing alternative. However, it is worth remembering that, due to the geometry of the building, only the East and West facades are equipped with windows. Other orientations of the building have not been analysed, and, according to the work by Persson et al. [96], other orientations may give other results than those in the present work. In addition, due to the technical limitation of the use of monolithic aerogel as insulation for windows, only a part of the total glazing is equipped with this material (maximum 39%). A full substitution of all the argon-insulated windows with double-glazing windows with aerogel would result in much higher energy savings.

The greenhouse gas analysis has been performed in three steps. First, the retrofitting alternatives were compared by varying the electricity-to-emissions conversion factors. Second, the alternatives were compared by introducing the building lifetime as a new variable. Third, the alternatives were compared by adding to the above the maintenance cycle of the building components as a further variable. The first analysis showed that the variation of the conversion factors for the energy mix is the key element in determining which alternative has the lowest total emissions. When the European average energy mix or the “ZEB energy mix” are used, the emissions due to the energy use for building operation are predominant. For this reason, the alternatives with higher energy uses have higher total emissions. These are the retrofit alternatives with argon-insulated windows. It must be noted, however, that the inclusion of the embodied emissions in the calculation reduces the difference between the alternatives with the triple-glazing with argon and the alternatives with the double-glazing with aerogel. This is due to the high embodied emissions per unit of mass for the production of aerogel (4.20 $kgCO_{2-eq}kg^{-1}$). In current literature there is no data regarding the expected service life of windows with aerogel insulation. It is therefore assumed that their service life is half of that of standard triple-glazing with argon windows. As a consequence, the difference in total emissions between the use of the two alternative glazing technologies is maximum 7.7% for the alternatives with 50% glazing ratio. If the service life of the glazing with aerogel and the windows with argon were the same, the savings in total emissions when using aerogel would be comparable to the savings in total energy demand.

When using the conversion factor for the Norwegian production of electricity the embodied emissions of the building components are predominant in any of the retrofitting alternatives. In this case the total emissions of the alternatives with the glazing with aerogel are only slightly lower than those of the alternatives with the triple-glazed windows with argon. This is because with the Norwegian conversion factor the share of the embodied emissions increases considerably. It is therefore difficult, then, to determine to what extent the use of aerogel as window insulation is advantageous. In general, the total emissions vary considerably with conversion factors, regardless of the retrofitting alternative. The maximum achievable savings are up to four times higher with the European conversion factor than with the Norwegian conversion factor.

The introduction of the variation of building lifetime was aimed at evaluating to what extent the embodied emissions of the building components are counterbalanced by the emissions due to building operation. The results showed that the influence of the variation of the building lifetime on the share of the embodied emissions is strongly dependent on the electricity conversion factor used. With the European conversion factor there is no significant change, and the emissions due to the building operation are predominant in both the 25-year and in the 75-year lifetime, as before. This means that the use of aerogel is still more advantageous that the use of argon, regardless of the glazing ratio. With the ZEB conversion factor, the picture is more complicated. Since with this conversion factor the calculation of the emissions per each kWh of produced electricity is dependent on the building lifetime, the results show that the savings in emissions when using the glazing with aerogel tend to diminish when the lifetime is extended from 25 years to 75 years. This is because the influence of the emissions from the building operation decreases as well. It can be assumed then, that for a building service life longer than 75 years the use of aerogel for windows insulation loses any advantage.

With the Norwegian conversion factor, the results depend on the building lifetime. Since the replacement rate for the glazing with aerogel is double that of the windows with argon, the savings in the alternatives with aerogel do no exceed 2.4% for the 50% glazing retrofit in the 25-year lifetime. However, for the 75-year lifetime the savings of emissions due to the use of aerogel is very close to zero for all the alternatives. This implies that for a lifetime longer than 75 year, the total emissions of the retrofits with aerogel tend to be larger than the total emissions of the retrofits with the triple-glazing with argon.

In conclusion, the results from this part of the work showed that the variation of the building lifetime has an effect on determining which of the glazing types is advantageous, and that it depends on the conversion factor used. Longer lifetimes do no influence the results given by the use of the European conversion factor, as seen before. However, they tend to favour the alternatives with the argon-insulated windows when either the ZEB or the Norwegian conversion factors are used.

The last sensitivity analysis introduced the variation of the maintenance cycle. This was done in order to see to what extent this influences the results. When using the European conversion factor the variation of the maintenance schedule does not affect the distribution of the results, because of the predominance of the emissions due to the building operation in any of the retrofitting alternatives. When using the ZEB conversion factor, the variation of the maintenance schedule has an influence that depends on the building service life. For the 25-year lifetime the savings of emissions between the alternatives with the same glazing ratio but with different glazing technologies remain unchanged and favour the use of aerogel. For the 75-year lifetime, a large variation in the savings in emissions between the alternatives with the aerogel-insulated and the argon-insulated glazing occurs when changing the maintenance schedule. It shows that the differences between the two alternatives with the 50% glazing ratio are 1.5 times higher with the long maintenance cycle than with the short maintenance cycle. However, the use of aerogel is still advantageous for any of the glazing ratios considered. When using the Norwegian conversion factor the variation of the maintenance cycle is critical only for the retrofit alternatives with longest lifetime. More specifically, with the long maintenance cycle the *50% aerogel* alternative is slowly becoming less competitive than the *50% argon* alternative when the building lifetime is extended from 25 years to 75 years. This trend is magnified when the short maintenance cycle is applied, where the alternatives with the glazing with aerogel have higher emissions than their counterparts with the windows with argon. In conclusion, the last sensitivity analysis shows that the variation of the maintenance schedule has a significant effect only when the building lifetime is set to 75 years for the ZEB and the Norwegian conversion factor. In such a perspective, for longer building lifetimes, the use of aerogel as insulation for windows becomes less competitive. If there also is a short substitution rate for the building components, the glazing with aerogel has absolutely no advantage.

In conclusion, it is difficult to determine a choice among the proposed retrofitting alternatives because the use of different conversion factors produces different results. However, if it assumed that the future European energy mix is moving towards a considerable use of renewable energy sources, this would lead to a reduction in the emissions due to the building operation phase. As a consequence, the use of aerogel for insulating windows may not be advantageous.

7. Comparison of finishing types

The comparison of alternative finishing types for the facades of the Myhrerenga Borettslag is presented in this section. The variation of the finishing type is assessed by changing the glazing ratio of the East and West facades of the building. The first set of data shows the results of the building energy demand of the retrofitting alternatives with the 24%, 33%, and 50% glazing ratios. The variation of the finishing type is not considered in the energy analysis because it is assumed that the finishing layer has no influence on the building energy demand. The second set of data presents the greenhouse gas emissions from the comparison of five alternatives for façade finishing: cement tiles, untreated wood, copper impregnated wood, insulated sandwich panels, and polymer-cement tiles. A sensitivity analysis estimates the emissions due to the variation of the maintenance cycle of the building materials. This variation is assessed by first setting the building lifetime to 25 years, and then by extending the building lifetime to 75 years. In each group of analyses the greenhouse gas emissions of the various alternatives are calculated for the three different kWh-to-CO_2 conversion factors.

7.1. Objective

The objective of the work is to compare and assess the lifecycle emissions from the use of five different finishing types applied to the East and West façades. The U-value of the external facades of each of the retrofitting alternative is set to 0.10 $Wm^{-2}K^{-1}$, the insulation material used is mineral wool, and the glazing ratios are 24%, 33%, and 50%. The variation of the façade glazing ratio is aimed at understanding the influence on the total building emissions of the relationship between the opaque and the transparent parts of the façade. The facades equipped with cement tiles and polymer cement tiles are coated with 0.1 mm of paint. The facades with copper impregnated wood cladding are coated with a layer of wood preservative. The facades with either the untreated wood cladding or the insulated sandwich panels do not have any paint coating. The insulated sandwich panels consist of a mineral-wool layer enclosed by two layers of zinc-coated steel sheets [78]. Considering that the thermal transmittance of these panels (0.039 $Wm^{-1}k^{-1}$) is higher than the thermal transmittance of mineral wool (0.034 $Wm^{-1}K^{-1}$), their thickness is set to 300 mm in order to equalize the insulation level of the façade with the 250-mm-thick mineral-wool layer (0.10 $Wm^{-2}K^{-1}$). The use of different finishing types has as a consequence the use of different maintenance cycles of the façade's outermost layer. As seen in the previous analyses, the emissions given by the replacement of materials has an effect on the building's lifecycle emissions, depending on the electricity-to-emissions conversion factor. This is because the use of the different conversion factors gives different shares of the emissions for building operation. It is interesting, then, to estimate the influence of the use of different finishing materials on the building's lifecycle emissions when varying the conversion factor. The reference kWh-to-CO_2 conversion factor of the power grid is based on the model developed at the Research Centre on Zero Emission Buildings

(ZEB), and this is compared to the EU average value and the Norwegian energy mix at inland production. The reference lifetime retrofitting alternatives is set to 50 years. The maintenance cycle for the building components is taken from [86] and is set to a long rate of replacement. Details of the maintenance cycles for the different building components are presented in Table III- b in Appendix III.

Since the outermost layer of a façade is strongly prone to deteriorate due to the temperature, humidity, and insolation cycles, it is replaced relatively frequently in order to maintain its pristine technical and aesthetical characteristics. The report by SINTEF Byggforsk *Intervaller for vedlikehold og utskifting av bygningsdeler* sets short, medium, and long replacement rates for commonly used materials in buildings in Norway [86]. Each rate of replacement relates to a combination of material technical characteristic and weather stress. A short maintenance rate corresponds to low technical quality of the materials and strong or medium weather stress, while a long maintenance rate corresponds to a high technical quality of the materials and little or medium weather stress. The sensitivity analysis is aimed at defining to what extent the variation of both the maintenance schedule of the building materials and the service life of the building influence the total emissions. For this reason, the reference lifetime is reduced to 25 years, and the long and short maintenance cycles are compared. This shows the effect on the total emissions when materials with a shorter service life are installed. Secondly, the building lifetime is extended to 75 years, and the long and short maintenance cycles are compared. The variation of the building lifetime influences the total emissions of the building because the embodied emissions from the installation of the components and their replacement rate vary accordingly. By lengthening the building lifetime to 75 years or shortening it to 25 years, it is possible to see what is the share of the embodied emissions in the total emissions and how it varies. The emissions due to building operation of the different retrofitting alternatives is calculated by applying the three electricity-to-emissions conversion factors, as explained above.

Details of the East and West façade constructions with the different finishing types are presented in Table II- f in Appendix II.

7.2. Energy use and lifecycle emissions

The variation of the finishing type is not considered when calculating the building energy demand, because it is assumed that the outermost layer of the façade does not affect the energy flow through the wall construction. The energy use for building operation is dependent only on the variation of the glazing ratio of the façade. As a consequence, the results of this analysis refer to the alternative with mineral wool insulation, triple glazing with argon windows and 24%, 33%, and 50% glazing ratios, shown in Figure 39.

Figure 47 presents the results of the emissions of the five finishing alternatives for the 50-year building service life and the long maintenance schedule. The emissions are calculated for the average European, the ZEB, and the Norwegian electricity-to-emission conversion factors. Considering the alternatives with the European conversion factor, the share of the embodied emissions (*EE* and *M+EOL*) is limited to an average of 6%. As a consequence, the differences between any of the finishing type are approximately 1%, regardless of the glazing ratio. The alternatives with a higher glazing ratio have higher emissions, as a consequence of the increasing emissions of the building operation phase (*BOP*). The difference between the total emissions of any of the alternatives with the 50% glazing ratio and any of the alternatives with the 24% glazing ratio is approximately 7%.

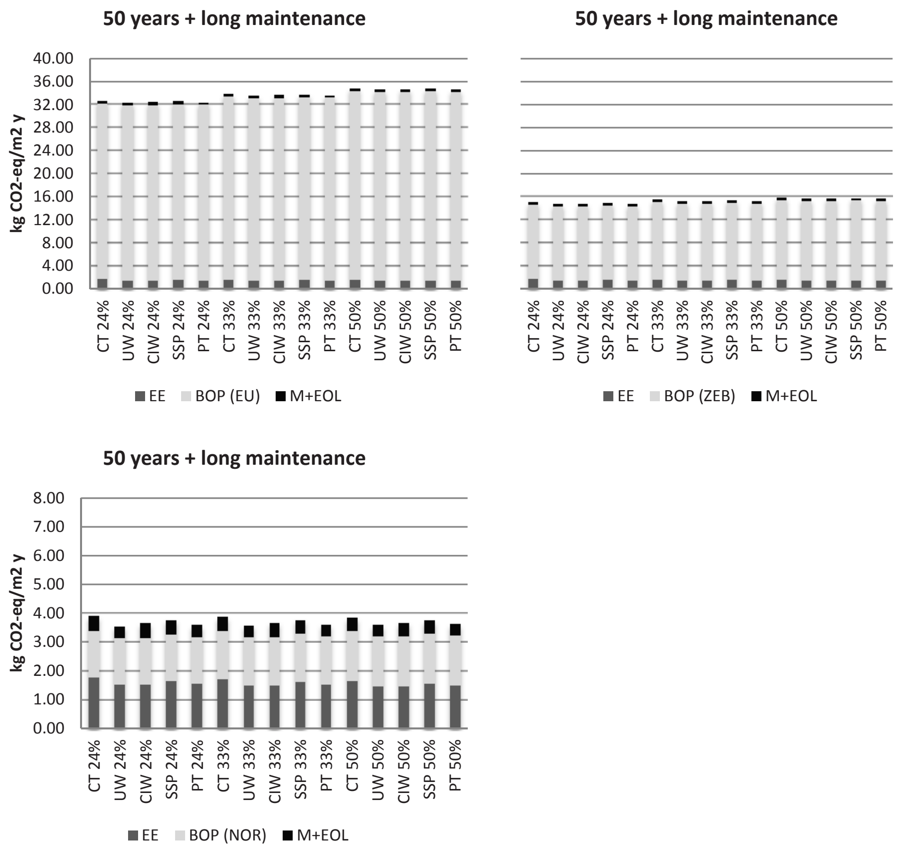


Figure 47. CO_2 emissions for finishing alternatives for the 50-year lifetime and long maintenance scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile.

When using the ZEB energy mix, the share of the embodied emissions is on average 13% of the total for all the alternatives, and the share of the replacement and disposal of the building materials (*M+EOL*) is on average 3% of the total emissions.

For these reasons, the maximum difference in emissions between different finishing types is 2.5%. This is between the *UW 24%* (untreated wood) and the *CT 24%* (cement tiles) alternatives. It is worth noticing that this difference is 1.5% when considering the same alternatives with the 50% glazing ratio. Because the share of the embodied emissions in the alternatives when using the ZEB conversion factor is twice that of the alternatives when using the EU conversion factor, the difference between alternatives with 50% and 24% glazing ratios is 6% for any of the alternatives.

The use of the Norwegian conversion factor increases the share of the embodied emissions for all the alternatives and is on average 55% of the total. As a consequence, the difference in total emissions between the alternatives with different finishing types increases. Assuming the total emissions of the *CT 24%* (cement tiles) as a reference, the *UW 24%* (untreated wood), the *CIW 24%* (copper impregnated wood), the *SSP 24%* (insulated sandwich panels), and the *PT 24%* (polymer-cement tiles) alternatives emit 90.8%, 94.0%, 95.7%, and 92.1% of this, respectively. These differences decrease to 93.5%, 95.7%, 96.8%, and 94.5% for the same alternatives with the 50% glazing ratio.

All the retrofitting alternatives have a variation in total emissions less than 1% when increasing the glazing ratio. This is due to the fact that the emissions because of the increasing energy use for space heating are counterbalanced by the total embodied emissions, regardless of the finishing type and the glazing ratio. This shows that the choice of conversion factor largely influences the differences in total emissions for different finishing types. A conversion factor that credits higher shares of emissions to the energy use for operation does not result in substantial differences between any of the finishing types. On the other hand, a conversion factor that credits higher shares of emissions to the building's embodied energy results in differences up to 9%.

7.3. Sensitivity analysis: 25-year lifetime and variation of maintenance cycle

Figure 48 shows the total emissions of the retrofitting alternatives for the 25-year lifetime, the long and short maintenance schedule, and for the three conversion factors. In the 25-year lifetime the embodied emissions (*EE*) have a share which is twice that of the share of the embodied emissions in the 50-year lifetime. On the other hand, the emissions of the materials replacement and disposal phases (*M+EOL*) have much less influence than in the 50-year lifetime. When using the European conversion factor, the average total embodied emissions (*EE* and *M+EOL*) are 10.2% and 11.3% for all the alternatives, with the long and the short maintenance scenarios, respectively. As a consequence, the maximum difference between the alternative with cement tile and the alternative with untreated wood is 2%, regardless of the glazing ratio and the maintenance cycle. Similarly, the difference between the 24% and 50% glazing ratios is 6% for any of the finishing alternatives. This shows that when using the European conversion factor, using different building lifetimes and different maintenance cycles does not influence the total emissions, as also shown in the previous case.

The use of the ZEB conversion factor produces results that are very similar to the ones with the EU conversion factor. This is, as mentioned before, due to the fact that the calculation of the emissions with the ZEB factor is time dependent and favours the alternatives with a long service life. The average total emissions for the alternatives when using the EU factor are approximately 35.4 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$, regardless of the maintenance schedule. These are 30.5 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ on average for the same alternatives when using the ZEB factor, regardless of the maintenance schedule. This shows that with both the EU and the ZEB conversion factors, the alternatives with different finishing types do not differ very much in total emissions. Similar results are given when using either the EU or the ZEB factors with the 50-year lifetime and the long maintenance schedule.

When using the Norwegian conversion factor and the long maintenance schedule, the share of the initial embodied emissions (*EE*) is on average 60% of the total, and the share of the embodied emissions of the *M+EOL* phase is on average 8.6% of the total. As a consequence, the alternatives which use a greener finishing type (such as untreated wood) result in reduced emissions. These are almost 10% lower than the emissions for the alternatives with cement tiles.

Assuming the total emissions of the *CT 24%* alternative as reference, the alternatives named *UW 24%*, *CIW 24%*, *SSP 24%*, and *PT 24%* are 9.8%, 7.6%, 3.0%, and 8.3% lower, respectively. These reductions decrease to 7%, 5.4%, 2.4%, and 6% for the same alternatives with the 50% glazing ratio. When the short maintenance schedule is applied, the variation between the emissions due to the use of different finishing types increases for the alternatives with the same glazing ratio. The total emissions of the alternative with the 24% glazing ratio and untreated wood (*UW*) are 12.5% lower than for the alternative with the 24% glazing ratio and cement tiles (*CT*). This difference decreases to 9% when these two finishing alternatives with the 50% glazing ratio are compared. It is worth noticing that the use of copper impregnated wood (*CIW*) and insulated sandwich panels (*SSP*) produces very similar results, regardless of the glazing ratio. These correspond to an approximate difference of 6.5% when these two alternatives with the 24% glazing ratio are compared with the *CT 24%*. The alternative with polymer-cement tiles (*PT*) is always the second best option, regardless of the glazing ratio. When increasing the glazing ratio, the alternatives with the same finishing type do not differ very much in total emissions.

It is worth noticing that the variation of the maintenance cycle has more influence on the total emissions when the used finishing type needs a frequent maintenance, such as the copper impregnated wood cladding. For the long maintenance cycle, the total emissions of the alternative *CIW 24%* are approximately 4.5% lower than those of the alternative *SSP 24%*. This difference is eliminated when comparing the same alternatives with the short maintenance schedule. It shows that the variation of the maintenance schedule has some effect on the emissions of the different alternatives when the Norwegian conversion factor is used and the building lifetime is set to 25 years. The extent of this variation is dependent on the finishing type used.

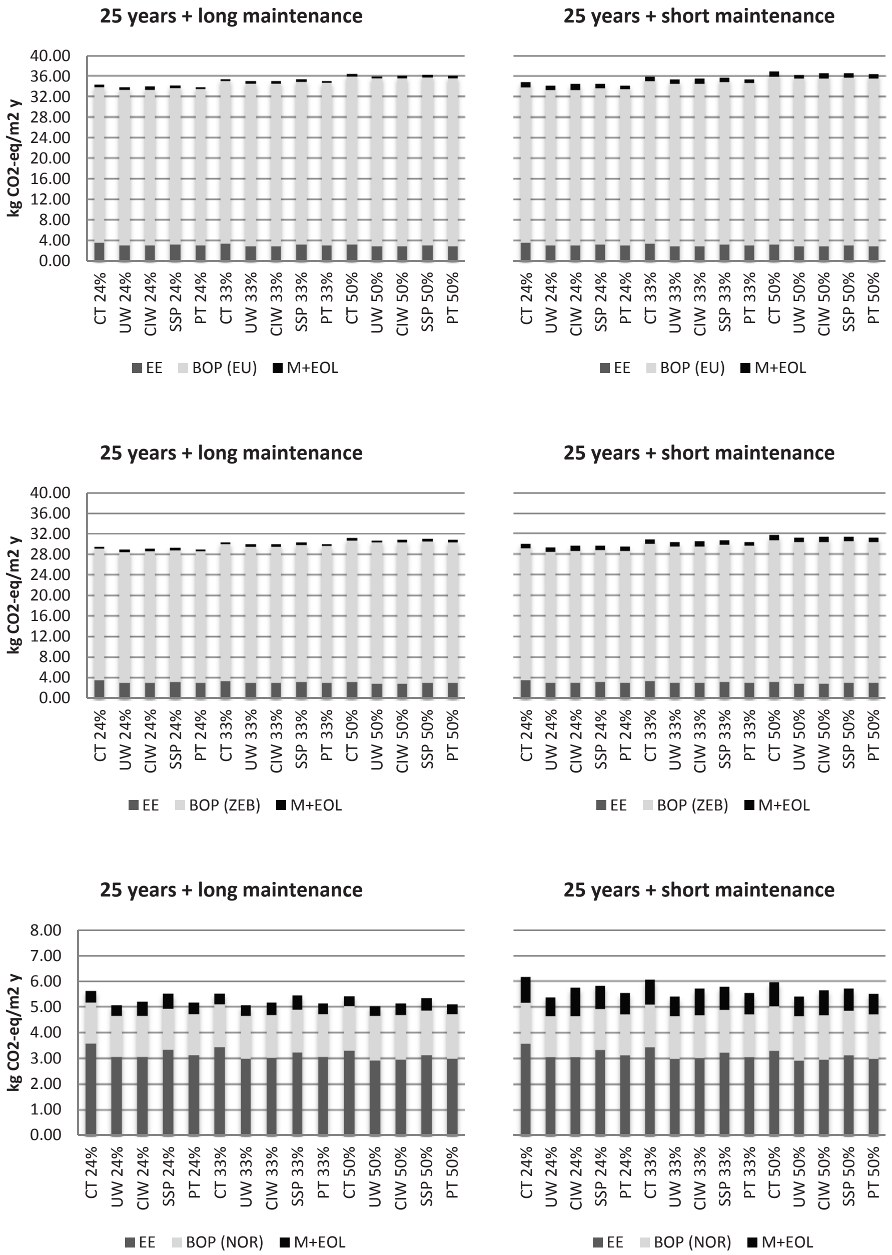


Figure 48. CO_2 emissions for finishing alternatives for the 25-year lifetime, and long and short maintenance scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile.

7.4. Sensitivity analysis: 75-year lifetime and variation of maintenance schedule

Figure 49 shows the total emissions of the retrofitting alternatives for the 75-year lifetime, the long and short maintenance cycles, and for the three conversion factors. This differs from the case of the 25-year building service life, as the share of the initial embodied emissions (*EE*) here is minimal, and as the share of the embodied emissions due to the maintenance and disposal phases (*M+EOL*) gains importance. It is expected, then, that the alternatives with the finishing types that needs frequent maintenance have higher total emissions. When using the European conversion factor, the average share of the emissions for building operation phase (*BOP*) is 95.2% for the long maintenance cycle and 92.9% for the short maintenance cycle. As a consequence, the influence of the embodied emissions is so small than any variation in finishing type does not substantially modify the total emissions. As a matter of fact, the difference between the total emissions of any of the alternatives is less than 1%, regardless of the glazing ratio and the maintenance cycle. The retrofits with the highest glazing ratio have on average 7% higher emissions that the retrofits with the lowest glazing ratio.

Since the calculation of the ZEB conversion factor is time-dependent, the resulting emissions of the building operation phase tend to diminish with longer lifetimes. However, this is also the case for the embodied emissions, because these are spread over a longer period of time. As a consequence, the relative differences in emissions between the finishing alternatives are similar for the cases with 25-year and 50-year lifetimes for the long maintenance cycle.

When using the short maintenance cycle, the differences in total emissions between the alternative finishing types tend to increase when the lifetime increases. Assuming the *CT 24%* retrofit (cement tile) as a reference, the *UW 24%* retrofit (untreated wood) emits 93.1% of that (95.1% in the 50-year lifetime and 97.4% in the 25-year lifetime), and is the best alternative. As in the previous examples, the increase in glazing ratio tends to reduce the differences in emissions between the various finishing types. Comparing the same retrofits as above and increasing the glazing ratio to 50%, their relative difference decreases to 4.6%. The second best alternative is the one with polymer-cement tiles (*PT*), which emits 94.2% for the 24% glazing ratio and 96.2% for the 50% glazing ratio. The alternatives with copper impregnated wood and sandwich panels show very similar results. These are approximately 96.5% for the 24% glazing ratio and 97.6% for the 50% glazing ratio. As seen in the cases with the 25-year lifetime, increasing the maintenance schedule causes the alternative with the copper impregnated wood to lose its advantage in comparison to the sandwich-panel finishing.

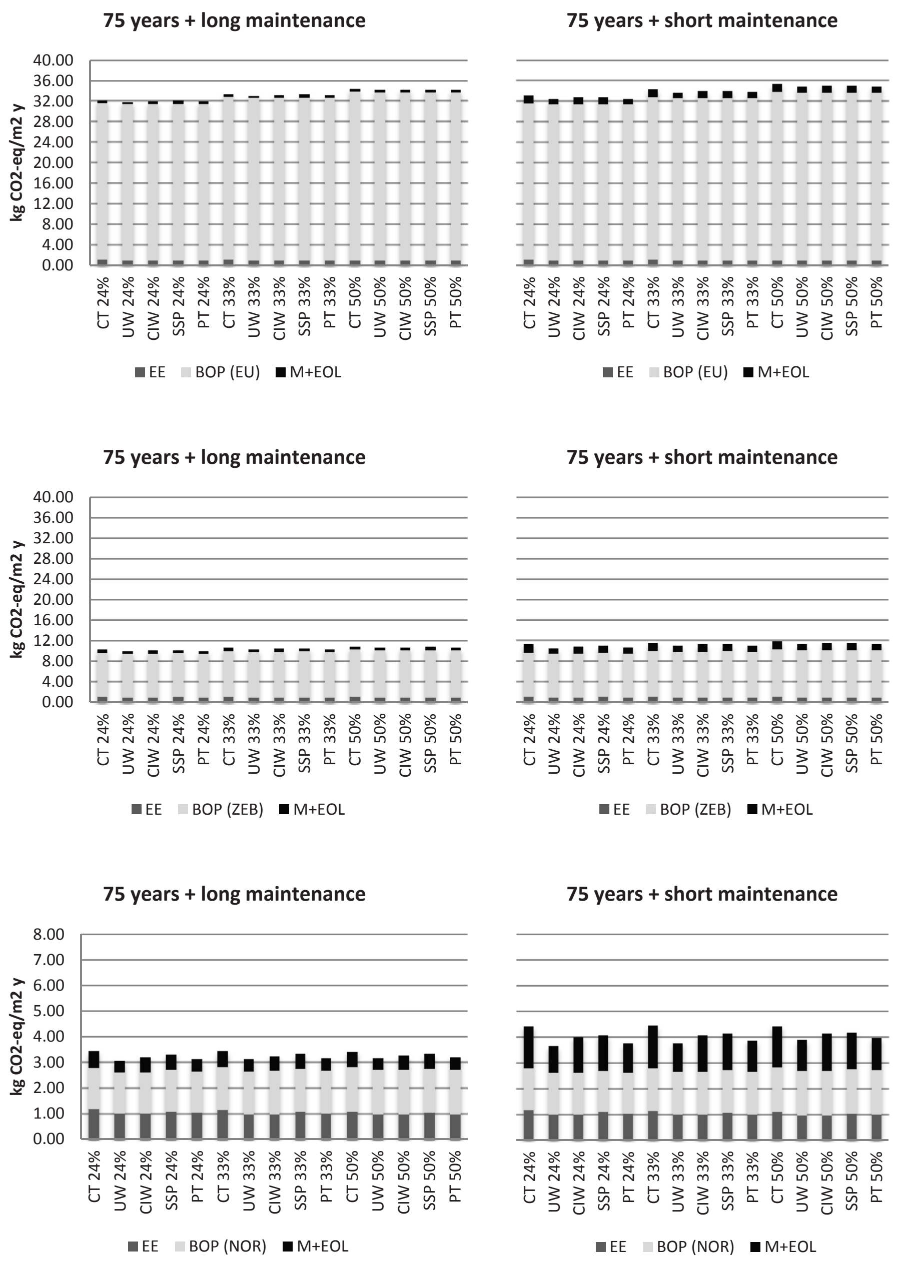


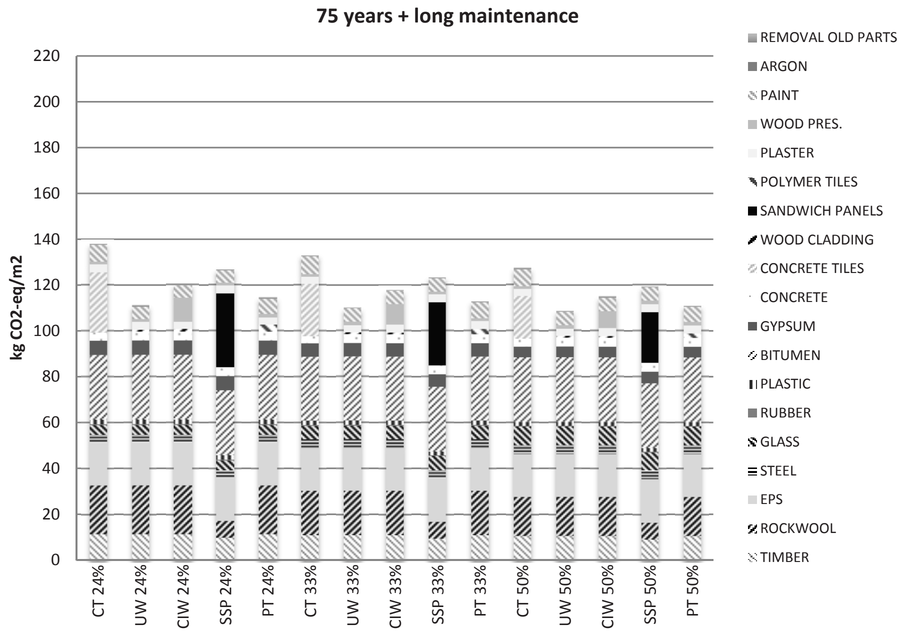
Figure 49. CO_2 emissions for finishing alternatives for the 75-year lifetime, and long and short maintenance scenario. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European average energy mix (BOP EU), the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile.

As seen in Figure 48, the use of the Norwegian conversion factor drastically reduces the emissions due to the building operation phase (*BOP*). As a consequence, the share of the embodied emissions rises accordingly. However, this differs from the alternatives with the 25-year lifetime in that the share of the embodied emissions (*EE*) and the share of the embodied emissions of the phases of material replacement and disposal (*M+EOL*) here are almost the same. For this reason, the variation of the maintenance cycle has considerable effects on the total emissions. When examining the alternatives with the long maintenance cycle, the average shares of emissions are 32% for the *EE* phase, 51% for the *BOP* phase, and 17% for the *M+EOL* phase. Assuming the alternative with cement tile and 24% glazing (*CT 24%*) as a reference, the *UW 24%*, *CIW 24%*, *SSP 24%*, and *PT 24%* alternatives emit 89.5%, 93.1%, 95.6%, and 90.9%, respectively. For the same alternatives with the 50% glazing ratio, their values when compared to the *CT 50%* retrofit are 92.7%, 95.2%, 96.9%, and 93.6%, respectively. This shows that both the polymer-cement finishing (*PT*) and the untreated wood (*UW*) have similar emissions, regardless of the glazing ratio used. The use of copper impregnated wood (*CIW*) has results that are just 2% lower than the ones using sandwich panels (*SSP*), despite the fact that by using this last finishing type, the whole insulation layer (a 300-mm-thick mineral wool panel) has to be removed during maintenance. The average total emissions of all the alternatives are 3.3 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$, and there is no noticeable increase in emissions for any of the retrofitting alternatives when increasing the glazing ratio. Therefore, any glazing ratio can be chosen since this does not influence the final result when using the NOR conversion factor.

When applying the short maintenance cycle and the NOR factor, the share of emissions of the *M+EOL* phase rises accordingly. In this case the average shares of emissions are 26% for the *EE* phase, 41% for the *BOP* phase, and 33% for the *M+EOL* phase. Assuming the total emissions of the *CT 24%* alternative as a reference, the alternative with untreated wood (*UW 24%*) emits 82.4%, with copper impregnated wood (*CIW 24%*) 90.5%, with sandwich panels (*SSP 24%*) 91.8%, and with polymer-cement tiles (*PT 24%*) is 85.2%. This shows that by increasing the replacement rate of materials, the difference between the use of any of the finishing types increases. As a matter of fact, the use of untreated wood and the short maintenance cycle reduces the emissions 7% more than with the long maintenance cycle. Assuming the *CT 50%* alternative as reference, the *UW 50%* retrofit emits 87.8%, the *CIW 50%* retrofit 93.4%, the *SSP 50%* retrofit 94.2%, and the *PT 50%* retrofit 89.7%. This shows that by increasing the glazing ratio the differences between the alternatives decrease and results in similar values for the total emissions of the retrofits with the untreated wood and the sandwich panel finishing. The average total emissions of all the alternatives are 4.1 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$, which are more than 1.2 times the total average emissions of the alternatives with the long maintenance cycle. The embodied emissions of the *M+EOL* phase for the *CT 24%* alternative are 1.65 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the short maintenance schedule and 0.65 $kgCO_{2\text{-}eq}m^{-2}y^{-1}$ for the long maintenance schedule. This means that by shortening the substitution rate of the materials, their emissions for this phase increase by 2.5 times.

Figure 50 shows the compositions of the embodied emissions (*EE* and *M+EOL*) of the retrofitting alternatives with the different finishing types for the 75-year lifetime. The results for the alternatives with the 25-year and the 50-year building lifetimes are not presented because they do not add any significant information. For the alternatives with the long maintenance schedule and the 24% glazing ratio, the finishing types that have significant shares are the concrete tiles (19.1%) and the sandwich panels (25.3%). The other finishing types have shares that are below 2.5%. In the *CT 24%* alternative, the emissions are 26.4 $kgCO_{2\text{-}eq}m^{-2}$ for the concrete tiles and 7.6 $kgCO_{2\text{-}eq}m^{-2}$ for the paint, while in the *SSP 24%* alternative the emissions for the sandwich panels are 32.2 $kgCO_{2\text{-}eq}m^{-2}$ and for paint 5.5 $kgCO_{2\text{-}eq}m^{-2}$. It is worth noticing that the use of sandwich panels does not require external paint, and the panels themselves substitute the mineral wool layer of the other alternatives. For this reason, the alternatives with sandwich panels always have lower emissions than the alternatives with concrete tiles, regardless of the glazing ratio. The alternatives with the untreated wood (*UW*) is the greenest option, regardless of the glazing ratio, because the embodied emissions of the wood cladding are maximum 0.8 $kgCO_{2\text{-}eq}m^{-2}$, and there is no paint layer. In the alternatives with copper impregnated wood, the embodied emissions of the finishing layer are maximum 1.0 $kgCO_{2\text{-}eq}m^{-2}$. However, the use of wood preservative increases the total emissions by 10.2 $kgCO_{2\text{-}eq}m^{-2}$ in the alternative with 24% glazing ratio and makes this finishing type less advantageous than the polymer-cement tiles, which has approximately 6 $kgCO_{2\text{-}eq}m^{-2}$ lower emissions.

When increasing the glazing ratio, the total embodied emissions tend to diminish or remain stable, depending on the finishing type used. Comparing the *CT 24%* and *CT 50%* alternatives there is an 8% difference. Comparing the *UW 24%* and *UW 50%* alternatives there is a 2% difference. This is because with the concrete-tile finishing type 1 m^2 of opaque surface has higher embodied emissions than 1 m^2 of transparent surface on the same facades. With the untreated-wood finishing type, the opaque and transparent parts of the facades have the same emissions per unit of surface. When increasing the replacement rate of the building materials, the total embodied emissions increase accordingly, regardless of the alternative. The embodied emissions increase by 1.5 times for the alternatives with the 24% glazing ratio and the concrete-tile finishing, and 1.4 times for the alternatives with untreated wood and the same glazing ratio. In the *CT 24%* alternative the sum of the embodied emissions of the concrete tiles (52.9 $kgCO_{2\text{-}eq}m^{-2}$) and paint (20.3 $kgCO_{2\text{-}eq}m^{-2}$) corresponds to 36% of the total. On the other hand, in the *UW 24%* alternative the sum of the embodied emissions of the wood cladding (1.2 $kgCO_{2\text{-}eq}m^{-2}$) and paint (11.6 $kgCO_{2\text{-}eq}m^{-2}$) corresponds to 9% of the total.



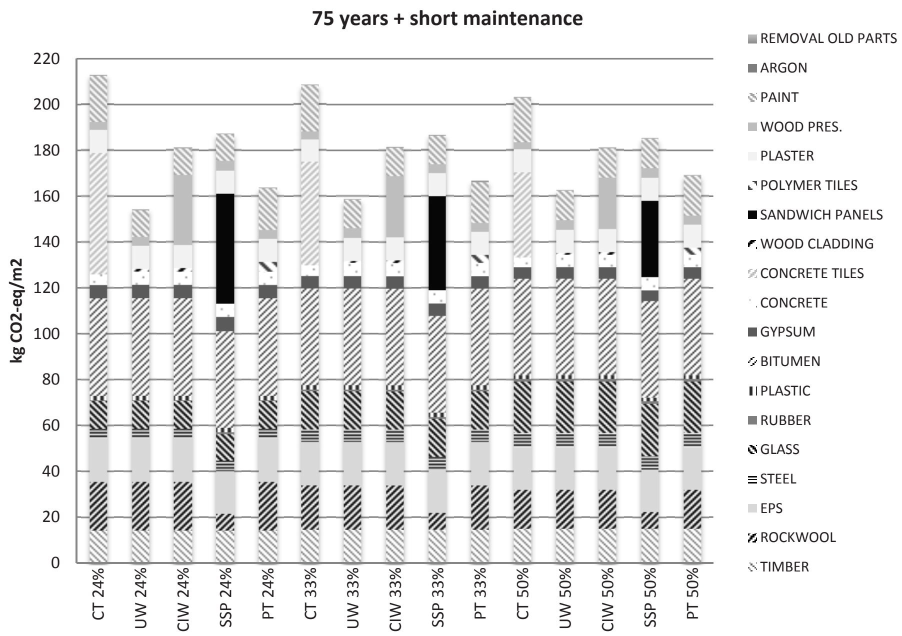


Figure 50. Composition of embodied CO_2 emissions for the materials used in the retrofitting alternatives for the 75-year lifetime, and short and long maintenance scenarios. All values are normalized to 1 m² of heated building area. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile.

The use of sandwich panels and copper impregnated wood have the same results, which is approximately 183 $kgCO_{2\text{-}eq}m^{-2}$. This is because the savings achieved by using wood cladding are overturned by the massive use of wood preservative, which takes up to 17% of the total emissions. In this regard, the retrofit with the polymer-cement tiles has much lower emissions (163.8 $kgCO_{2\text{-}eq}m^{-2}$) than these two alternatives. A comparison of the alternatives with the same finishing type and increasing glazing ratios shows that the retrofits with concrete tiles (*CT*), copper impregnated wood (*CIW*), and sandwich panels (*SSP*), have emissions that tend to decrease (5% difference). On the other hand, the emissions of the alternatives with untreated wood (*UW*) and polymer-cement tiles (*PT*) increase when the glazing ratio increases (up to 5%). This is because, in these last two cases, the replacement of the windows results in more emissions than the replacement of the finishing on the opaque parts. The variation of the maintenance cycle also influences the mutual relationships between the different finishing alternatives. With the long maintenance, the *CT 24%* alternative has 1.2 times higher emissions than the *UW 24%* alternative. This difference increases to 1.4 times with the short maintenance schedule.

7.5. Discussion and conclusions

This work presents the results of the greenhouse gas analysis of five finishing type alternatives applied to the external East and West facades of the residential building. The finishing types are concrete tiling, untreated wood cladding, copper impregnated wood cladding, mineral-wool-insulated sandwich panelling, and polymer-cement tiling. The glazing ratio of the façades is varied from 24% to 33% and 50%. The maintenance cycle and the building lifetime are varied in order to estimate the extent of the variation of the total emissions due to the use of the different finishing alternatives. The building lifetimes used are 25 year, 50 years and 75 years, and long and short maintenance cycles of the building materials are considered. The different electricity-to-emissions conversion factors are used to evaluate the total emissions for each alternative.

The results from the energy analysis show that by increasing the glazing ratio the total building energy use increases by 7%. On the other hand, when analysing the greenhouse gas emissions of the same alternatives, the results present a less clear picture. Using the EU conversion factor the results presented in energy analysis do not change. The alternatives with a higher glazing ratio have higher emissions, and the use of different finishing types does not alter this picture. Moreover, in terms of total emissions, the variation of the building lifetime and of the maintenance cycle has no influence on the choice of finishing type, regardless of the glazing ratio.

Using the ZEB conversion factor results in emissions that are dependent on the building lifetime. Considering the time-dependency of the calculation of the emissions for the ZEB conversion factor, both the emissions due to the building operation phase and the embodied emissions decrease for increasing building lifetimes. The relative contribution of the embodied emissions tends to slowly increase for longer lifetimes. As a consequence, the advantage of one or another finishing type depends on the building lifetime used. For the 25-year building lifetime, the distribution of the total emissions of the alternatives are very similar to the results given by the use of the EU conversion factor, regardless of the finishing type and the maintenance schedule. For the 50-year lifetime the difference in total emissions between the uses of alternative finishing types is maximum 2.5%. This difference increases to 3.5% when using the 75-year lifetime. By applying the short maintenance schedule this difference increases to 7%.

In conclusion, when using the ZEB conversion factor, the use of untreated wood appears to be better only when the building lifetime is set to 75 years and the maintenance cycle is short. This implies that in the case of materials with low technical quality and high weather stress the choice of finishing layer has some effect on the total emissions. For all the other combinations of building lifetimes and maintenance cycles, the choice of finishing type does not noticeably influence the total emissions. In conclusion, it is not possible to determine a clear choice for finishing and glazing ratios when using the ZEB conversion factor, because the results are strongly dependent on the building lifetime.

When using the Norwegian conversion factor, the share of emissions of the building operation phase is maximum 50% of the total. For this reason, when the glazing ratio is increased, the resulting emissions from building operation do not significantly influence the total emissions. However, the balance of the embodied emissions between the transparent and the opaque parts of the façade is dependent on the finishing type, the building lifetime, and the maintenance cycle used. For this reason, the alternatives with both increasing glazing ratios and building lifetimes tend to have up to 3% higher emissions when the untreated wood cladding or the polymer-tiles are used, in the case of a long maintenance cycle. This trend increases when the short maintenance cycle is applied and results in a difference of 6% between the 24% and the 50% glazing ratios for the untreated wood finishing type. This is due to the increasing emissions from the frequent replacement of the windows. Moreover, the differences between the different finishing types are significant (up to 12%), especially when a low-embodied-emissions material, such as the untreated wood, is used together with a 24% glazing ratio. In conclusion, the use of the Norwegian conversion factor eliminates the differences in building energy demand due to the different glazing ratios but increases the differences between the uses of alternative finishing types.

There are some aspects of this work that have not been considered in the calculation and are worth noticing. The emissions due to transporting workers to the building site during the maintenance phase of the building components has not been included in the calculation due to lack of data. Clearly, in addition to a higher substitution rate, this factor can be critical and is extremely dependent on which finishing type is used. For instance, a finishing that requires a coating layer, such as paint or a wood preservative, would result in higher emissions (due to more frequent transportation of workers) than a finishing that does not need any coating, such as steel sheeting or ceramic tiling. In conclusion, it is difficult to decide what is the best choice among the proposed retrofitting alternatives because the use of different conversion factors produces different results.

8. Comparison of balconies types

The comparison of the use of alternative balcony types for the facades of the Myhrerenga Borettslag is presented in this section. The results from the analysis of the different retrofitting alternatives are normalized to 1 m^2 of heated building area per year. The variation of balcony types is assessed by changing the glazing ratio of the East and West facades of the building. This is because, when increasing the glazing ratio the use of glazed doors on the facades becomes possible. The first set of data shows the results of the building energy demand of the balcony alternatives with the 24%, 33%, and 50% glazing ratios. The second set of data presents the greenhouse gas emissions from the comparison of alternatives for balconies.

The *B0* alternatives represent the use of balconies on the West façade with the 24%, 33%, and 50% glazing ratios. The *B1* alternatives represent the use of balconies on the West facade with the 24% glazing ratio and balconies on both the East and West facades with the 33% and 50% glazing ratio. In such a perspective, the *B0 24%* and *B1 24%* alternatives are identical. The *B2* alternatives represent the use of sunspaces on the West façade with the 24% glazing ratio and sunspaces on both the East and West facades with the 33% and 50% glazing ratio. A scheme of the different combinations of balconies, sunspaces and glazing ratios is found in Table II- g in Appendix II. The share of emissions due to the production of the materials for balconies and their maintenance is very small due to the fact that the amount of materials used in balconies is very small (less than 5%) compared to the amount of materials used in the facades and in the rest of the building. As a consequence, the CO_2 analysis is limited to the use of the 75-year lifetime and the short maintenance cycle. Any other combination of building lifetime and maintenance cycle would give results that do not significantly change the building lifecycle emissions. The maintenance cycle for the building components is taken from [86], and details of the maintenance cycles for the different building components are found in Table III- b in Appendix III. As in the previous analyses, the emissions for building operation are calculated using different electricity-to-emissions conversion factor. This is because the use of sunspaces is expected to give lower energy use for space heating than that of the alternatives with normal open balconies. It is interesting, then, to see how using different conversion factors influences the energy savings given by substituting the normal balconies with sunspaces. The reference kWh-to-CO_2 conversion factor of the power grid is based on the model developed at the Research Centre on Zero Emission Buildings (ZEB), and this is compared to the EU average value and the Norwegian energy mix at inland production.

8.1. Energy and greenhouse gas emissions

In Figure 51 the yearly energy demands of the use of the alternative balcony options are shown. The use of balconies in both the East and West facades (*B1* alternatives) does not change the use of energy for space heating from that of the *B0* alternatives. The total energy demand of the alternatives with either the *B0* or the *B1* balcony options is the same. Substituting the balconies with sunspaces (*B2* alternatives) reduces the energy demand for space heating by 2.3% for the façade with the 24% glazing ratio. This difference increases to 2.9% for the 33% glazing ratio, and 3.4% for the 50% glazing ratio. These differences are due to the lower thermal losses of the windows and glazed doors adjacent to the sunspaces. The energy saving given by the use of sunspaces is approximately 2 kWhm^{-2}y^{-1}, regardless of the glazing ratio of the facades.

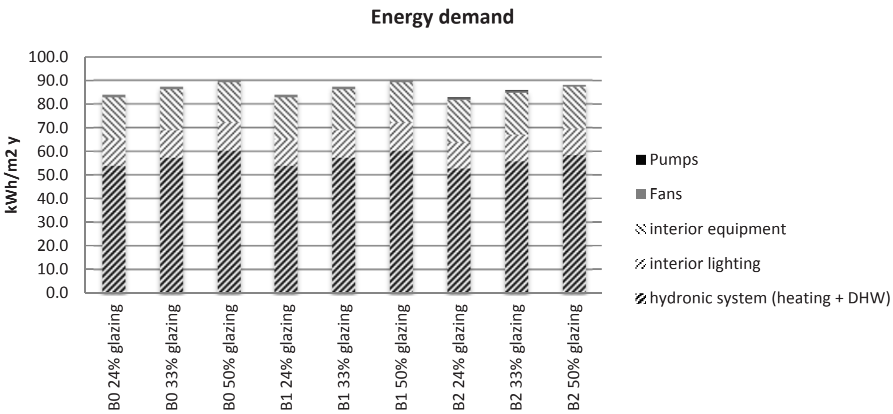


Figure 51. Composition of the yearly energy demand of the alternatives with three balcony alternatives and the 24%, 33%, and 50% glazing ratios. B0 is normal balconies on the West façade. B1 is normal balconies on both the East and West facades (in the 33% and the 50% glazing ratio). B2 is sunspaces on both the East and West façades (in the 33% and the 50% glazing ratios). Values are normalized to 1 m² of building heated area.

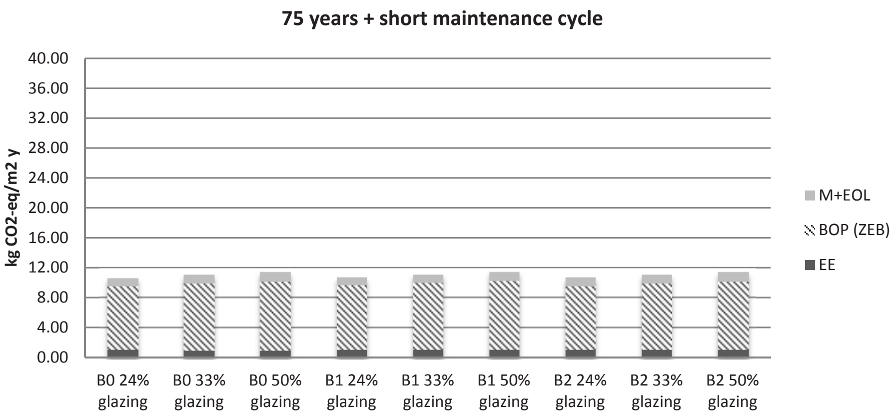


Figure 52. CO_2 emissions for balcony and glazing alternatives for the 75-year lifetime and short maintenance cycle. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m² of heated building area for 1 year. B0 is normal balconies on the West façade. B1 is normal balconies on both the East and West facades (in the 33% and the 50% glazing ratios). B2 is sunspaces on both the East and West facades (in the 33% and the 50% glazing ratios).

Figure 52 shows the lifecycle emissions of the use of alternative balcony options calculated with the ZEB conversion factor for a 75-year lifetime and a short maintenance cycle. The use of any balcony alternative does not significantly change the lifecycle emissions of the building. The *B1* alternatives have the highest variation, and it is limited to a 1% increase in total emissions, regardless of the glazing ratio.

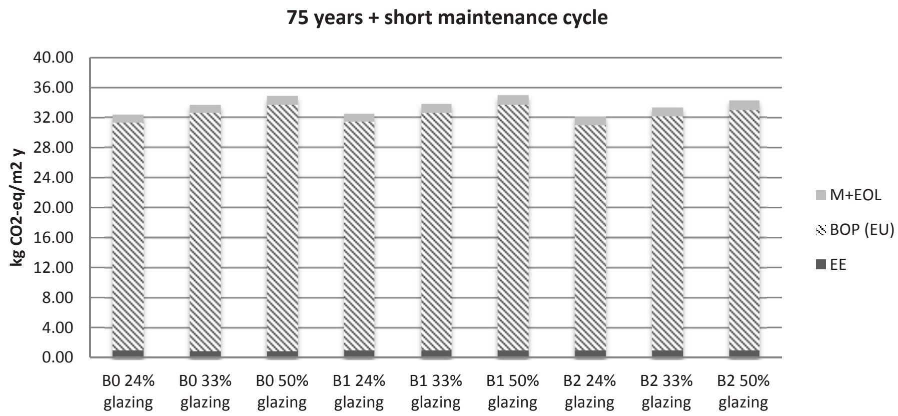


Figure 53. CO_2 emissions for balcony and glazing alternatives for the 75-year lifetime and short maintenance cycle. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the European average energy mix (BOP EU), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year. B0 is normal balconies on the West façade. B1 is normal balconies on both the East and West facades (in the 33% and the 50% glazing ratios). B2 is sunspaces on both the East and West facades (in the 33% and the 50% glazing ratios).

Figure 53 shows the lifecycle emissions of the alternative balcony options when using the EU conversion factor for a lifetime of 75 years and a short maintenance cycle. The lifecycle emissions of any of the retrofits with the same glazing ratio for the *B0* and the *B1* alternatives do not show any significant difference. The use of sunspaces (*B2* alternatives) reduces the total emissions by maximum 1.8% between the *B0 50% glazing* and the *B2 50% glazing* alternatives. This is due to the fact that when using the EU conversion factor the share of emissions for the building energy use is higher than that of the alternatives calculated with the ZEB conversion factor. This is 93% when using the EU factor and 80% when using the ZEB factor.

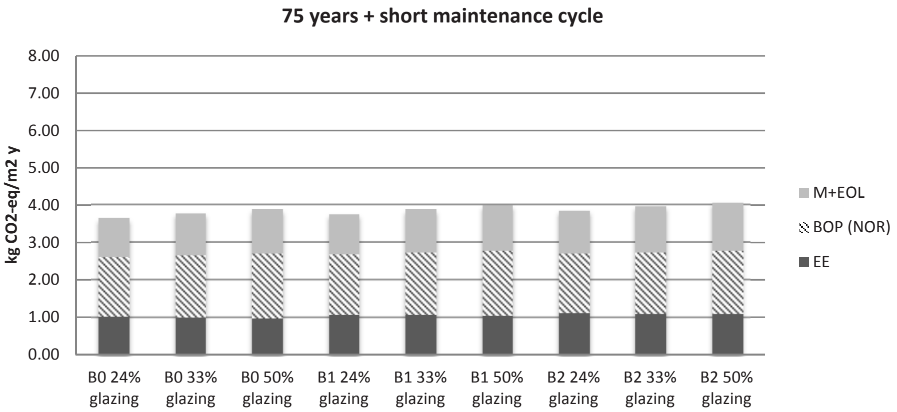


Figure 54. CO_2 emissions for balcony and glazing alternatives for the 75-year lifetime and short maintenance cycle. The bars show the initial embodied emissions (EE), the emissions from energy use for operation using the Norwegian energy mix (BOP NOR), and the emissions from the maintenance and substitution of building components and their end-of-life treatment (M+EOL). All values are normalized to 1 m^2 of heated building area for 1 year. B0 is normal balconies on the West façade. B1 is normal balconies on both the East and West facades (in the 33% and the 50% glazing ratios). B2 is sunspaces on both the East and West facades (in the 33% and the 50% glazing ratios).

Figure 54 shows the lifecycle emissions of the different balcony alternatives calculated with the NOR conversion factor for a 75-year lifetime and a short maintenance cycle. When having both balconies on the East and West facades, the difference from the *B0* alternatives is approximately a 3% increase in total emissions, regardless of the glazing ratio. When substituting the balconies with sunspaces, the lifecycle emissions of the alternative with the 24% glazing ratio are 5.3% higher than those of the *B0* alternative with the same glazing ratio. This difference decreases to 4.9% when the glazing ratio is 33%, and 4.5% when the glazing ratio is 50%. The *B2* alternatives have a higher mass of materials than that of the B0 alternatives. On the other hand, the *B2* alternatives have a lower energy use for space heating (and emissions) than that of the B0 alternatives. As a consequence, this last factor compensates for the higher embodied emissions of the *B2* alternatives and reduces their lifecycle emissions when the glazing ratio increases.

8.2. Conclusions

The calculation of the greenhouse gas emissions has been carried on by considering the worst case only: a lifetime of 75 years and a short maintenance scenario for the materials. Shorter lifetimes and longer maintenance scenarios give results in which the differences in lifecycle emissions between the uses of any of the alternative balcony options are not significant. For this reasons, such alternatives have not been considered in the calculation. In conclusion, the use of different balcony options does not significantly change the lifecycle emissions of any of the retrofitting alternatives. This is due to the very small amount of materials used in the balconies, compared to the amount of materials used in the retrofitting of the building. In terms of use of space, sunspaces have a higher degree of flexibility than that of simple balconies. This is because the glazing envelope of the sunspace can either be closed or open, which allow the building users to use the sunspace as an extension of the apartment in winter or as a normal balcony in summer. This flexibility of use adds also an economical value to the apartments because the area of the sunspace can be considered as part of the apartment itself. In such a perspective, the use of sunspaces is a favourable option in the energy retrofitting of apartment buildings. However, it might represent an economical drawback due to the use of a higher quantity of glazing.

9. Summary and conclusions

This research focused on the analysis of greenhouse gas emissions of several alternative retrofitting packages applied to an apartment building located in Oslo, the Myhrerenga Borettslag. The choice of retrofitting alternatives was based on comparing the current practice of energy retrofitting of apartment buildings with the use of different insulation materials, glazing ratios, windows, finishing, and balcony types.

The alternative insulation materials and glazing technologies are the measures applied when a technical approach to the energy retrofitting of a building is considered. These measures focus on the variation of the insulation values of the facades given by the use of materials with different thermal conductivities. The alternative glazing ratios, finishing types, and balcony types are the measures applied when an architectural approach is considered. These measures focus on the variation of the façade's appearance given by different combinations of glazing ratios, finishing, and balcony types.

The purpose was to investigate the effect that the combination of the above-described measures has on the lifecycle emissions of an apartment building. It was motivated by the fact that the current energy retrofitting practice is mostly aimed at reducing the energy use of the European building stock. On the other hand, the objective of the European 20-20-20 climate and energy target goes beyond the assessment of the energy use in the European building stock and includes a 20% reduction in EU greenhouse gas emissions from 1990 levels. However, the use of the greenhouse gas emissions as a metric for evaluating and comparing the interventions on the building stock is not yet common practice. It was therefore decided to analyze some possible energy retrofitting packages from the perspective of greenhouse gas emissions and to evaluate their effectiveness. The main research question was therefore:

> What are the lifecycle CO_2 emissions of a residential building when using alternative energy retrofitting measures?

This led to two sub-questions:

> To what extent is the use of advanced insulation materials advantageous in the energy retrofitting of apartment buildings?

> To what extent will the choice of architectural solutions for the façade's appearance affect the emissions of the building?

The first sub-question deals with the energy measures for residential buildings from a technical point of view. In such a perspective, the energy measures chosen are limited to the ones used to improve the insulation level of the building facades. The second sub-question deals with the visual aspects of the building facades and compares some possible changes of the appearance of the facades.

The components of the building's facades that are subject to change during an energy upgrade were consequently divided according to their relevance for either the technical or the architectural approach of investigation. In such a perspective, the different insulation materials and thicknesses used on the opaque part of the façade and the different glazing technologies are included in the technical approach. The insulation materials studied are mineral wool, vacuum insulation panels, and aerogel for the opaque part of the façade, and a triple-glazed window with argon and a double glazing with monolithic aerogel for the transparent part of the façade. The different façade glazing ratios (from 24% to 33% and 50%), the façade finishing (cement tile, untreated wood, copper impregnated wood, insulated sandwich panel with steel sheeting, and polymer-cement tile), and the balcony types (open balconies or attached sunspaces) are included in the architectural approach.

The above variables were combined in a matrix of the greenhouse gas emissions of possible retrofitting alternatives. In order to evaluate the effect of non-building-related variables on the results, three electricity-to-emissions conversion factors were introduced (European average, Norwegian inland production, and the conversion factor developed at the Research Centre on Zero Emission Buildings - ZEB). In addition, the building lifetime (25, 50 and 75 years) and the service life of the façade components (short, medium, and long) were varied for the same reasons.

The analysis of the greenhouse gas emissions of the proposed retrofitting alternatives showed that the conversion factor is critical and that results for each alternative will differ with different conversion factors. As a consequence, in this section the results will be listed separately for the different conversion factors in order to ease the comparison between the alternatives and to draw some final conclusions. First, the results given by using the EU conversion factor are summarized. Second, the results given by using the Norwegian conversion factor, and third the results given by using the ZEB factor are summarized.

Figures 55, 56, and 57 show graphs representing the $CO_{2\text{-eq}}$ emissions of the alternatives for the European, ZEB, and Norwegian electricity-to-emissions conversion factors, respectively. The $CO_{2\text{-eq}}$ emissions are calculated for the 75-years building lifetime and short maintenance. In all the three figures the alternatives of the architectural approach are on the X axis. The alternatives of the technical approach on the Y axis. The lifecycle emissions normalized to the reference building (= 100%) on the Z axis. 0.10, 0.15, and 0.18 are the U-values of the building's façade. AGN is triple glazing with argon, AGL is double glazing with aerogel. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios. 24%, 33%, and 50% are the façade glazing ratios.

9.1. The use of the EU conversion factor

When using the EU conversion factor the share of the emissions from energy use for building operation is maximum (90% and more of the total). As a consequence, any change in the energy use for space heating (such as by using a lower insulation value of the external walls or a higher glazing ratio for facades) has an effect on the lifecycle emissions. On the other hand, the share of the embodied emissions of the building materials and components has very little influence on the total lifecycle emissions of the building. As a consequence, using different types of insulation materials, of external finishing, or of balconies does not noticeably affect the lifecycle emissions. Similarly, the building lifetime and the maintenance cycle have very little influence, as shown in Figure 55.

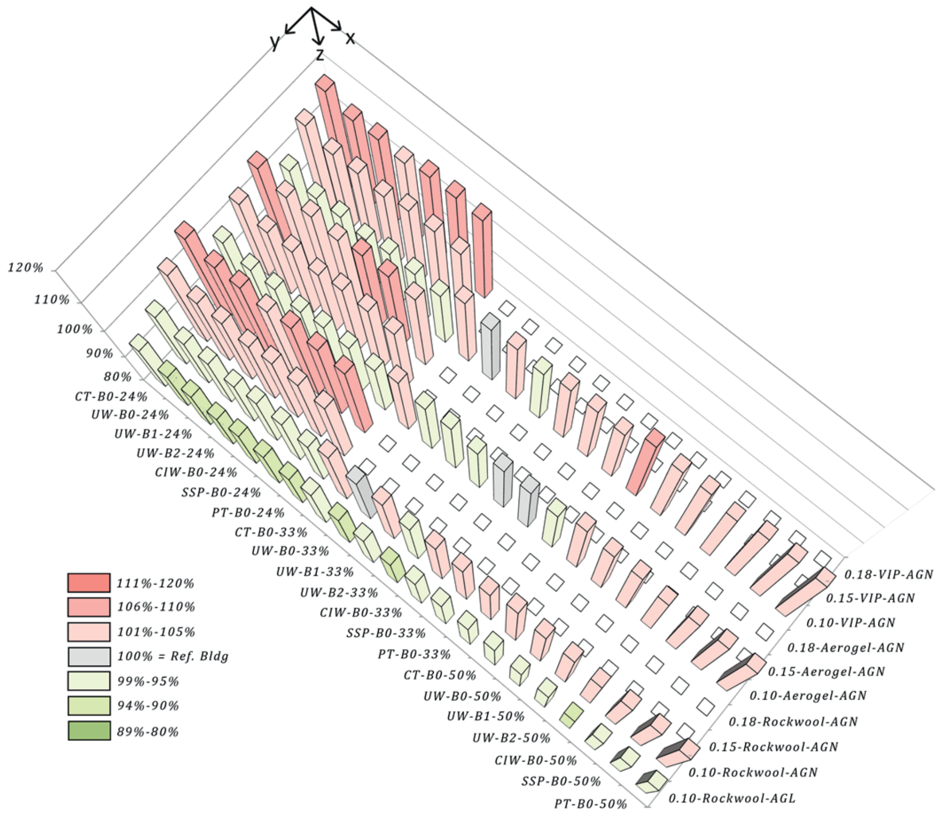


Figure 55. Matrix of the lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the EU factor for a 75-year lifetime and a short maintenance cycle.

Table IV- a and Table IV- b in Appendix IV show the lifecycle emissions of all the proposed alternatives normalized to the emissions of the reference buildings, for the 25-year and the 75-year lifetimes and the short maintenance cycle. From the tables it can be seen that the critical factors for the total emissions of the different alternatives are the choice of insulation thickness, of glazing ratio, and of glazing technology. The insulation type has only a little influence on the total emissions when the building lifetime is 25 years, as shown in Table IV- a.

In conclusion, an energy-retrofitting package should have a low façade glazing ratio, use super-insulated windows (such as glazing with aerogel), and have a thickness of the insulation layer sufficient to achieve a U-value of 0.12-0.10 $Wm^{-2}K^{-1}$, when using the EU factor. As stated above, the finishing type, the insulation type, and balcony type do not significantly influence the lifecycle emissions. In such a perspective, the economical cost and the service life of the insulation materials are more important than their embodied emissions. Considering that the cost of vacuum insulation panels and aerogel is higher than that of other, more conventional insulation materials, such as mineral wool and EPS [65, 97], it is clear that at present time these advance materials cannot compete with mineral wool. In addition, it must be noted that the high thermal resistance of VIP (4 $mWm^{-1}K^{-1}$) is for a vacuum and perfectly sealed panel. This increases to 8 $mWm^{-1}K^{-1}$ (the value used in this research) for a panel that is subject to an artificial process of "ageing" performed in laboratories. However, there is no clear evidence of the real performance of this material in a 75-year lifetime, and it is likely that the service life of VIPs is much shorter than that of mineral wool. This increases the total lifecycle emissions. Similarly, data on the emissions for the production of aerogel is based on very few literature references. It has been demonstrated that these emissions can increase by three times, depending on the production method used [90]. This will definitely have an impact on the lifecycle emissions of the alternatives with this insulation material.

The double glazing with monolithic aerogel is still at a prototyping stage, and there is no clear evidence that it will be introduced on the market as a commercial product. Monolithic aerogel is very fragile, due to the structure of the insulation, and most of the capability of this glazing of maintaining a high insulation value is due to the fact that the layer between the two glass panes is vacuumed. This implies that a durable sealing and a good handling of these windows is critical for maintaining their pristine thermal characteristics. For this reason, the use of this technology for normal operable windows in residential buildings has several limitations [76]. The use of other systems that have loose aerogel as insulation is not a very attractive option in residential buildings as they result in translucent and not transparent surfaces [98].

When considering the above limitations, one can say that the use of mineral wool and triple-glazed windows with argon is the best option for the energy upgrade of an apartment building in the Oslo area, when using the European conversion factor. With regard to the façade appearance, the small influence on the lifecycle emissions of the proposed alternatives for finishing and balconies gives ample opportunity for alternative architectural expressions, albeit within the limitation of a small fenestration area.

9.2. The use of the Norwegian conversion factor

The use of the Norwegian conversion factor gives results that are opposite to those with the European conversion factor. This is because the NOR factor attributes very small emissions to each unit of electricity produced. As a result, it maximizes the influence of the emissions from the production, replacement, and disposal of the building materials and components in the calculation of the building total lifecycle emissions. As a consequence, any factor that influences the embodied emissions of the materials composing the building facades has a large effect on the lifecycle emissions. This is the case for practically all the variables that were used in this study. In addition, the building lifetime and the maintenance cycle also have an influence on the total emission.

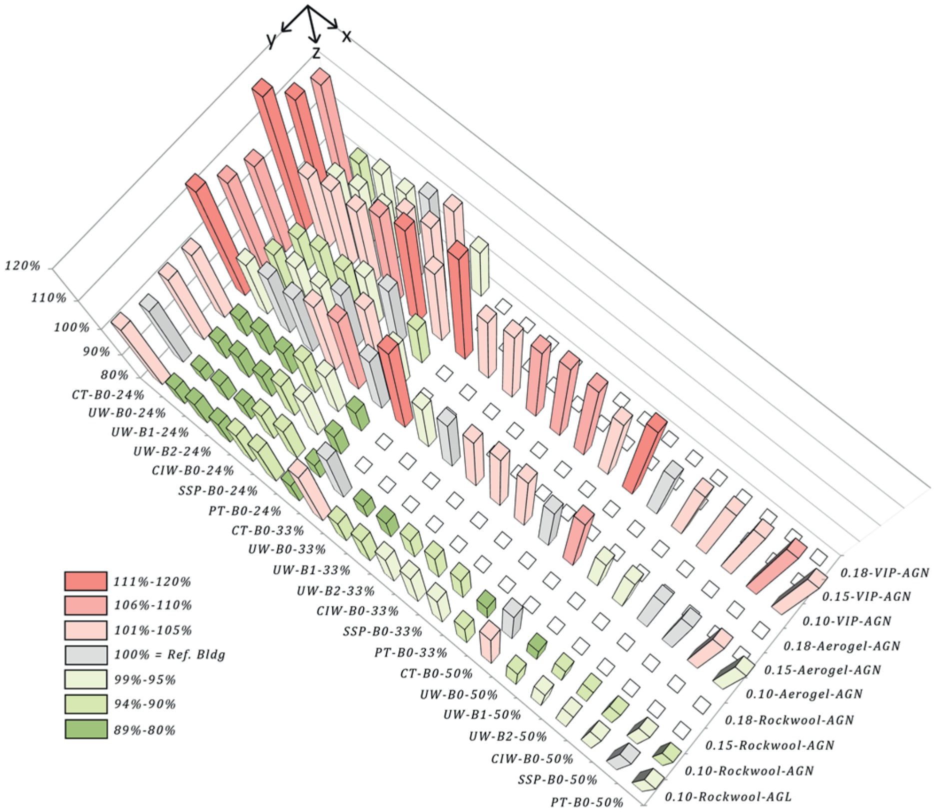


Figure 56. Matrix of the lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the NOR factor for a 75-year lifetime and a short maintenance cycle.

Table IV- c and Table IV- d in Appendix IV show the lifecycle emissions of all the proposed alternatives normalized to the emissions of the reference buildings, for the 25-year and the 75-year lifetimes and the short maintenance cycle. Figure 56 shows the matrix of all the retrofitting alternatives calculated with the NOR factor for the 75-year lifetime and the short maintenance cycle. The most critical factor appears to be the combination of the type of insulation material and its thickness. In general, the use of VIP and aerogel cannot be considered good choices. The insulation thickness has a very large effect on the lifecycle emissions when VIP and aerogel are used (especially with the 25-year lifetime), and the glazing ratio is only relevant when VIP and aerogel are used. The optimal choice is to use mineral wool, regardless of the thickness of the insulation layer and the glazing ratio, as the other insulation types considerably increase the lifecycle emissions.

The use of aerogel as insulation for the windows gives a slight increase in lifecycle emissions. This means that the use of this technology is not especially attractive when also considering its limits, as previously explained. The finishing also has a large effect on the total emissions, but it is not so much influenced by the choice of glazing ratio. As a consequence, the combination of mineral wool and low-impact finishing (such as untreated wood) appears to be the best option. It must be noted that the difference in lifecycle emissions between the alternative finishings, with the exception of the cement tile, is very small and that any proposed alternatives for finishing give lower emissions. Similarly, the use of alternative balcony types does not significantly change the emissions.

The maintenance cycle and the building service life have a strong influence on the lifecycle emissions. The use of durable materials and a longer building lifetime reduce the total emissions substantially. It must be noted that when using the NOR factor a variation of the emissions for the production of VIP and aerogel would have a much stronger consequence than that in the case of using the EU factor.

In conclusion, the use of the NOR factor frees the designer from prioritizing the energy saving aspects but poses more limits to the use of finishing materials. Moreover, since the energy use for space heating has very little influence, a different building orientation and location (within the Nordic climate) is not expected to change the results. In such a perspective, the use of the NOR factor provides a palette of retrofitting options that could be applied to a larger area than that of Oslo, within the limitation of considering the influence of the emissions given by the different transportation distances.

9.3. The use of the ZEB conversion factor

The ZEB conversion factor differs from the EU and the NOR factors in that the calculation of the $kgCO_{2\text{-}eq}$ per each KWh of produced electricity depends on the building lifetime. As a consequence, the lifecycle emissions due to the energy use for operation decrease when the building lifetime increases. Concurrently, the embodied emissions also decrease because they are spread over longer periods. Still, the share of the embodied emissions increases slowly when the building lifetime increases because for longer lifetimes the conversion factor gives less $kgCO_{2\text{-}eq}$ emissions per each KWh of electricity produced. When the building lifetime is short (25 years), the greenhouse gas emissions are therefore similar to the emissions given by the use of the EU factor. When the building lifetime is long (75 years), the results approach a limit at which the differences in emissions between the retrofitting alternatives are zero.

Table IV- e and Table IV- f in Appendix IV show the lifecycle emissions of all the proposed alternatives normalized to the emissions of the reference buildings, for the 25-year and the 75-year lifetimes and the short maintenance cycle. The results for the 75-year lifetime are represented as graphics in Figure 57.

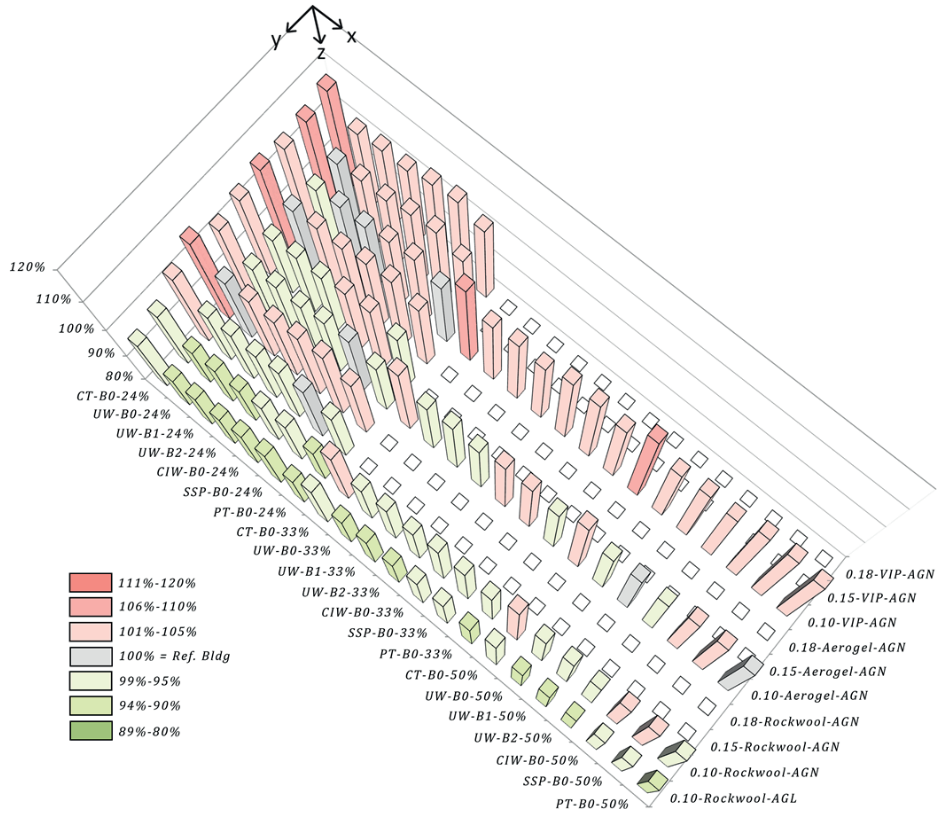


Figure 57. Matrix of the lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the ZEB factor for a 75-year lifetime and a short maintenance cycle.

For the 25-year lifetime, the emissions of the alternative retrofitting scenarios are very similar to the results given by using the EU factor and the same lifetime. In this case the embodied emissions are somewhat important, but the critical factor is the energy use for space heating. As a consequence, increasing the glazing ratio and decreasing the insulation thickness both lead to higher greenhouse gas emissions. The optimal alternatives are the ones that use mineral wool with a U-value of 0.10 $Wm^{-2}K^{-1}$ and either triple glazing with argon or double glazing with aerogel and a 24% glazing ratio. When increasing the glazing ratio, the alternatives with triple glazing with argon become less advantageous while the alternatives with double glazing with aerogel still result in lower emissions than the reference building. This is due to the CO_2 emissions that are given by the maintenance cycles of the glazing components, which have a replacement rate higher than that of the opaque surfaces. The difference in emissions between the two window technologies is due to the fact that the window with argon has one layer of glass more than the window with aerogel and its insulation value is lower that that of the window with aerogel.

When increasing the lifetime to 75 years, the share of the emissions due to the building energy use decreases. As a consequence, the alternatives that have lower emissions than the reference building are the ones that have either mineral wool or aerogel with either U-values of 0.10 or 0.15 $Wm^{-2}K^{-1}$ and low-impact finishing. Increasing the glazing ratio does not change the picture much when mineral wool is used.

In conclusion, it is difficult to point at an optimal retrofitting scenario when using the ZEB conversion factor, as the emissions are strongly dependent on the building lifetime. It must be added that the maintenance cycle also has a strong influence on the results, depending on the building lifetime used. The emissions presented in Table IV- e and Table IV- f are calculated for a short maintenance cycle only. This represents the worst case. When considering a long maintenance cycle, the difference in total emissions between the alternative finishings is reduced. It must be noted that the difference between the alternatives does not exceed 10%, regardless of the building lifetime used. Considering the uncertainty in the emission data from the production of VIP and aerogel, this difference might actually be higher. In addition, as stated above, the cost per m^2 of aerogel and VIP is higher than that for mineral wool. For these reasons, the use of these materials is not a good choice for the energy retrofitting of an apartment building.

The results that are described above can be summarized as follows.

When using the European conversion factor:

- High share of emissions due to building energy use
- Building optimized for little energy use (high insulation level, small glazing ratio).

When using the Norwegian conversion factor:

- High share of emissions due to the material production and maintenance
- Building optimized for low-emissions materials (either insulation or finishing).

When using the ZEB conversion factor:

- The relationship between the shares of embodied emissions and the emissions due to building energy use depend on the building lifetime
- Building optimized for low-emissions insulation materials and high insulation value.

9.4. Final consideration and conclusions

This work has shown that it is difficult to define an optimal choice for the energy retrofitting of an apartment building, due to the different emissions given by the use of different electricity-to-emissions conversion factors. However, the three conversion factors might be seen as projection of the emissions given by the electricity use of the future European energy grid. By assuming that the European energy grid eventually will become carbon neutral in 40 years [95], it is possible to use the three conversion factors as a rough chronological description of the European energy grid for the next 100 years and more, as shown in Figure 58 and Figure 59. In such a perspective, the European factor can approximate the emissions for the energy use for the next 10 years or so, and the ZEB factor can represent the emissions for the energy use for the next 70 years (Figure 58). Considering that the NOR factor represents an energy grid with very small emissions per kWh of electricity produced, it can approximate the emissions for the energy use for building operation from year 2060 onwards, as shown in Figure 59. Assuming this is the case, the optimal retrofitting alternative can be found by using the conversion factor most suitable for the specific time in which the building is used.

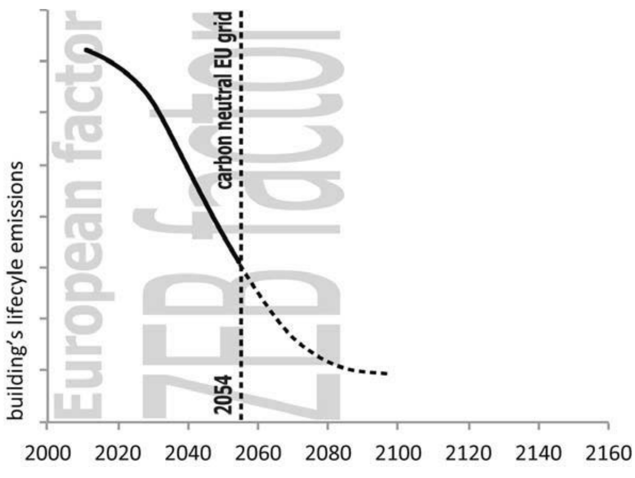


Figure 58. Projection of the lifecycle emissions of a building calculated considering the hypothetical development of the future European energy grid for the next 50 years. It is assumed that by year 2054 the EU power grid will be carbon neutral [95].

A building that is expected to be renovated now and to have a short service life (25 years) is located in the first left part of the diagram. In this part the share of the emissions given by the building energy use is predominant (EU factor), and, as a consequence, the optimal retrofitting alternative is defined according to the results given by the use of the European conversion factor. A building that is expected to be renovated now but that will have a long service life (75 years) is located in the central part of the diagram, where the ZEB factor best describes the European energy grid, as shown in Figure 58.

The use of the Norwegian conversion factor is applicable to a building for which the renovation activity is started around year 2060. This is because from 2054 the European energy grid is assumed to be carbon neutral and, as a consequence, the optimal choice will follow the options given by using the Norwegian conversion factor. When using this factor the share of the embodied emissions is the critical factor in determining the lifecycle emissions of the retrofitting package. It is then important to also have knowledge of where the production of the building materials is located, since this aspect strongly influences the results. It is difficult calculate the emissions for the production phase of the building materials, since it is not possible to define a clear geographical boundary of the material production chain. It is possible, though, to propose some scenarios, depending on where most of the production plants will be located. Based on these scenarios, it is then possible to get an idea of what may be the optimal choices for the energy retrofitting of apartment buildings.

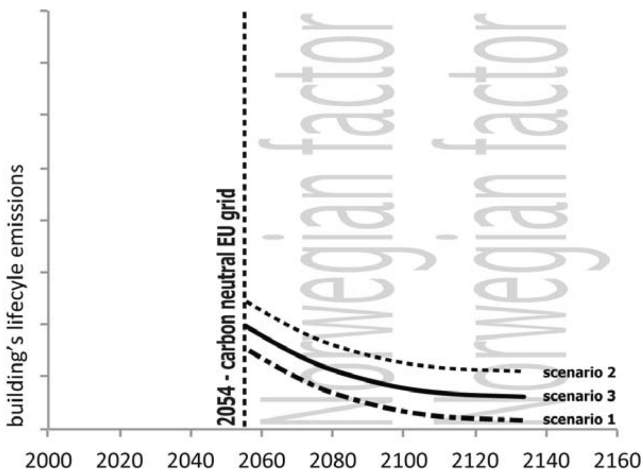


Figure 59. . Projection of the lifecycle emissions of a building calculated considering the hypothetical development of the future European energy grid from year 2054 onwards. It is assumed that by year 2054 the EU power grid will be carbon neutral. The scenarios represent the future building's lifecycle emissions depending on where the production plants of materials and components are located. Scenario 1 assumes that the production of the building materials and components is entirely located within the European Union border. Scenario 2 assumes that the production of the building materials and components is entirely located in countries where the energy grid is less green than that of the EU grid. Scenario 3 is a combination of scenarios 1 and 2.

As shown in Figure 59, three future scenarios are proposed. Scenario 1 assumes that most of the production plants for building materials and components are located in Europe. As a consequence, the emissions given by the production of these materials will be based on a very low carbon power grid. This will result in having a low share for the embodied emissions, as described in the breakdown of the emissions for any of the alternatives calculated with the EU factor. As a consequence, future improvement of those buildings will be achieved by applying measures that are similar to the ones for the alternatives calculated with the EU factor. In this case, the best way of reducing the lifecycle emissions of a building would be to first increase the insulation level and then to offset the remaining energy use by use of onsite renewable sources.

Scenario 2 assumes that the location of most of the production plants is outside Europe, in countries where the energy grid may be less green than the European one. In that case, the share of the embodied emissions will be higher than what it is for the emissions currently calculated with the Norwegian factor. The best way of decreasing the lifecycle emissions of a building would then be to first increase the use of offsite renewable energy sources, and then to increase the insulation level as needed by using low-embodied-emissions materials.

Scenario 3 is a combination of scenarios 1 and 2 and is currently represented by the calculation of the emissions given by using the Norwegian conversion factor.

In the projections of the three scenarios any future technological development in the material production that will improve the efficiency of the production itself or that will lead to better performing solutions, is not considered. Similarly, the development of existing technologies or future, innovative solutions for energy harvesting from renewable sources are not considered, nor the global population growth and the future needs of access to energy sources. These further aspects are critical in determining the relationship between the lifecycle embodied emissions and the emissions from the building operation in the future building stock. As an example, if it is assumed that the technological development leads to solutions that result in a substantial reduction of energy and emissions of the production of future insulation materials, the findings of this research have to be reconsidered. The limitations of this work are given by the methodology used for the calculation of the emissions, which gives a picture of the current industrial chain of material production and assumes that this does not change with time. It is, then, very difficult to clearly give a future overview of these factors that relate to a scale larger than the boundaries that were defined for the object of this research. In such a perspective, the choice of the optimal energy retrofitting practice goes beyond any geographical boundary and gives a picture in which the relationship between energy and emissions is dependent on many, unpredictable factors.

In conclusion, the results of this research show that it is not possible to find an optimal solution for the energy retrofitting of an apartment building that results in minimal CO_2 emissions. These conclusions somehow contradict the policies of energy savings in buildings that have been proposed in Norway in the past years.

According to these policies the latest energy-saving regulations, such as the NS 3700:2010, were proposed based on the fact the buildings, either new or renovated, were optimized in order to reduce their energy use for operation. It shows, instead, that the best practice for energy retrofitting apartment buildings in Norway will depend on how much emissions will derive from the use of energy from the grid and on the location of the production plants for materials and components. If considering the current trend, in which many countries outside Europe are developing strongly industrialized economies, such as in Asia and partially in Africa, it is rather difficult to have a clear idea of what measures to apply in the energy retrofitting of future buildings.

The results presented in this work showed that in future buildings the embodied emissions of materials might be as critical as the energy use. In such a perspective, a further investigation of other insulation materials is then an interesting development. There are currently several materials available that have good insulating properties and eventually low embodied emissions, such as wood-based and recycled-polyethylene-based (PET) materials. These materials might be a good compromise between energy savings and embodied emissions and worth being analysed. Moreover, this work was limited to a specific type of building, and it was seen how the relationship between the emissions of the façade's components and the emissions from the building energy use vary according to several factors, such as the electricity-to-emissions conversion factor, the ratio between the transparent and the opaque surfaces, and the materials that compose the façade. This indicates that when the ratio between the building envelope and its volume changes, the relationship between the above factors changes too. An investigation of other residential types, such as single family houses and high-rise apartment buildings, would therefore also be useful.

10. Appendix I

Variation of architectural features	Minimal changes of the facade design	Changes of the roof design	Widening of the existing balconies	Closure of the existing balconies	New windows design	Changes of the original plan	Addition of new volumes/balconies	New design
Austria – Single-family House in Mautern		X			X	X	X	X
Austria - Apartment Building in Kierling		X	X	X		X	X	
Austria – Single-family House in St.Martin		X			X	X	X	X
Austria – Detached House in Kufstein		X	X	X	X	X		
Belgium - Semi-detached House in DePinte		X	X	X	X	X	X	X
Germany - Building Ensemble in Freiburg	X		X		X		X	
Germany – Apartment Building in Ludwigshafen			X			X	X	
Germany – Apartment Building in Ludwigshafen		X	X		X	X		
Austria - Home for Elderly in Landeck		X	X	X	X		X	
Belgium – Apartment Block in Wesenbeeck			X	X	X	X	X	
Germany – Apartment Building in Nürnberg							X	
Switzerland – Apartment Building in Zurich		X						
Switzerland - Apartment Building in Staufen			X					
Switzerland - Apartment Building in Ostermundigen			X	X				
Germany – Apartment Building in Freiburg			X					
Germany – Apartment Building in Heidelberg	X	X			X			
Denmark – Apartment Houses in Engelsby			X	X	X			
Germany – Apartment Building in Frankfurt am Main	X	X						
Switzerland – Apartment Building Volketswil			X					
Austria – Apartment Buildings in Dornbirn			X	X	X	X		
Switzerland – CAYLA apartment Towers in Geneva	X							
Germany – Historical Building in Normand		X					X	
Switzerland – Apartment Building Birmensdorferstr, Zürich	X	X			X	X	X	
Austria - Apartmenthouse in Linz		X	X	X	X	X	X	
Sweden – Apartment Building in Alingsås					X	X	X	
Sweden – Apartment Building in Backa							X	
Norway – Apartment Buildings Myhrerenga			X					
Denmark – Apartment Houses in Albertslund					X	X	X	
Germany – Nursing Home in Stuttgart			X	X	X			
Belgium – Row Houses in Eupen		X			X	X		
Belgium – 19th Century Building in Brussels		X			X	X		
Germany – Row House in Mannheim	X				X			

Table I- a. List of the variations of architectural features after the renovation of some of the project published in the IEA-SHC Task 37.

Technical solution	New internal insulation layer	New external insulation layer	Substitution of the insulation layer	Prefabricated elements	New insulation type	Thickness (mm)	Wall U-Value ($Wm^{-2}K^{-1}$)
Austria – Single-family House in Mautern			X	X	Cellulose	300	0.143
Austria - Apartment Building in Kierling		X			EPS	200	0.138
Austria – Single-family House in St.Martin			X	X	Mineral wool	240	0.127
Austria – Detached House in Kufstein		X	X		Mineral wool	200	0.133
Belgium - Semi-detached House in DePinte		X	X		Cellulose + wood fibre board	240 + 18 + 60	0.126
Germany - Building Ensemble in Freiburg		X			Mineral wool	120	0.230
Germany – Apartment Building in Ludwigshafen		X	X		EPS	300	0.100
Germany – Apartment Building in Ludwigshafen		X	X		EPS	260	0.110
Austria - Home for Elderly in Landeck			X	X	Wood fibre insulation	230	0.193
Belgium – Apartment Block in Wesenbeeck		X			Mineral wool	80	0.410
Germany – Apartment Building in Nürnberg		X			EPS	200	0.150
Switzerland – Apartment Building in Zurich		X	X	X	Mineral wool	240	0.130
Switzerland - Apartment Building in Staufen		X			Mineral wool	200	0.170
Switzerland - Apartment Building in Ostermundigen		X			Mineral wool	140	0.190
Germany – Apartment Building in Freiburg		X			Mineral wool	180	0.150
Germany – Apartment Building in Heidelberg		X			Mineral wool	200	0.150
Denmark – Apartment Houses in Engelsby		X	X		Not specified	120	0.290
Germany – Apartment Building in Frankfurt am Main		X		X	EPS	260	0.120
Switzerland – Apartment Building Volketswil		X			Not specified	140	0.200
Austria – Apartment Buildings in Dornbirn		X			Polyurethane foam sheets + insulating bricks + EPS	30 + 90 + 250	0.109

Switzerland – CAYLA apartment Towers in Geneva		X			Not specified	40 - 80	0.420 - 0.660
Germany – Historical Building in Normand	X				Mineral wool	10	0.250
Switzerland – Apartment Building Birmensdorferstr, Zürich			X		"Flumroc" + "Saglan" + wood fibreboard	140 + 200 + 60	0.110
Austria - Apartmenthouse in Linz		X	X	X	Mineral wool + solar comb	60 + 130 + 50	0.158
Sweden – Apartment Building in Alingsås		X			Not specified + mineral wool + not specified	80 + 240 + 50	0.120
Sweden – Apartment Building in Backa		X			EPS	200	0.170
Norway – Apartment Buildings Myhrerenga		X			Mineral wool	200	0.120
Denmark – Apartment Houses in Albertslund		X			Not specified	220	0.190
Germany – Nursing Home in Stuttgart			X		Mineral wool	200	0.160
Belgium – Row Houses in Eupen	X				Wood fibre panels + cellulose	60 + 180	0.135
Belgium – 19th Century Building in Brussels			X		Wood fibre panels + cellulose	180	0.244
Germany – Row House in Mannheim		X			EPS	250	0.120

Table I- b. List of the technical solutions adopted for some of the retrofit examples from the IEA-SHC Task 37.

11. Appendix II

Class	**Value**	**Schedule (hh/d/ww)**
Occupancy	100%	16/7/52
Installed light power	1.95 Wm^{-2}	16/7/52
Installed appliance power	3.00 Wm^{-2}	16/7/52
DHW	5.1 Wm^{-2}	16/7/52
Infiltration rate	0.6 ach	24/7/52
Ventilation rate	0.023-0.026 $m^3s^{-1}m^{-2}$	24/7/52
Designed indoor temperature	21 C	16/7/52
Designed indoor temperature	19 C	8/7/52

Table II- a. List of the variables used in the energy model.

Details of the external façade construction							
Reference building		*Aerogel*		*Rockwool*		*VIP*	
Layers	Thickness	Layers	Thickness	Layers	Thickness	Layers	Thickness
External paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm
Concrete tiling	8 mm	Concrete tiling	8 mm	Concrete tiling	8 mm	Concrete tiling	8 mm
Air gap	28 mm	Air gap	28 mm	Air gap	28 mm	Air gap	28 mm
Wind barrier	1 mm	Wind barrier	1 mm	Wind barrier	1 mm	Wind barrier	1 mm
Timber framework	200 mm	Timber framework	100 mm	Timber framework	250 mm	Timber framework	100 mm
Rockwool	200 mm	Aerogel	100 mm	Rockwool	250 mm	VIP	60 mm
OSB board	18 mm	OSB board	18 mm	OSB board	18 mm	OSB board	18 mm
Existing structure	100 mm	Existing structure	100 mm	Existing structure	100 mm	Existing structure	100 mm
Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm
Internal paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm
Screws and connectors	-	Screws and connectors	-	Screws and connectors	-	Screws and connectors	-

Table II- b. Details of the facade construction with the different insulation alternatives.

Details of the external façade construction

	Referenc e building 0.12	*Aerogel 0.10*	*Aerogel 0.15*	*Aerogel 0.18*	*Rock wool 0.10*	*Rock wool 0.15*	*Rock wool 0.18*	*VIP 0.10*	*VIP 0.15*	*VIP 0.18*
External paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Concrete tiling	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm
Air gap	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm
Wind barrier	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm
Timber framework	200 mm	100 mm	58 mm	43 mm	250 mm	140 mm	100 mm	100 mm	33 mm	25 mm
Insulation	200 mm	100 mm	60 mm	45 mm	250 mm	140 mm	100 mm	60 mm	35 mm	25 mm
OSB board	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm
Existing structure	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm
Gypsum plasterboa	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm
Internal paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Screws and	-	-	-	-	-	-	-	-	-	-

Table II- c. Details of the facade construction with the different insulation alternatives and different thicknesses. The number following each solution's name represents the corresponding U-value.

Details of the windows technologies

	Reference building	*24% argon*	*33% argon*	*50% argon*	*24% aerogel*	*33% aerogel*	*50% aerogel*
Window technology	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon 3-20-3 aerogel	3-10-3-10-3 argon 3-20-3 aerogel	3-10-3-10-3 argon 3-20-3 aerogel
WWR	24%	24%	33%	50%	24%	33%	50%
Share of aerogel	-	-	-	-	28%	28%	39%

Table II- d. Details of the glazing technologies and the alternatives of glazing ratios (WWR).

Details of the external façade construction

	Reference building	*Aerogel 24%*	*Aerogel 33%*	*Aerogel 50%*	*Rock wool 24%*	*Rock wool 33%*	*Rock wool 50%*	*VIP 24%*	*VIP 33%*	*VIP 50%*
External paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Concrete tiling	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm
Air gap	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm
Wind barrier	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm
Timber framework	200 mm	100 mm	100 mm	100 mm	250 mm	250 mm	250 mm	100 mm	100 mm	100 mm
Insulation	200 mm	100 mm	100 mm	100 mm	250 mm	250 mm	250 mm	60 mm	60 mm	60 mm
OSB board	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm
Existing structure	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm
Gypsum plasterboa	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm
Internal paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Screws and	-	-	-	-	-	-	-	-	-	-
Façade glazing ratio	24%	24%	24%	24%	33%	33%	33%	50%	50%	50%

Table II- e. Details of the facade construction with the different glazing ratios and the different glazing technologies. The number following each solution's name represents the corresponding glazing ratio.

Details of the external façade construction					
	CT	*UW*	*CIW*	*SSP*	*PT*
External paint	0.1 mm	-	-	-	0.1 mm
Concrete tiling	8 mm	-	-	-	-
Untreated wood	-	20 mm	-	-	-
Copper imp. wood	-	-	20 mm	-	-
Sandwich panels	-	-	-	300 mm	-
Polymer cement tiles	-	-	-	-	7 mm
Air gap	28 mm	28 mm	28 mm	28 mm	28 mm
Wind barrier	1 mm	1 mm	1 mm	1 mm	1 mm
Timber framework	250 mm	250 mm	250 mm	-	250 mm
Insulation	250 mm	250 mm	250 mm	-	250 mm
OSB board	18 mm	18 mm	18 mm	18 mm	18 mm
Existing structure	100 mm	100 mm	100 mm	100 mm	100 mm
Gypsum plasterboard	13 mm	13 mm	13 mm	13 mm	13 mm
Internal paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Screws and connectors	-	-	-	-	-

Table II- f. Details of the facade construction with the different finishing types. CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is sandwich panel, PT is polymer-cement tile.

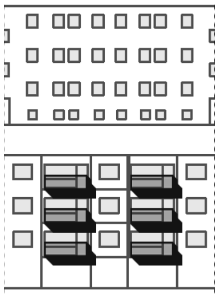
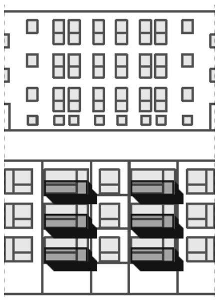
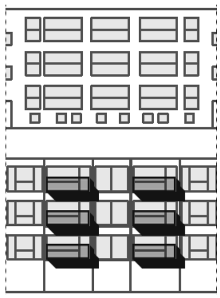
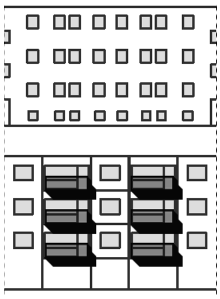
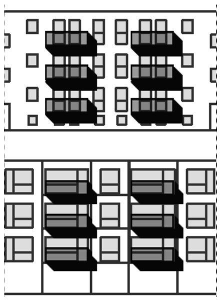
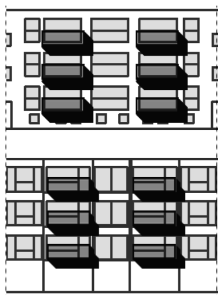
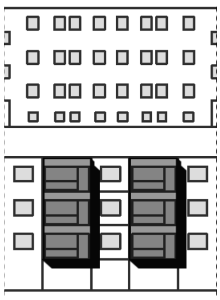
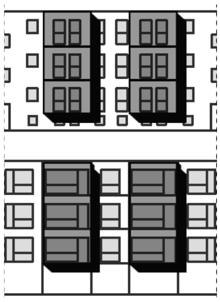
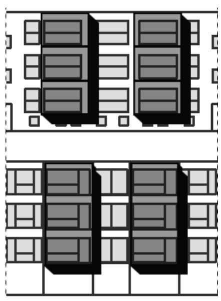
List of the architectural solutions	24%	33%	50%
B0			
B1			
B2			

Table II- g. List of the alternatives for balconies and sunspaces. In each cell on top the East facade, on bottom the West facade. B0, B1, and B2 represent different solutions of balconies. 24%, 33%, and 50% represent different glazing ratios.

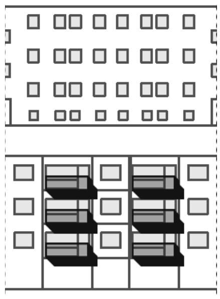
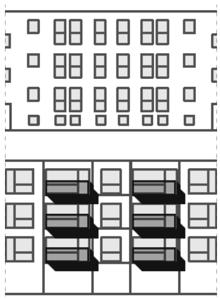
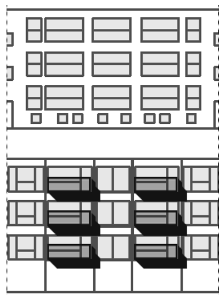
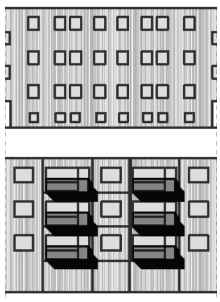
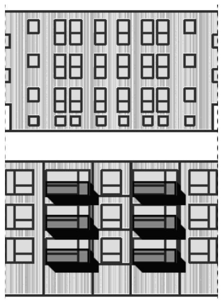
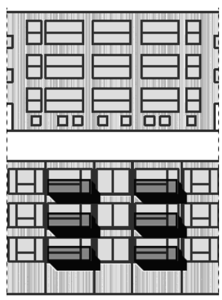
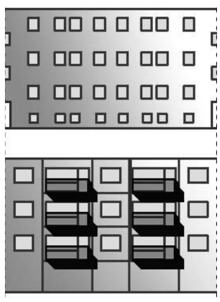
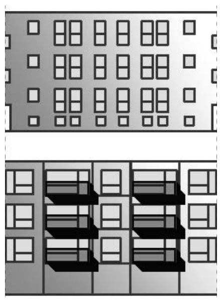
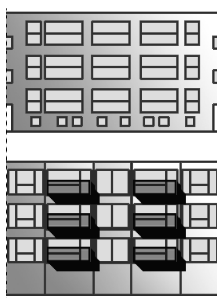
List of the architectural solutions	24%	33%	50%
Cement tile and Polymer-cement tile			
Untreated wood and copper-impregnated wood			
Steel-coated sandwich panel			

Table II- h. List of the alternatives for finishing. In each cell on top the East facade, on bottom the West façade. 24%, 33%, and 50% represent different glazing ratios.

12. Appendix III

Material	Waste treatment (%)			Factory gate-building site distance (km)	Means of conveyance	Waste at building site (%)	Notes
	Incineration	Landfilling	Recycling				
Argon[1]	-	-	-	25	Lorry 16-32t	0	[1] No end-of-life scenario for argon.
Paint[2]	100	-	-	175	Van < 3.5t	5	[2] End-of-life scenario not included in NHP2, sourced from Blom et al. [81].
Wood preservative[3]	100	-	-	50	Van < 3.5t	10	[3] Impacts of end-of-life aggregated to wood products.
Plaster[4]	-	100	-	150	Lorry 16-32t	5	[4] End-of-life scenario not included in NHP2, assumed as landfilled.
Concrete	-	-	100	150	Lorry 16-32t	5	[5] No specific fractions of the EOL scenario are defined in the NHP2 which are sourced from Bohne et al. [17].
Gypsum	-	60	40	150	Lorry 16-32t	10	[6] End-of-life process not included in the NHP2, fractions sourced from Bohne et al. [17].
Asphalt	100	-	-	150	Lorry 16-32t	10	[7] End-of-life process not included in the NHP2, assumed as landfilling.
Plastic[5]	20	-	80	150	Van < 3.5t	7	
Sealants[5]	20	-	80	25	Lorry 16-32t	5	
Glass	-	20	80	25	Lorry 16-32t	0	
Steel[6]	-	10	90	525	Lorry 16-32t	0	
VIP[7]	-	100	-	1525	Lorry 16-32t	3	
Aerogel[7]	-	100	-	1525	Lorry 16-32t	5	
EPS	-	100	-	100	Lorry 16-32t	10	
Mineral wool	-	100	-	100	Lorry 16-32t	10	
Timber	100	-	-	175	Lorry 16-32t	10	
Polymer cement tiles[4]	-	100	-	100	Lorry 16-32t	5	
Sandwich panels[4]	-	100	-	900	Lorry 16-32t	5	
Cement tiles	-	100	-	100	Lorry 16-32t	5	
Untreated wood	100	-	-	175	Lorry 16-32t	5	
Copper imp. wood	100	-	-	175	Lorry 16-32t	5	

Table III- a. List of the end-of-life scenarios, transportation distances, and means of transportation for the materials used in the reference building and in the retrofitting alternatives.

Building component/material			
	Long	*Medium*	*Short*
Façade carpentry			
Timber frame	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
OSB boards	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Steel connectors/screws	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Insulation layer			
Insulation	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Wind barrier	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Vapour barrier	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Steel connectors/screws	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Finishing			
External paint	4	10	18
Internal paint	10	12	16
Cement tiling	20	30	40
Wood cladding	40	50	60
Polymer cement tiling	40	50	60
Sandwich panels	40	50	60
Wood preservative	1	2	3
Gypsum plaster boards	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Plaster	20	40	60
Windows and doors			
Argon windows	20	40	60
Argon windows (paint)	(2+6)/2	(4+9)/2	(6+12)/2
Aerogel windows	10	20	30
Aerogel windows (paint)	(2+6)/2	(4+9)/2	(6+12)/2
Internal doors	30	40	50
Internal doors (paint)	8	16	20
External doors	20	30	40
External doors (paint)	(2+8)/2	(4+16)/2	(8+20)/2
Balconies			
Steel structure	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Timber flooring	15	20	30

Wood preservative	1	2	3
Glass (balusters)	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Glass (sunspace)	20	40	60
Paint	8	10	12
Roof			
Bitumen	20	25	30
Water barrier	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Insulation	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle
Plaster	20	40	60
Paint	10	12	16
Basement			
Cement tiling	20	30	40
Plaster	20	40	60
Bitumen	20	25	30
Insulation	Equal to building lifecycle	Equal to building lifecycle	Equal to building lifecycle

Table III- b. List of the maintenance schedules of the materials used in the retrofitting solutions. From [86].

13. Appendix IV

Technical solutions		Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	*Finishing type*	*Balcony type*										
24%	CT	B0	95	99	104	107	101	105	107	104	107	109
	UW	B0	94	97	102	105	99	103	105	102	105	107
	UW	B1	94	97	102	105	100	103	106	102	105	107
	UW	B2	96	96	101	104	99	102	105	101	104	106
	CIW	B0	94	97	103	106	100	104	106	103	106	108
	SSP	B0	94	97	103	106	100	104	106	103	106	108
	PT	B0	94	97	102	105	100	103	106	102	105	107
33%	CT	B0	96	102	-	-	103	-	-	106	-	-
	UW	B0	94	100	-	-	102	-	-	105	-	-
	UW	B1	95	100	-	-	102	-	-	105	-	-
	UW	B2	99	99	-	-	101	-	-	103	-	-
	CIW	B0	95	101	-	-	103	-	-	105	-	-
	SSP	B0	95	101	-	-	103	-	-	105	-	-
	PT	B0	95	100	-	-	102	-	-	105	-	-
50%	CT	B0	96	104	-	-	105	-	-	108	-	-
	UW	B0	94	103	-	-	104	-	-	106	-	-
	UW	B1	95	103	-	-	104	-	-	107	-	-
	UW	B2	101	101	-	-	102	-	-	105	-	-
	CIW	B0	95	103	-	-	104	-	-	107	-	-
	SSP	B0	95	104	-	-	105	-	-	107	-	-
	PT	B0	95	103	-	-	104	-	-	106	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	*100%*
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- a. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the EU factor for a 25-year lifetime and a short maintenance cycle. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

Technical solutions		Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type	Balcony type										
24%	CT	B0	95	99	104	108	99	104	107	99	105	108
	UW	B0	93	96	102	106	97	101	104	97	103	106
	UW	B1	93	96	102	106	97	101	105	97	103	106
	UW	B2	92	96	101	105	96	101	104	96	102	105
	CIW	B0	94	97	103	107	98	102	106	98	104	107
	SSP	B0	94	97	103	107	98	102	106	98	104	107
	PT	B0	93	97	103	106	97	102	105	98	104	106
33%	CT	B0	96	102	-	-	101	-	-	102	-	-
	UW	B0	94	100	-	-	99	-	-	100	-	-
	UW	B1	95	101	-	-	99	-	-	101	-	-
	UW	B2	93	99	-	-	98	-	-	99	-	-
	CIW	B0	95	101	-	-	100	-	-	101	-	-
	SSP	B0	95	101	-	-	100	-	-	101	-	-
	PT	B0	95	101	-	-	99	-	-	101	-	-
50%	CT	B0	96	105	-	-	104	-	-	106	-	-
	UW	B0	95	104	-	-	102	-	-	104	-	-
	UW	B1	95	104	-	-	103	-	-	104	-	-
	UW	B2	93	102	-	-	101	-	-	102	-	-
	CIW	B0	95	104	-	-	103	-	-	105	-	-
	SSP	B0	96	104	-	-	103	-	-	105	-	-
	PT	B0	95	104	-	-	103	-	-	104	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	100%
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- b. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the EU factor for a 75-year lifetime and a short maintenance cycle. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

Technical solutions		Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type	Balcony type										
24%	CT	B0	103	103	100	98	130	117	115	142	122	117
	UW	B0	90	90	87	85	117	103	102	128	108	103
	UW	B1	92	92	88	87	118	105	103	130	110	105
	UW	B2	92	93	90	88	120	107	105	132	112	107
	CIW	B0	97	97	93	92	123	110	108	135	115	110
	SSP	B0	97	97	93	92	123	110	108	135	115	110
	PT	B0	92	92	88	87	118	105	103	130	110	105
33%	CT	B0	103	102	-	-	125	-	-	137	-	-
	UW	B0	92	90	-	-	113	-	-	125	-	-
	UW	B1	95	93	-	-	117	-	-	128	-	-
	UW	B2	95	93	-	-	117	-	-	128	-	-
	CIW	B0	97	95	-	-	118	-	-	130	-	-
	SSP	B0	97	95	-	-	118	-	-	130	-	-
	PT	B0	93	92	-	-	115	-	-	127	-	-
50%	CT	B0	102	98	-	-	115	-	-	123	-	-
	UW	B0	93	90	-	-	107	-	-	115	-	-
	UW	B1	97	93	-	-	110	-	-	118	-	-
	UW	B2	97	93	-	-	110	-	-	118	-	-
	CIW	B0	98	95	-	-	112	-	-	120	-	-
	SSP	B0	98	95	-	-	112	-	-	120	-	-
	PT	B0	95	92	-	-	108	-	-	117	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	100%
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- c. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the NOR factor for a 25-year lifetime and a short maintenance cycle. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

		Technical solutions: Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type	Balcony type										
24%	CT	B0	102	100	102	102	114	109	107	118	111	109
	UW	B0	86	84	86	86	98	93	91	102	95	93
	UW	B1	89	86	89	89	100	95	93	105	98	95
	UW	B2	89	86	89	89	100	95	93	105	98	95
	CIW	B0	93	91	93	93	105	100	98	109	102	100
	SSP	B0	95	93	95	95	107	102	100	111	105	102
	PT	B0	89	86	89	89	100	95	93	105	98	95
33%	CT	B0	105	100	-	-	111	-	-	116	-	-
	UW	B0	91	86	-	-	98	-	-	102	-	-
	UW	B1	93	89	-	-	100	-	-	105	-	-
	UW	B2	95	91	-	-	102	-	-	107	-	-
	CIW	B0	98	93	-	-	105	-	-	109	-	-
	SSP	B0	98	93	-	-	105	-	-	109	-	-
	PT	B0	93	89	-	-	100	-	-	105	-	-
50%	CT	B0	105	100	-	-	107	-	-	111	-	-
	UW	B0	93	89	-	-	95	-	-	100	-	-
	UW	B1	95	91	-	-	98	-	-	102	-	-
	UW	B2	98	93	-	-	100	-	-	105	-	-
	CIW	B0	98	93	-	-	100	-	-	105	-	-
	SSP	B0	100	95	-	-	102	-	-	107	-	-
	PT	B0	95	91	-	-	98	-	-	102	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	100%
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- d. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the NOR factor for a 75-year lifetime and a short maintenance cycle. All values are normalized to 1 m² of heated building area for 1 year. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

	Technical solutions	Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type	Balcony type										
24%	CT	B0	96	99	104	107	102	105	108	106	108	110
	UW	B0	93	96	101	104	100	103	105	103	105	107
	UW	B1	94	97	102	105	100	103	106	104	106	108
	UW	B2	94	96	100	104	99	102	104	102	104	106
	CIW	B0	94	98	102	106	101	104	106	104	106	108
	SSP	B0	94	98	102	106	101	104	106	104	106	108
	PT	B0	93	97	101	105	100	103	105	103	105	107
33%	CT	B0	96	102	-	-	104	-	-	108	-	-
	UW	B0	94	100	-	-	102	-	-	105	-	-
	UW	B1	95	100	-	-	103	-	-	106	-	-
	UW	B2	95	99	-	-	101	-	-	104	-	-
	CIW	B0	95	101	-	-	103	-	-	106	-	-
	SSP	B0	95	101	-	-	103	-	-	106	-	-
	PT	B0	94	100	-	-	102	-	-	106	-	-
50%	CT	B0	96	104	-	-	106	-	-	109	-	-
	UW	B0	94	103	-	-	104	-	-	107	-	-
	UW	B1	95	103	-	-	104	-	-	107	-	-
	UW	B2	94	101	-	-	102	-	-	105	-	-
	CIW	B0	95	103	-	-	105	-	-	108	-	-
	SSP	B0	95	103	-	-	105	-	-	108	-	-
	PT	B0	95	103	-	-	104	-	-	107	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	100%
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- e. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the ZEB factor for a 25-year lifetime and a short maintenance cycle. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

	Technical solutions	Insulation type	Rockwool				Aerogel			VIP		
		Wall U-value	0.10	0.10	0.15	0.18	0.10	0.15	0.18	0.10	0.15	0.18
Architectural solutions		Glazing type	AGL	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN	AGN
Glazing ratio	Finishing type	Balcony type										
24%	CT	B0	97	98	103	106	103	104	106	105	106	108
	UW	B0	90	92	97	100	97	98	100	99	100	102
	UW	B1	91	93	97	101	97	99	101	100	101	103
	UW	B2	91	93	97	101	97	99	101	100	101	103
	CIW	B0	93	95	99	103	99	101	103	102	103	104
	SSP	B0	94	96	100	103	100	102	103	103	103	105
	PT	B0	91	93	97	101	97	99	101	100	101	103
33%	CT	B0	97	101	-	-	103	-	-	106	-	-
	UW	B0	92	96	-	-	98	-	-	101	-	-
	UW	B1	93	97	-	-	99	-	-	102	-	-
	UW	B2	92	96	-	-	98	-	-	101	-	-
	CIW	B0	95	98	-	-	101	-	-	103	-	-
	SSP	B0	95	98	-	-	101	-	-	103	-	-
	PT	B0	93	97	-	-	99	-	-	102	-	-
50%	CT	B0	98	103	-	-	104	-	-	107	-	-
	UW	B0	93	98	-	-	99	-	-	102	-	-
	UW	B1	94	99	-	-	100	-	-	103	-	-
	UW	B2	93	98	-	-	99	-	-	102	-	-
	CIW	B0	96	101	-	-	102	-	-	104	-	-
	SSP	B0	96	101	-	-	102	-	-	104	-	-
	PT	B0	94	99	-	-	100	-	-	103	-	-

< -40%	
-21-40%	
-11-20%	
-6-10%	
-0-5%	
Ref. bldg.	100%
+0-5%	
+6-10%	
+11-20%	
+21-40%	
> +40%	

Table IV- f. Lifecycle emissions of all the technical and the architectural retrofitting alternatives calculated with the ZEB factor for a 75-year lifetime and a short maintenance cycle. AGN is triple glazing with argon, AGL is double glazing with aerogel . CT is cement tile, UW is untreated wood, CIW is copper impregnated wood, SSP is insulated sandwich panel, and PT is polymer-cement tile. B0 is normal balconies on the West façade with the 24%, 33%, and 50% glazing ratios. B1 is normal balconies normal balconies on the West façade with the 24% glazing ratio, and normal balconies on both the East and West facades with the 33% and the 50% glazing ratios. B2 is sunspaces on the West façade with the 24% glazing ratio, and is sunspaces on both the East and West facades with the 33% and the 50% glazing ratios.

14. References

1. WBCSD, *Energy Efficiency in Buildings full report: business realities and opportunities*. 2008, World Business Council for Sustainable Development.
2. Uihlein, A. and P. Eder, *Policy options towards an energy efficient residential building stock in the EU-27.* Energy and Buildings, 2010. **42**(6): p. 791-798.
3. Dodoo, A., L. Gustavsson, and R. Sathre, *Building energy-efficiency standards in a life cycle primary energy perspective.* Energy and Buildings, 2011. **43**(7): p. 1589-1597.
4. Fernandez, R. and J. Watterson, *End-user GHG emissions from energy : reallocation of emissions from energy industries to end users 2005-2009*, in *EEA Technical report*. 2011, European Environmental Agency.
5. Nemry, F., et al., *Options to reduce the environmental impacts of residential buildings in the European Union--Potential and costs.* Energy and Buildings, 2010. **42**(7): p. 976-984.
6. McKinsey&Company, *Pathways to a Low-Carbon Economy*. 2009, McKinsey & Company.
7. Thormark, C., *Environmental analysis of a building with reused building materials.* International Journal of Low Energy and Sustainable Buildings, 2000. **1**.
8. Thormark, C., *Conservation of energy and natural resources by recycling building waste.* Resources, Conservation and Recycling, 2001. **33**(2): p. 113-130.
9. Thormark, C., *A low energy building in a life cycle--its embodied energy, energy need for operation and recycling potential.* Building and Environment, 2002. **37**(4): p. 429-435.
10. Thormark, C., *The effect of material choice on the total energy need and recycling potential of a building.* Building and Environment, 2006. **41**(8): p. 1019-1026.
11. Adalberth, K., *Energy use during the life cycle of single-unit dwellings: Examples.* Building and Environment, 1997. **32**(4): p. 321-329.
12. Winther, B.N. and A.G. Hestnes, *Solar Versus Green: The Analysis of a Norwegian Row House.* Solar Energy, 1999. **66**(6): p. 387-393.
13. Sartori, I. and A.G. Hestnes, *Energy use in the life cycle of conventional and low-energy buildings: A review article.* Energy and Buildings, 2007. **39**(3): p. 249-257.
14. Blengini, G.A. and T. Di Carlo, *The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings.* Energy and Buildings, 2010. **42**(6): p. 869-880.
15. Blengini, G.A., *Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy.* Building and Environment, 2009. **44**(2): p. 319-330.
16. Gao, W., et al., *Energy impacts of recycling disassembly material in residential buildings.* Energy and Buildings, 2001. **33**(6): p. 553-562.

17. Bohne, R.A., H. Brattebø, and H. Bergsdal, *Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level.* Journal of Industrial Ecology, 2008. **12**(1): p. 52-68.
18. Bergsdal, H., R.A. Bohne, and H. Bratteb√∏, *Projection of construction and demolition waste in Norway.* Journal of Industrial Ecology, 2007. **11**(3): p. 27-39.
19. Bergsdal, H., et al., *Dynamic material flow analysis for Norway's dwelling stock.* Building Research and Information, 2007. **35**(5): p. 557-570.
20. P. Torcellini, S.P., M. Deru, D. Crawley, *Zero Energy Buildings: a critical look at the definition*, in *ACEEE Summer Study*. 2006, U.S. Department of Energy: California. p. 12.
21. Sartori, I., et al., *Criteria for Definition of Net Zero Emission Buildings*. 2010, International Energy Agency.
22. IEA-SHC Task 37, *5-storey Apartment House in Linz, Austria*. Available from: http://task37.iea-shc.org/.
23. IEA-SHC Task 37, *Elderly Home in Landek, Austria*. Available from: http://task37.iea-shc.org/.
24. IEA-SHC Task 37, *Apartment buildings in Dornbirn, Austria*. Available from: http://task37.iea-shc.org/.
25. Power, A., *Estates on the edge: the social consequences of mass housing in Northern Europe*. 1997, New York: St. Martin's Press. XXII, 432 s.
26. Mumford, E., *Defining urban design: CIAM architects and the formation of a discipline, 1937-69*. 2009, New Haven: Yale University Press. IX, 262 s.
27. Bevilacqua, M.*, Alexander Klein and the Existenzminimum: A 'Scientific' Approach to Design Techniques.* Nexus Network Journal, 2011. **13**(2): p. 297-313.
28. Wassenberg, F., *Large social housing estates: From stigma to demolition?* Journal of Housing and the Built Environment, 2004. **19**(3): p. 223-232.
29. Standard Norge, *NS 3700:2010*, in *Criteria for passive houses and low energy houses - Residential buildings*. 2010.
30. Brattbakk, I. and H. Thorbjørn, *Post-war large housing estates in Norway - Well-kept residential areas still stigmatised?* Journal of Housing and the Built Environment, 2004. **19**(3): p. 311-332.
31. UNFCCC. *List of Annex I Parties to the Convention*. Cited 2012; Available from: http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php.
32. *The Use of Exterior Timber Cladding in Buildings*. Wood Marketing Federation. Available from: www.wood-ni.com.
33. Klinski, M. and T.H. Dokka. *The first apartment house renovation with Passive House components in Norway*. in *14th International Passive House Conference*. 2010. Dresden.
34. *Vindu av tre*, in *byggdetaljer*, Byggforskserien, Editor. 1981.
35. Standard Norge, *NS 3031:2007*, in *Calculation of energy performance of buildings - Method and data*. 2007.
36. EERE. *EnergyPlus Energy Simulation Software*. Cited 2012; Available from: http://apps1.eere.energy.gov/buildings/energyplus/.

37. Baumann, H. and A.-M. Tillman, *The hitch hiker's guide to LCA: an orientation in life cycle assessment methodology and application*. 2004, Lund: Studentlitteratur. 543 s.
38. Rebitzer, G., et al., *Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications.* Environment International, 2004. **30**(5): p. 701-720.
39. Tillman, A.-M., et al., *Choice of system boundaries in life cycle assessment.* Journal of Cleaner Production, 1994. **2**(1): p. 21-29.
40. Chevalier, J.L. and J.F. Le Teno, *Requirements for an LCA-based model for the evaluation of the environmental quality of building products.* Building and Environment, 1996. **31**(5): p. 487-491.
41. Erlandsson, M. and M. Borg, *Generic LCA-methodology applicable for buildings, constructions and operation services-today practice and development needs.* Building and Environment, 2003. **38**(7): p. 919-938.
42. Verbeeck, G. and H. Hens, *Life cycle inventory of buildings: A calculation method.* Building and Environment, 2010. **45**(4): p. 1037-1041.
43. Hernandez, P. and P. Kenny, *Development of a methodology for life cycle building energy ratings.* Energy Policy, 2011. **39**(6): p. 3779-3788.
44. Verbeeck, G. and H. Hens, *Life cycle inventory of buildings: A contribution analysis.* Building and Environment, 2010. **45**(4): p. 964-967.
45. Kellenberger, D. and H.-J.r. Althaus, *Relevance of simplifications in LCA of building components.* Building and Environment, 2009. **44**(4): p. 818-825.
46. Crawford, R.H., I. Czerniakowski, and R.J. Fuller, *A comprehensive model for streamlining low-energy building design.* Energy and Buildings, 2011. **43**(7): p. 1748-1756.
47. Adalberth, K., *Energy use during the life cycle of buildings: a method.* Building and Environment, 1997. **32**(4): p. 317-320.
48. Malmqvist, T., et al., *Life cycle assessment in buildings: The ENSLIC simplified method and guidelines.* Energy. **In Press, Corrected Proof**.
49. Citherlet, S. and T. Defaux, *Energy and environmental comparison of three variants of a family house during its whole life span.* Building and Environment, 2007. **42**(2): p. 591-598.
50. Feist, W., *Life-cycle energy analysis: comparison of low-energy house, passive house, self-sufficient house*. 1997, Passive House Institut.
51. Gustavsson, L. and A. Joelsson, *Life cycle primary energy analysis of residential buildings.* Energy and Buildings, 2010. **42**(2): p. 210-220.
52. Leckner, M. and R. Zmeureanu, *Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem.* Applied Energy, 2011. **88**(1): p. 232-241.
53. Hertwich, E. and J. Hammitt, *A decision-analytic framework for impact assessment.* The International Journal of Life Cycle Assessment, 2001. **6**(5): p. 265-272.
54. Jolliet, O., et al., *The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative.* The International Journal of Life Cycle Assessment, 2004. **9**(6): p. 394-404.

55. *Framework and requirements for Life Cycle Impact Assessment models and indicators*, in *ILCD Handbook*. 2010, European Commission, Joint Research Centre, Institute for Environment and Sustainability.
56. Zwerger, M. and H. Klein. *Integration of VIP's into external wall insulation systems*. in *Proceedings of the 7th International Vacuum Insulation Symposium, EMPA*. 2005. Duebendorf, Switzerland.
57. Aspen Arogel, *Aerogel Insulation Converts Old Mill House Into Modern Energy-Saving Passive House*. Available from: http://www.aerogel.com/.
58. Schmidt, A.C., et al., *A Comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax: Part 1: Background, Goal and Scope, Life Cycle Inventory, Impact Assessment and Interpretation.* International Journal of Life Cycle Assessment, 2004. **9**(1): p. 53-66.
59. Schmidt, A.C., et al., *A Comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax Part 2: Comparative Assessment.* International Journal of Life Cycle Assessment, 2004. **9**(2): p. 122-129.
60. IEA-SHC Task 37, *Apartment building in Heidelberg, Germany*. Available from: http://task37.iea-shc.org/.
61. Baetens, R., et al., *Vacuum insulation panels for building applications: A review and beyond.* Energy and Buildings, 2010. **42**(2): p. 147-172.
62. Jelle, B.P., A. Gustavsen, and R. Baetens, *The path to the high performance thermal building insulation materials and solutions of tomorrow.* Journal of Building Physics, 2010. **34**(2): p. 99-123.
63. Simmler, H. and S. Brunner. *Aging and Service Life of VIP in Buildings*. in *Proceedings of the 7th International Vacuum Insulation Symposium, EMPA*. 2005. Duebendorf, Switzerland.
64. Schonhardt, U., et al., *Okobilanz eines Vakuum-Isolations-Paneels (VIP)*, in *Auftrag des Bundesamtes für Energie*. 2003, Institut fur Energie: Bern.
65. Baetens, R., B.P. Jelle, and A. Gustavsen, *Aerogel insulation for building applications: A state-of-the-art review.* Energy and Buildings, 2011. **43**(4): p. 761-769.
66. Hüsing, N. and U. Schubert, *Aerogels—Airy Materials: Chemistry, Structure, and Properties.* Angewandte Chemie International Edition, 1998. **37**(1-2): p. 22-45.
67. Reim, M., et al., *Silica-aerogel granulate – Structural, optical and thermal properties.* Journal of Non-Crystalline Solids, 2004. **350**(0): p. 358-363.
68. Smith, D.M., A. Maskara, and U. Boes, *Aerogel-based thermal insulation.* Journal of Non-Crystalline Solids, 1998. **225**: p. 254-259.
69. Aspen Aerogel. Available from: http://www.aerogel.com/.
70. Rubin, M. and C.M. Lampert, *Transparent silica aerogels for window insulation.* Solar Energy Materials. **7**(4): p. 393-400.
71. Duer, K. and S. Svendsen, *Monolithic silica aerogel in superinsulating glazings.* Solar Energy, 1998. **63**(4): p. 259-267.
72. Jensen, K.I., F.H. Kristiansen, and J.M. Schultz, *Highly Insulating and LIght Transmitting Aerogel Glazing for Super Insulating Windows*. 2005,

Department of civil engineering (BYG•DTU) Technical University of Denmark.
73. Jensen, K.I., J.M. Schultz, and F.H. Kristiansen, *Development of windows based on highly insulating aerogel glazings.* Journal of Non-Crystalline Solids, 2004. **350**(0): p. 351-357.
74. Jensen, K.I., *Passive solar component based on evacuated monolithic silica aerogel.* Journal of Non-Crystalline Solids, 1992. **145**: p. 237-239.
75. Schultz, J.M. and K.I. Jensen, *Evacuated aerogel glazings.* Vacuum, 2008. **82**(7): p. 723-729.
76. Schultz, J.M., K.I. Jensen, and F.H. Kristiansen, *Super insulating aerogel glazing.* Solar Energy Materials and Solar Cells, 2005. **89**(2-3): p. 275-285.
77. Hutchins, M.G. and W.J. Platzer, *The thermal performance of advanced glazing materials.* Renewable Energy, 1996. **8**(1–4): p. 540-545.
78. PAROC Sandwich Panels. Cited 2013; Available from: http://www.paroc.com/solutions-and-products/solutions/sandwich-panels/paroc-sandwich-panels.
79. Gustavsson, L., A. Joelsson, and R. Sathre, *Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building.* Energy and Buildings, 2010. **42**(2): p. 230-242.
80. *Nasjonal handlingsplan for bygg- og anleggs-avfall 2007 - 2012*. 2007. Available from: http://www.dibk.no/.
81. Blom, I., L. Itard, and A. Meijer, *Environmental impact of dwellings in use: Maintenance of facade components.* Building and Environment, 2010. **45**(11): p. 2526-2538.
82. Chen, T.Y., J. Burnett, and C.K. Chau, *Analysis of embodied energy use in the residential building of Hong Kong.* Energy, 2001. **26**(4): p. 323-340.
83. Haapio, A. and P. Viitaniemi, *Environmental effect of structural solutions and building materials to a building.* Environmental Impact Assessment Review, 2008. **28**(8): p. 587-600.
84. Sartori, I., et al., *Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock,1900-2100.* BUILDING RESEARCH & INFORMATION, 2008. **36**(5): p. 416-425.
85. de Wilde, P., W. Tian, and G. Augenbroe, *Longitudinal prediction of the operational energy use of buildings.* Building and Environment, 2011. **46**(8): p. 1670-1680.
86. *Intervaller for vedlikehold og utskifting av bygningsdeler*, in *Byggforskserien*. 2010. Available from: http://bks.byggforsk.no/.
87. Frischknecht, R. and G. Rebitzer, *The ecoinvent database system: a comprehensive web-based LCA database.* Journal of Cleaner Production, 2005. **13**(13-14): p. 1337-1343.
88. Pierre, A.C. and G.M. Pajonk, *Chemistry of Aerogels and Their Applications.* Chemical Reviews, 2002. **102**(11): p. 4243-4266.
89. Gurav, J.L., et al., *Silica Aerogel: Synthesis and Applications.* Journal of Nanomaterials, 2010. **2010**.
90. Dowson, M., et al., *Streamlined life cycle assessment of transparent silica aerogel made by supercritical drying.* Applied Energy, 2012. **97**(0).

91. Sørnes, K., *Environmental declaration ISO 14025 - Norwegian sawn dried timber*. 2012, epd-norge.
92. Grini, C., *Environmental declaration ISO 14025 - Copper-impregnated wood*. 2010, epd-norge.
93. Fossdal, S., *Environmental declaration ISO 14025/ISO 21930 - Steni Colour type 6 and 7*. 2007, epd-norge.
94. Folvik, K., *Environmental declaration ISO 14025/ISO 21930 - Paroc fire proof panel AST S*. 2011, epd-norge.
95. Graabak, I. and N. Feilberg, *CO2 emissions in a different scenario of electricity generation in Europe*, in *SINTEF Energy Research*. 2011, SINTEF.
96. Persson, M.-L., A. Roos, and M. Wall, *Influence of window size on the energy balance of low energy houses.* Energy and Buildings, 2006. **38**(3): p. 181-188.
97. Alam, M., H. Singh, and M.C. Limbachiya, *Vacuum Insulation Panels (VIPs) for building construction industry – A review of the contemporary developments and future directions.* Applied Energy, 2011. **88**(11): p. 3592-3602.
98. OKAGEL. Cited 2013; Available from: http://www.okalux.de/en/solutions/brands/okagel.html.