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Sustainability performance analyses in zero emission buildings:

A case study of an office for the Norwegian
Defence Estate Agency

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MASTER THESIS

for
Student Ellen Ramsnes

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Sustainability performance analyses in zero emission buildings:

A case study of an office building for the Norwegian Defence Estate Agency

Bærekraft ytelsesanalyse i netto nullenergibygg:
en case-studie av et kontorbygg tilhørende Forsvarsbygg

Background and objective

Nowadays, buildings constitute a significant field of intervention to achieve the Sustainable Development goals, being responsible for several environmental impacts, as well as economic and social consequences. Therefore, the construction of zero emission buildings (ZEBs) could be noteworthy in a holistic sustainability perspective.
In the last years, specific methodologies have been employed for sustainability evaluation of buildings throughout the life cycle, e.g., life cycle assessment (LCA) and life cycle costing (LCC). Currently, there is few case-studies looking into both the LCC and LCA of buildings. With the increased implementation of low-energy buildings, there is a need for combining LCA and LCC, to integrate quantitative information in the construction process, to determine the buildings sustainability level and to make comparisons between the environmental performance and the associated costs. As new regulations for environmental requirements within public procurements take effects, environmental costs can now be included in the investment decision. LCA and LCC are tools that can be used for calculating the environmental/economic costs and form the basis for how these are weighted.
The objective of this master thesis is to define a methodological approach to evaluate the sustainability performance of ZEBs, which might be integrated in the decision and business context. Therefore, a specific case study from the Norwegian Defence Estates Agency will be examined and its sustainability level will be assessed, by identifying significant performance indicators. Such indicators will be assessed, through specific methodologies, such as LCA and LCC, for the project as built and some alternatives, including different solutions for building materials and technical systems. The decision and business context of the examined project and a possible approach to integrate sustainability performance indicators will also be discussed. The findings of this research work might be used in the decision-making context for the assessment of the different sustainability-related impacts of different solutions in nZEBs. Furthermore, the results might be useful both for academics and practitioners who are interested in nZEBs and would like to increase their knowledge about the sustainability performance of such buildings and its possible integration in the business context, towards business models delivering sustainability.
The work will be carried out in collaboration with Forsvarsbygg, with Magnus Sparrevik as contact person.

The following tasks are to be considered:

1. Carry out a literature and document study on topics of relevance to this thesis, with a focus on recent developments in sustainable performance analysis, in line with a set of research questions that you define as basis for your work. Be sure to align these research questions with the interests of Forsvarsbygg, so that the work is likely to contribute to their needs.
2. Collect the information needed to describe and analyze the case study selected for analysis. Describe the case, its characteristics and technological choices. Collect data and information that is needed for a quantitative analysis of this case, with the aim to analyze and document how this building performs in relation to selected criteria and performance metrics.
3. Develop a methodology that is suitable for use when doing a systematic analysis of sustainability performance, focusing on life cycle energy use, life cycle costs and emissions, with a structure and scope that reflects the interests and needs of Forsvarsbygg in a sustainable business model strategy.
4. Carry out the analysis of your case, using the information you collected and the methodology you developed above, in order to provide results you can use to inform the research questions you defined.
5. Test selected alternative solutions in terms of materials and technical system for the case study, and explore the results by conducting sensitivity analyses. Present the results in an effective way.
6. Discuss the main findings of your work and how these agree with or add to what is available in literature. Discuss strengths and weaknesses in your work, and the main practical/methodological implications, together with recommendations and aspects to follow-up on in later research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

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Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2017

H. Brattebø

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Professor Helge Brattebø
Academic Supervisor

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Abstract

Energy consumption in the building sector account for 40 % of the total energy use in Norway. One of the actions to lower the sectors impact on the climate change is to improve the energy efficiency in buildings and increase the use of renewable energy sources. Political incentives are taken to obtain a considerable reduction of CO_2 -emissions. From 2020, all new buildings should be nearly zero energy buildings (nZEB), pursuant to the directive on Energy Performance of Buildings.

With a higher focus on the environmental impacts from products and processes, the demand for including sustainability analyses in the decision context under the construction planning increases. By taking advantage of life cycle analyses (LCA), the energy use and environmental impact connected to the different life stages of a building can be calculated.

In this case-study, the sustainability performance of a nearly zero emission building has been investigated. The owner is the Norwegian Defence Estates Agency, which is one of the main stakeholders in the construction sector in Norway. Due to their position, they want to investigate the value of constructing low-energy buildings compared to standard buildings.

Five sustainability performance analyses of the office with different material solutions have been conducted in SimaPro. The performance of the building is computed for:

- Alternative 1:as built (with low-CO_2 emission concrete).
- Alternative 2: as built, but with normal concrete.
- Alternative 3: as built, but with timber bearing structures.
- Alternative 4: as built, but timber bearing structures, timber façade and wooden windows.
- Alternative 5: as built and with PV panels attached to the façade facing south

The analyses include the following life cycle phases: construction, use phase, transport and replacements. Through LCA certain chosen environmental indicators were quantified, i.e. Global Warming Potential (GWP), Cumulative Energy Demand (CED) and Net Present Costs (NPC). Through life cycle costing (LCC) methodology, the life cycle costs related to the different building alternatives have been calculated.

For the performed analyses, the results reveal that the main differences between the alternatives are found in the GWP. Some alternatives had less CED than the others, but no big savings were found when comparing the NPC. Alternative 4 performed best in terms of GWP with an annual

emissions of 7.5 kg CO2-eq. per m^2. Alternative 5 showed the lowest CED, 56 kWh/ m^2yr. The construction phase and operation had the greatest contribution to the analysed indicators.

Preface

This case study is part of the master thesis in the 2-year Master in Industrial Ecology at the Norwegian University of Science and Technology, Department of Energy and Process Engineering.

I would like to thank my supervisor Helge Brattebø for guidance and suggestions, and a special thanks to my co-supervisor Roberta Moschetti for her help in teaching me new computer programs, advising and encouragement during the semester. You have been a very valuable helper. Another thank to Magnus Sparrevik at Forsvarsbygg for providing information and data on the given case.

I would also address a word of thanks to my class for two good years with a lot of fun and for useful help, discussions and motivation during the work with the thesis. Good memories!

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Abbreviations

AC	Equivalent Annual Cost
CO_2	Carbon dioxide
EEA	The European Economic Area
EU	The European Union
GHG	Greenhouse gas emissions
GWP	Global warming potential (100 years-time horizon)
IPCC	The Intergovernmental Panel on Climate Change
kton	Kilo ton
LCA	Life cycle assessment
LCC	Lice costs assessment
LCI	Life Cycle Inventory
LT	Lifetime
NAFLO	The Norwegian Armed Forces Logistic Organisation
NDEA	The Norwegian Defence Estates Agency
NPV	Net present value
nZEB	Nearly zero energy building
PV	Photovoltaic cell
ZEB	Zero emissions building

1 Introduction

1.1 Background

The energy use in buildings amount to 40 % of the energy consumption and about 36 % of the CO_2-emissions in the European Union (EU) [3]. Globally, buildings account for 32 % of total energy use and one-third of black carbon emissions [4].

A considerable increase in energy usage in buildings is projected as the standard of living in developing countries improve. As more and more people gain access to cooking facilities, household appliances, and better living conditions, it leads to a greater electricity demand [4]. Also, a global change related to migration takes. Cities are growing as people move away from rural areas. The cities' residential areas increase, while at the same time the size of households in terms of persons per m^2 decreases [4]. In addition to the above, the forecasted population growth, and the continued development of countries, the expected increase in energy demand in the building sector is significant.

With the available technologies to improve energy efficiency in buildings and the use of renewable energy sources, there is a potential to evade an increase in the final energy usage. According to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report, the implementation of cost-effective energy efficient technology, knowledge about building design, construction, and human behavioural changes allow a two to ten-fold reduction in energy demand in new buildings and up to four times reduction in energy demand in existing buildings [4]. The use of home automation (smart home technology) as well as energy efficient appliances and lighting are listed in the report as other measures to decrease energy consumption.

A greater reduction in the energy demand in buildings is important to reduce their contribution to climate change. Implementation of nearly zero energy buildings (nZEBs) and zero emissions buildings (ZEBs) can work as one alternative initiative in this action. These buildings have low energy demand due to effective energy measurements in e.g. lighting and ventilation systems as well as compact thermal building envelopes.

Norway has committed to reduce the greenhouse gas emissions (GHG) by 40 % of 1990 emissions by 2030, and to become a low emissions society by 2050 [5]. About half of the Norwegian carbon footprint derives from government procurements, where buildings and infrastructures are the main contributors [5, 6]. Thus, the public sector is instructed to reduce their environmental impacts and promote sustainable solutions as well as make use of life cycle costs to evaluate new procurements [5].

In March this year, a new proposition on Norway's climate target was made, Klimaloven, aligning with the Paris agreement on reducing GHG-emissions and negative effects regarding global warming [7]. With this new proposition, the need for sustainability analyses increases. Hence, extensive usage of tools such as life cycle analyses (LCA) to compute the environmental impacts related to e.g. new construction will become more important.

1.2 Thesis objective

The aim of this case-study was to investigate the sustainability performance of an nZEB building owned by Forsvarsbygg, the Norwegian Defence Estates Agency (NDEA), with respect to energy requirements and emissions. This is their first nZEB classified office-building, and a pilot for implementing more energy efficient buildings in the future. The building is analysed as built, with low-emission concrete, and compared with the hypothetical use of standard concrete and other material solutions.

An LCA was performed using the SimaPro software to calculate the sustainability performance of the building with respect to energy consumption and climate gas emissions. This included energy use and CO_2-emissions from materials in the construction phase, replacements, transport of these and the materials to the construction site as well as the operation of the building in terms of energy usage. The net present costs and annual costs for the different alternatives have been computed. The objective is to answer the following research questions:

- How do the different material alternatives perform in terms of global warming potential, life cycle costs, and energy demand?
- Which building component influences the sustainability indicators the most?
- What are the uncertainties and sensitivities for the case?

1.3 Structure

Chapter 2 presents theory and literature relevant for the analyses of the case study. Chapter 3 elaborates and discusses the methods for the life cycle analyses and the life cycle costing, and the calculations for the different alternatives. The results from the analyses are given in chapter 4. Sensitivity analyses are found in chapter 5. The discussion of the results, methodology, weaknesses and strengthens are presented in chapter 6. Chapter 7 contains the conclusion from the findings in the thesis and gives suggestions for future work.

2 Theory and literature

2.1 Zero Emissions Building (ZEB)

An nZEB is defined as an energy efficient building with a near zero, or very low energy demand. Energy from renewable sources and renewable energy produced on-site or nearby, should cover as much as possible of the required energy [8]. In comparison, the definition of ZEB, according to the Norwegian Research Centre on Zero Emission Buildings, is based on greenhouse gas emissions during the lifetime of the building. A number of ZEB ambition levels exist, divided into different categories by the performance of the building as illustrated in Figure 1[9].

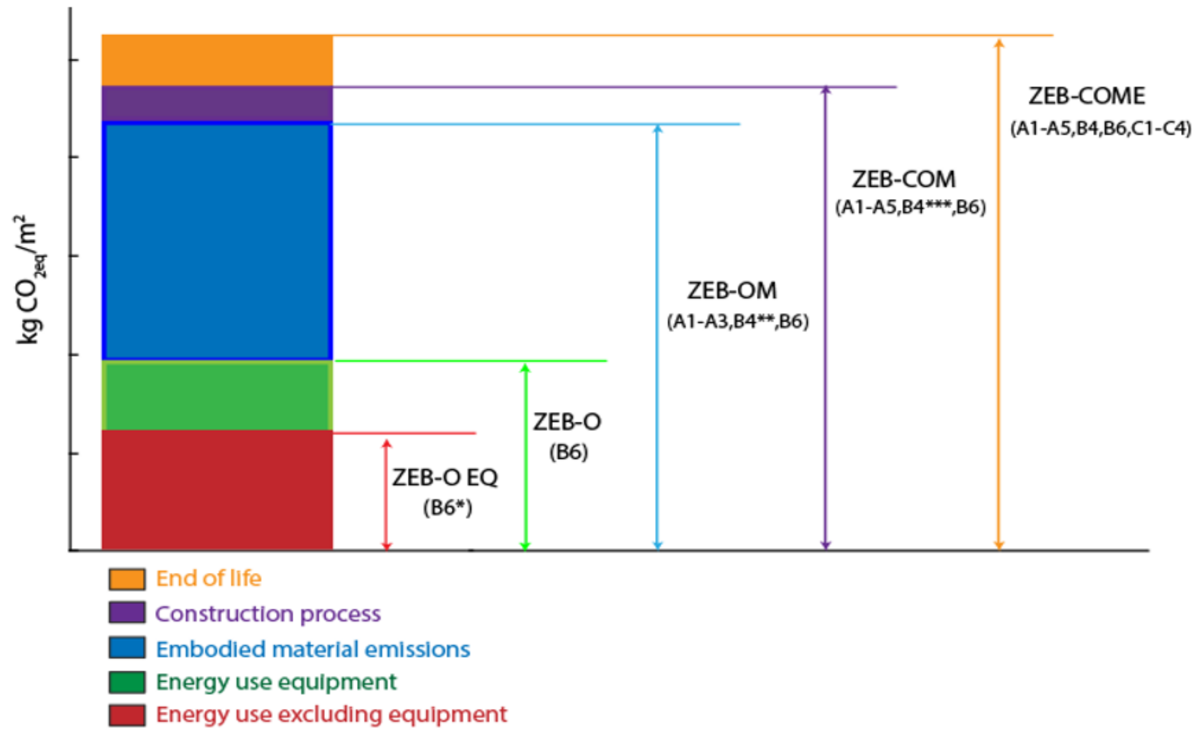


Figure 1: ZEB ambition levels from the Norwegian Research Centre on Zero Emission Buildings [6].

Categorisation of the different ZEB ambition levels for a ZEB [9]:

O: Emissions related to operational energy use.

M: Embodied emissions in the building materials.

EQ: Emissions from technical equipment during the use phase.

C: Emissions associated with construction and installation.

E: Embodied emissions connected to the end of life phase of the building.

The five ambition levels differ in how life cycle stages are included in the calculated emissions. In “A Norwegian ZEB definition guideline”, the product stage includes extraction and processing of raw material (A1), transport of raw materials (A2), and manufacturing (A3) [9]. Transport of materials to the construction site (A4), and energy and waste from the construction (A5) are part of the construction process stage in the guideline. The definition of the “use”-stage during the lifetime of a building, involves the usage of building components, maintenance, replacements, and repair (B1 – B5) as well as the operation of the building (B6 -B7). Demolishing (C1), transport to the waste treatment (C2), waste handling (C3), and disposal (C4) make up the end of the life stage [9].

The lowest level of a ZEB in the guideline is the ZEB-O EQ, which only includes emissions from the operation of the building, not accounting for emissions from technical equipment. The highest ambition level, as seen in Figure 1, ZEB-COME, takes all emissions from cradle-to-grave into account, thus from the extraction of materials to the end-of-life treatment.

2.1.1 Construction materials in ZEBs

2.1.2 Timber

Norway has a long tradition of using timber as a construction material, however, the use of steel and concrete has been significant in larger buildings during the last century [10]. With new wood-based construction components, the inclusion of these in the building regulations, and its environmentally friendly qualities, the use of timber in constructions has revived in recent years [11]. In the report «Bruk av tre i offentlige bygg», following characteristics with timber as a construction material are emphasized [11]:

- Versatile in most types of public buildings
- Low GHG-emissions from wood
- Often short construction period and less transport of materials
- Competitive pricing (especially massive wood)
- Can be combined with other materials, e.g. concrete, aluminium, glass, etc.

Precedent buildings with timber constructions are the apartment blocks «Treet» in Bergen, the student housings Moholt 50|50 in Trondheim and Olympiaparken in Lillehammer [12-15].

Figure 2:Moholt 50/50, student housing in timber [14].

Glue laminated timber and massive wood are common materials in bearing structures, walls, and roof. Fibreboard and oriented strand board, Masonite beams, and plywood are used for structural and panelling applications [10].

The use of wood in buildings has increased in Europe as it has become easier to utilize in industrial building processes, reduces emissions, and makes a favourable indoor environment [10]. The selection of construction materials depends on features regarding replacements, maintenance, architectural style, and costs. Timber cladding can reduce the need for painting and outer coating, cutting emissions from treatment and costs for maintenance, but may increase the demand for e.g. cleaning [10].

The production of materials is often energy intensive and the process that contributes most to GHG-emissions in a life cycle perspective of a building. Studies demonstrate that the production of wooden construction materials has lower emissions than the production of construction materials based on steel and concrete, low-carbon concrete and recycled steel included [10]. This is because the production of the last-mentioned materials is very energy demanding, in addition to the release of CO_2 during the calcination process of concrete [10]. To manufacture 1 m^3 of wood, 457 kWh are consumed, of which about 81 % is sourced from renewable energies [16]. In addition, timber products have lower emissions to air, water, and soil as well as less use of chemicals [16]. Åsveien elementary school has reduced the emissions by 40 % compared to the old school, and Moholt 50|50 has a reduction of 50-60 % compared to traditional construction standard [10, 15].

Timber construction materials, particularly massive wood, have been more expensive than other options as e.g. concrete [10]. But, as the usage of wood increases and mass production of timber construction components develops, wood becomes competitive as a material alternative. In an LCC perspective, a shorter construction period puts capital faster into circulation and improves the economic results. To make wood even more attractive, the value chain in the construction industry must continue to improve the efficiency and develop pre-cut solutions [10].

Additionally, an important type of wood used in ZEB construction is glue laminated timber, which is construction timber mainly used in load bearing structures [17]. To achieve longer spans, wood lamellas are joined together in parallel in the length direction and glued under force [17]. This makes it possible to use timber independent of the size and fit it to the building. Glue laminated timber can be used both inside and outside as long as it is used according to the climate class [17].

2.1.3 Low-carbon concrete

To reduce GHG-emissions related to concrete in constructions, different types of low-carbon concrete have been developed. These contain fly ash, silica dust and hydraulic binding material [18]. Low-carbon concrete is classified in three different levels based on emissions for a selection of combinations of strength classes and constancy classes [18]:

- Low-carbon concrete A: highest classification, demands special measures
- Low-carbon concrete B: obtained with ordinary technology
- Low-carbon concrete C: achieved with easy changes in the prescription

The different low-carbon concrete classes and their related CO_2-emissions are listed in the Appendix. The emissions are compared to the Norwegian industry references for standard concrete, retrieved from EPDs. However, there are great variations in GHG-emissions based on production locations [18]. Which means that standard concrete by some producers may have the same emissions as the low-carbon concrete. Standard Portland concrete contains limestone, quartz, iron oxide and aluminium oxide, crushed and burnt in a cement kiln [18]. Calcination occurs during the burning process, resulting in emissions when CO_2 splits from the calcium carbonate ($CACO_3$) [18].

2.1.4 Carbon storage in construction materials

Through the carbon cycle, wood bonds carbon by the absorption of CO_2 in the photosynthesis, until it is released by incineration or degradation [16]. The CO_2 released is referred to as biogenic CO_2 emissions. 1 kg of wood stores about 1.8 kg biogenic CO_2, but when cut down remaining biomass would be decomposed and make CO_2 again [10]. In the processing of wooden construction elements, by-products as bark and chips, often used in energy production, will release CO_2. And there will be additional emissions related to energy use in the different phases of processing forest to construction materials. As long as the same volume of biomass stock remains, use of wood in buildings can function as a biogenic carbon storage [16]. Construction materials of wood with low emissions in the production phase will reduce CO_2-emissions if they are replacing materials with higher emissions [16]. A building with timber materials can store between 700 to 1000 kg CO_2 per m3 [10]. However, the climate benefits from storing biogenic carbon in buildings depend on which source the wood is derived from. Wood from slow-growing biomass feedstock will not yield a reduction of CO_2 in the atmosphere and hence no cooling effect on the climate [19].

A carbonising process also takes place in concrete, where the calcium in concrete binds to CO_2 in the air. The total effect of carbonisation is moderate compared to carbon storage in biomass [10]. When assuming a life time of 100 years for concrete structures, 15 % of emissions from the yearly concrete consumption is absorbed [20].

The production of concrete is highly energy demanding, making electricity the main contributor to CO_2-emissions [19]. In Australia, the use of fly ash in concrete reduced the CO_2-emissions by 13-15 % compared to the standard concrete [19].

2.2 Sustainability performance analyses

Sustainability performance analyses are utilized in the construction sector to determine how a building performs with respect to selected criteria relevant for the involved parties. By looking at performance indicators within the domains of environmental, social and economic sustainability, different solutions for the construction materials can be compared. In the SEOPP research project on renovations of dwellings, Moschetti et al. [21] found important sustainability indicators for stakeholders in building projects to be:

- Climate change
- Energy use

- Non- renewable energy
- Indoor air quality
- Thermal comfort
- Investment costs
- Global costs

The results of the analyses gave the stakeholders the opportunity to decide which indicators are most important to them. Choices regarding design, materials, technical installations and energy sources can then be evaluated. The performance of a building can be calculated with the life cycle assessments and life cycle costs.

2.2.1 Life Cycle Assessment

LCA is a tool to quantify and evaluate the environmental aspects of products, processes, and services. The performance of a functional unit during the different phases within a life cycle is measured, making it possible to compare technologies and the environmental impacts from products and systems [22]. The functional unit is the object or service process under investigation. Stages included in the life cycle are; extraction of raw materials, refining, production, use phase, transport, maintenance, recycling, and end-of-life treatment [22].

The total impact for all processes associated with the functional unit includes direct and indirect emissions of the requirements. Direct emissions are emissions from the process by which the functional unit is defined, and emissions generated in the other processes related to this are indirect emissions [22]. The LCA method includes four steps as illustrated in Figure 3. Generic life cycle phases of a building are shown in Figure 4.

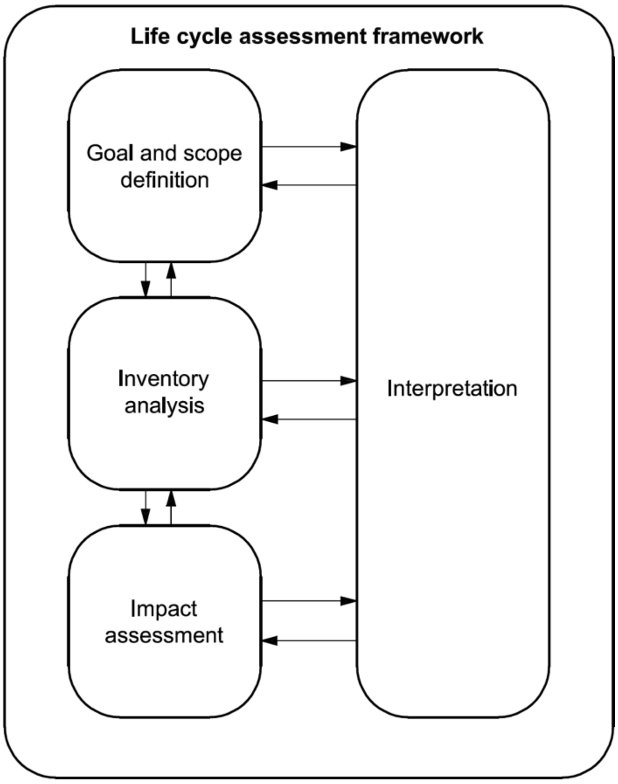


Figure 3: The LCA framework in ISO14040 [23].

Step 1: Goal and scope

The goal and scope define the functional unit, system boundaries, and the aim of the analyses [23]. This step takes the decision context, the purpose of the applications, and the audience into account. The object that is going to be evaluated is defined as specific as possible with regards to e.g. brand, regulations, processes etc.[24]. When deciding the goal, the reasons for performing the analysis, choice of methodology and limitation should be identified [24]. The system boundary is set due to processes, life cycle stages and the type of activity [24].

Step 2: Inventory analysis

Collection of data and information for the different life cycle stages are included in the inventory analysis [23]. This includes processes in the foreground system and the flow of products and waste connected to the background system [24]. The inventory for the different alternatives to be analysed is made.

Step 3: Life cycle impact

In this step the calculation of the impacts from the various life cycle stages makes it possible to track which processes, flows, parameters, etc. of the analysed system influence the environment the most [24]. In the life cycle impact assessment, the identified energy and material flows are assigned to different environmental impact categories, i.e. climate change, acidification, etc. [23].

Step 4: Interpretation

The last step is to interpret and evaluate the findings in the three previous stages. The main contributors to environmental impacts in total and for different categories should be identified [24]. Sensitivity analyses are used to check the consistency and to which extent the quality of the LCA is fulfilled [24]. The conclusion of the study and its assumptions and limitations forms the basis in the final recommendation.

These four steps also underlie LCA software. The importance of computing the environmental impact of products and buildings is increasing in business due to legislations and the market value of green goods. SimaPro is an LCA software that calculates sustainability performance of services and products by monitoring and analysing the supply chain [25]. The software can, among other things, measure water and carbon footprint, generate environmental product declarations, and deduce key performance indicators [25]. This makes SimaPro a useful tool for calculating the environmental impacts of products and services throughout the life cycle or in the different life cycle stages. The generic life cycle of a building, as is relevant for the present thesis, is shown in Figure 4 [26].

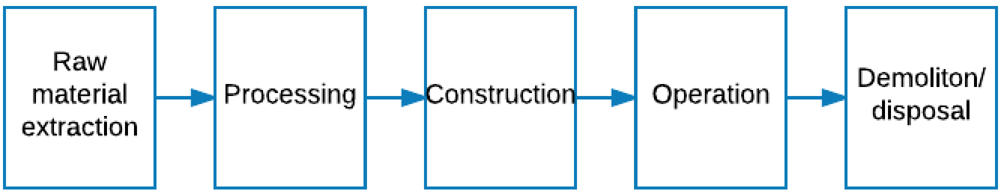


Figure 4: Life cycle phases of a building [26].

To describe the environmental impacts from a product, service or a component, labelling in accordance with the ISO-standard 14025, Environmental Product Declaration (EPD), are made [27]. LCAs make the foundation for the EPDs, reviewing the environmental performance with respect to resource use and emissions from cradle to gate, using the standard ISO 14040:2006 [28]. This makes it possible to compare products within the same product categories and across countries. Compulsory stages included are the following ones [28], as is also shown together with exemplary optional stages in Figure 5:

A1: upstream processes from cradle to gate

A2: external transportation to core processes and waste disposal

A3: manufacturing processes from gate to gate, (pre-treatment, extrusion, energy flows, etc.)

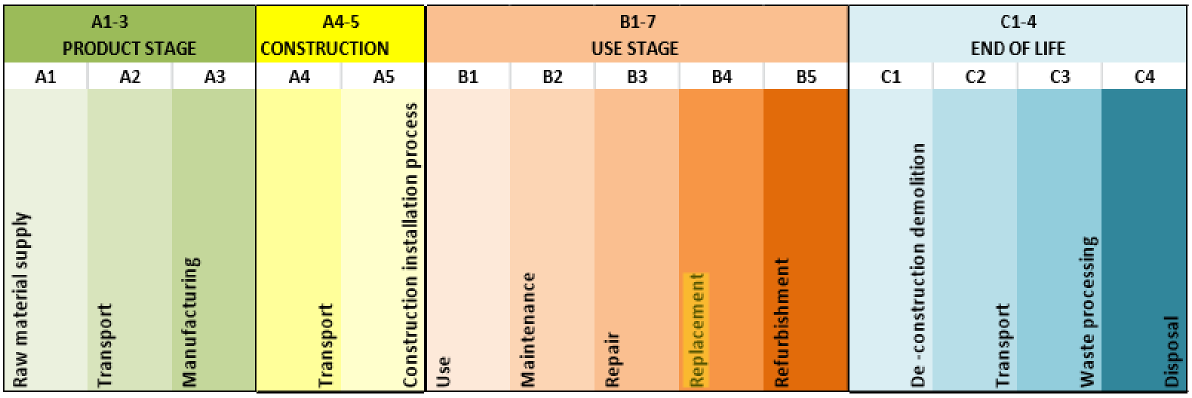


Figure 5: Stages in LCA from the standard EN15978 [29].

An EPD is valid for five years and contains [28]:

- Producer and program name (e.g. EPD-Norge)
- Description of the product
- System boundaries and list of inputs/outputs
- Data collection and modelling information
- Information of environmental performance
- Additional environmental specifications (recycling, end-of-life treatment, etc.)

The environmental performance of the product is in EPDs evaluated with respect to the impact categories listed in Table 1.

Table 1: Impact categories described in EPDs.

Impact category	**Unit**
Global Warming Potential (GWP100)	kg CO_2-eq
Ozone Layer Depletion (ODP)	kg CFC-11-eq
Acidification Potential (AP)	kg SO_2-eq
Eutrophication Potential (EP)	kg PO_4- eq
Photochemical Oxidation Potential (POCP)	kg C_2H_2-eq
Abiotic Depletion (elements)	kg Sb-eq
Abiotic Depletion (fossil)	MJ

2.2.2 Life cycle costing

Life cycle costing is a methodology that allows describing the accumulating costs over a building's life time, from the projecting phase to the demolition and disposal of materials (Figure 6, according to ISO 15686-5 [30]). It calculates the relation between capital costs (investments cost), and annual operation costs, including maintenance (referred to as O&M) [31].

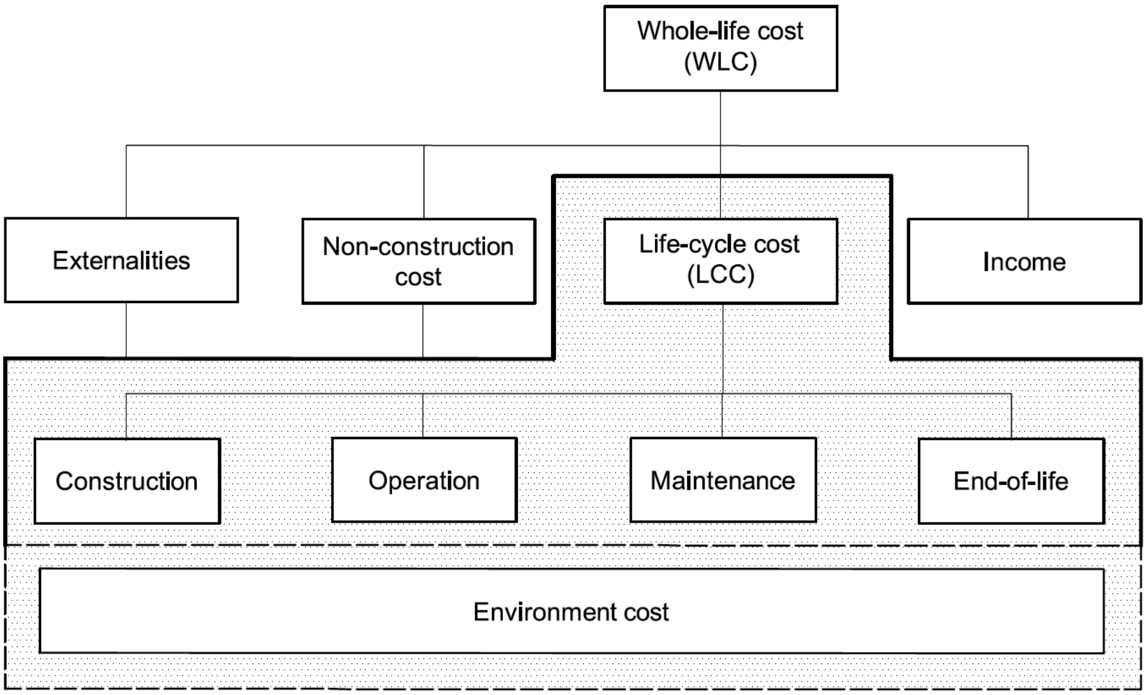


Figure 6:The phases included in LCC, from ISO 15686-5 [30].

Since the practice of applying life cycle costing started in the late 1990s, the interest of assessing life cycle costs (LCC) has coincided with the practice of sustainability performance analyses such as LCA [32]. The emphasis on the environmental impacts from the building sector as a main contributor to GHG-emissions make it reasonable to connect costs and sustainability to find the best options for design and performance with respect to the environment. LCC analyses the capital costs and operation costs over the life span of a building, and make the total annual costs visible [33]. By calculating the LCC in the beginning of a project, a greater scope of balancing capital costs and operation costs exist, which may potentially reduce the management, operation, maintenance, and development costs. Limitations in the application of LCC are related to the inconsistency in the use of input parameters like e.g. life span, discount rate and the ratio of investment costs to operation costs [32]. In earlier studies, LCC has been used to compare environmental performance and energy-efficiency with respect to materials and components, occupancy, technology systems, construction methods, and retrofits [32].

LCC is a useful tool for [26]:

- Decision making in planning of projects, by analysing different building parts, materials, technical systems in terms of costs or economic efficiency.
- Scheduling of maintenance and replacements.
- Comparing data with reference projects and other buildings.
- Understand trade-offs between investments and running costs.
- Establish value for sustainability certification, e.g. credit in BREEAM.

In Norway, the standard NS 3454, life cycle costs in buildings, defines the life time costs as the net present value (NPV) of the life cycle costs, and the annual costs as the annuity of the LCC [34]. NS 3454 can be used to calculate the costs in early stages of a project, for the construction and operation of a building [34]. The results can be e.g. utilised for comparing of alternative solutions, selection of components and systems, or an estimation of measurements and operation systems [34].

To calculate the life cycle costs, future costs are converted to present value by use of the real discount rate [33]. The net present cost (NPC), i.e. the NPV of the LCC, is calculated according to the equation:

$$NPC = I + \sum_{t=1}^{t=T} \frac{(MO\&M)_t}{(1+r)^t} + \frac{D-R}{(1+r)^T}$$

where I is the investment costs, t is the time with T being the period evaluated, and r the real discount rate. MO&M is the management, operation and maintenance of the building, D is the disposal costs and R the residual value [35].

To see what the Equivalent Annual Costs (EAC) would be if they were evenly distributed over a building’s lifetime, an annuity factor b which depends on r and T is applied [35].

$$EAC = NPC \cdot b(T), whera\ b(T) \frac{r}{1-(1+r)^{-T}}$$

2.3 Literature review

2.3.1 ZEB definition

Several articles providing definitions of ZEB are available in the literature, as well as studies on sustainability performance of ZEBs. Different definitions for ZEBs are based on political targets and national building codes. Some including only the thermal or electrical demand, other includes energy production on-site [36]. As the number of ZEBs increases and nZEB as the future building target, the need for an agreement on an international definition is fundamental.

Buildings connected to the grid can be called net ZEB, underlining the balance between energy consumed by the grid and energy exported to the grid over a period of time [36]. Igor Sartori et al [36] looked further into the problems connected with different definitions dependent on the requirements and condition in the country, in the article «Net zero energy buildings: A consistent definition framework» [36]. They found that defining ZEB based on the annual balance of energy is not sufficient, and that the interaction between the energy grid and buildings should be looked further into. It was concluded that a common framework describing criteria and specific characteristic with respect to; building system boundary, weighting system for energy carriers, Net ZEB balance, temporal energy characteristics and measurement and verification should be implemented internationally [36]. The balance between imported and exported electricity and load and generation is central in describing the ZEB.

In another article, «Zero Energy Building – A review of definitions and calculation methodologies», it was stated that a clear and consistent definition of ZEB should be developed before ZEB is completely implemented in national building codes and international standards [37]. Issues for making a new ZEB definition emphasised in this study regards: 1) energy balance, i.e. period, type of energy use included and what type of energy balance, units in the metrics (CO_2-eq, energy costs, etc.), 2) renewable energy supply options, 3) connection to the energy infrastructure and 4) energy efficiency requirement in terms of indoor climate and losses to the grid [37]. Elaboration of these parameters can contribute in the solution for making a ZEB definition that can be adopted in building regulations across countries.

Cellura et al. [38] extended the net ZEB methodological framework by introducing the life-cycle perspective in the energy balance. They analysed a case study, i.e. an Italian building tailored to be a net ZEB. The annual final energy balance showed a deficit which made the case study a nearly net ZEB when the encountered energy flows were measured at the final level; however, shifting from final to primary energy balance, the case-study moved to a non-net ZEB condition, because of the large difference between the conversion factors of photovoltaics generated and imported electricity. The introduction of a life cycle perspective led to an increasing complexity of the energy balance calculation and highlighted the importance of the embodied energy of the building, which should not be neglected in the exhaustive evaluation of the energy demand of low energy buildings.

2.3.2 LCA and LCC analyses in nZEB projects.

Only few studies were conducted on LCA and LCC in nZEB projects. In their paper titled "Life cycle emissions analysis of two nZEB concepts", Georges, Haase et.al. [39] investigated the operation phase and embodied emissions in materials to evaluate the correlation between their emissions over the building's lifetime. The analyses indicated that the CO_2-factor for electricity had significant impact on the overall CO_2-emissions, the factor in the baseline case was 132 g CO_2-eq/kWh [39]. In the alternatives with higher emission factors (European mixes), the operation phase dominated the contribution to CO_2-emissions, while low emission factors made the contribution from embodied emissions the largest [39]. In the base case, the embodied emissions were larger than the one from operation of the building [39]. The paper shows that for the office (~2000 m^2), PV panels, floors, and external walls yield the greatest CO_2-emissions. In the case where PV panels are produced with another energy mix than the Norwegian electricity used for the operation of the building, the electricity production on-site cannot compensate for the embodied emissions in the PVs [39]. The results in the paper also point out that the emissions in the construction phase are higher than the emission reductions achieved by using electricity from PV panels.

Dokka et al. [29]developed a zero-emission concept of an office building by modelling and calculating the energy use, embodied emission and the total CO_2 emissions for a typical Norwegian office building. The objective was to find the most important parameters in the design of a zero-emission office building, according to the current ZEB definition. The authors concluded that, for a typical medium raise office building (4 storey), the achievement of ZEB-O (Operation) level can be easily fulfilled, with the energy produced on-site by PV equalling the total electricity demand. However, when considering also the embodied emissions from materials and installations, the achievement of the ZEB-OM (Operation and Material) level seems very difficult, as embodied emission can be considerable higher than the emission related to operational energy use. The authors suggested a combination of further reduced energy demand, high performance thermal supply systems, reduced embodied emissions and increased PV-production, to achieve the ZEB-OM level.

Hofmeister et al. [40] presented a comparison of the life cycle GHG impact of a concrete/steel load-bearing structure with a wood load-bearing alternative. A theoretical ZEB office concept of a four story Norwegian office building was used as basis for the comparison. The results show that the wooden structure causes approximately half the emissions of the concrete/steel structure. At the same time, concrete and steel are responsible for 75 % of the production phase emissions, even in the building with the wooden load-bearing structure. The end-of-life emissions account for less than 10% of the overall GHG emissions from the load-bearing systems life cycle. The authors concluded that, end-of-life emission and production phase emissions, are strongly influenced by the system boundary and by the interdependencies and possible synergies within the system. Therefore, evaluating a building's life cycle emissions in the context of a larger 'ecosystem' could open untapped potentials.

As above mentioned, it is remarkable that only few studies including both LCA and LCC analyses in nZEBs are available. The here presented core results of three of them serve as a reference to the results from the present case study. However, the comparison of the results has not always been feasible due to too different methodologies or not transparent assumptions and data.

2.4 Building regulations

Political incentives are essential to accelerate the deployment of energy efficient buildings. To reduce the energy consumption and increase the use of renewables in Europe, the European Union Directive on the Energy Performance of Buildings has proposed that from 2020 on, all new buildings should be nearly ZEB [3]. As a member of the European Economic Area (EEA), Norway has committed to many of the same regulations for the climate and environmental politics within the European Union (EU), with the target of reducing climate gas emissions by 40 % by 2030 compared to 1990 [41].

Energy requirements in technical regulations for buildings are set through the Norwegian standard TEK10 introduced to the plan and building law in 2010 [42]. The standard includes requirements for [42]:

1) Quality and documentation on building materials, operation and maintenance of the building. Requirements for premises, parking and use area, building height and calculation methods.

2) Security against floods, erosion and forces of nature. Buildings should be adapted to the location and terrain, and minimise the impact from construction and waste on the environment.
3) Construction- and fire-safety, layout, and building components. Requirements for indoor environment (e.g. air quality, noise, lighting, ventilation, etc.)

The TEK10 standard aims to improve performance of new buildings, increasing the level of energy efficiency. For non-residential buildings, the minimum requirements to energy demand and building components for passive house and low-energy buildings are set in the passive house standard NS3701. This involves restrictions for buildings regarding [43]:

- Space-heating and ventilation
- Cooling demand
- Energy supply
- Energy demand for artificial lighting
- Heat transfer coefficient for transmission- and infiltration loss

3 Methods

3.1 Methodological approach

The methodological approach in this thesis includes a literature review of the state of the art in sustainability analyses and the definition of ZEB. Figure 7 illustrates the method used in the thesis. The chosen case-study represents an energy efficient nZEB constructed with low-emissions concrete. The involved proprietor is NDEA, that built their first nZEB and want to see if the building performs as calculated and how the results would have changed if other building materials were used.

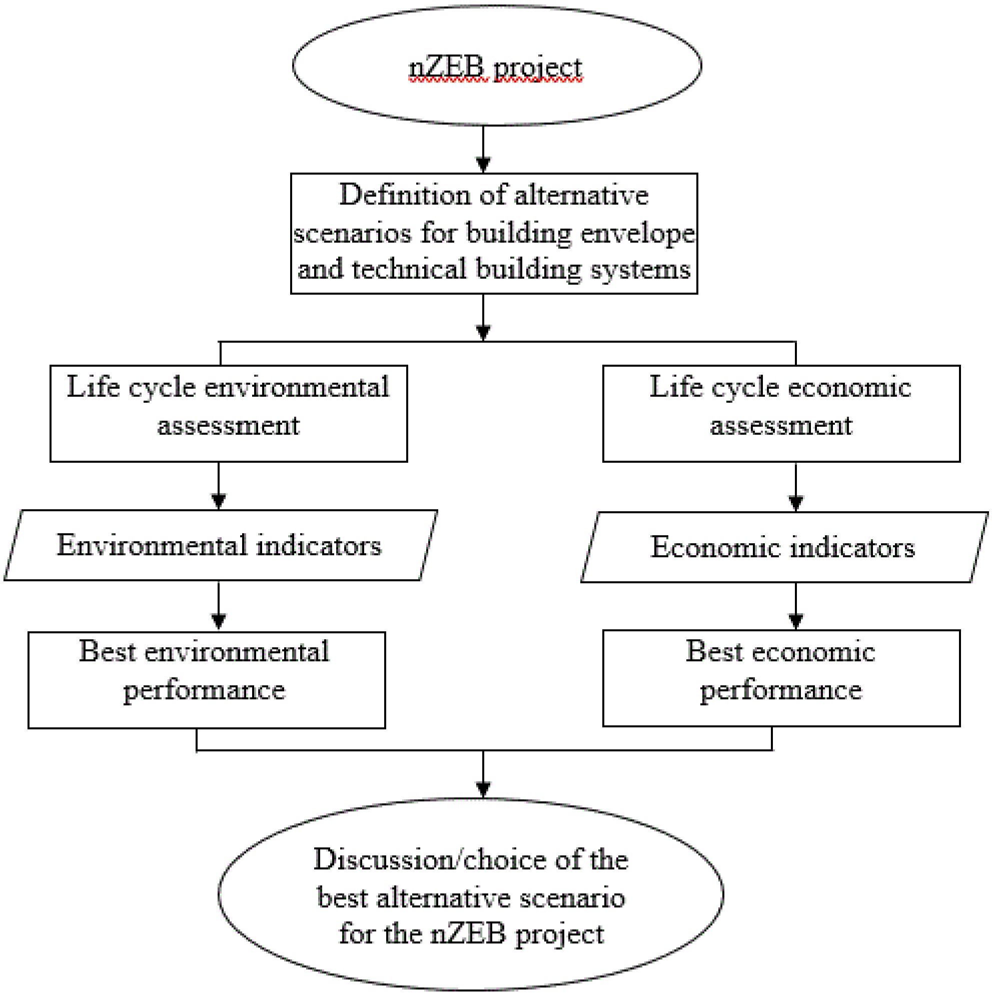


Figure 7: The methodological approach in thesis.

LCA and LCC are considered as well suited tools to perform environmental and economic performance analyses on buildings. GWP, cumulative energy demand (CED) and NPC are chosen as meaningful and relevant sustainability performance indicators, and assessed for the construction phase, transport of materials, and the use phase of the building. Life cycle environmental and economic assessments are used to compute the sustainable performance of the case-study. The obtained results are finally evaluated.

3.2 Case building

The Norwegian Defence Estates Agency (NDEA) is the major government stakeholder in estate management in Norway, with activities within construction, renting, administration and sale of properties [44]. NDEA is subordinated to the Ministry of Defence and is responsible for managing official buildings, facilities, and properties of a magnitude of around 4.1 million m^2, equivalent to 12 407 buildings [11, 44]. NDEA aims to be a driving force behind energy efficiency in buildings, and, as a public enterprise, new buildings should be constructed in accordance with the passive house standard as a minimum [11]. The climate benefits from the use of environmentally friendly solutions in new buildings and renovation projects will be illustrated in the examples to follow [45].

To increase the awareness on environment within the defence sector, NDEA focuses on three areas for the period 2016-2020 [45]:

- Climate, energy, and waste
- Reduction of emissions and noise related to military activity
- Nature and cultural values to secure biodiversity and public access.

Of these, the first focus area is relevant for the present thesis and includes a reduction in energy use and emissions of climate gasses, phasing out use of fossil fuel for space-heating as well as improved waste management [45]. A strategy for the selection of technical solutions for space heating should be developed by 2017 [45]. By renovation and construction of energy efficient new buildings, the aim is to reduce the energy need in the operation of the-properties with 15 % for this period [45].

In December 2015, Visund, a new administration building classified as, according to the ZEB definition, an nZEB, was built for the Norwegian Armed Forces Logistic Organisation (NAFLO) [11]. This is the Norwegian army`s most energy efficient building, initiated as a test project for investigating the performance of a ZEB, and the value potential for NDEA if they choose to construct more of these buildings [11]. It is a part of SINTEF and NTNU`s pilot project in The Research Centre on Zero Emission Buildings, which wants to increase the amounts of buildings that have zero emissions of greenhouse gases related to production, operation and demolition [46].

Figure 8: Model of the office [47]

The three-floor office located at Haakonsvern in Bergen is about 2035 m^2 large with 97 occupants, shown in Figure 8. The office has the ambition level ZEB-O-EQ (see Figure 8), which means that energy for the operation of the building, except technical equipment (computers, appliances, etc.) should be covered by renewable sources [9]. The estimated net energy consumption per year is approximately 16 kWh/m^2, which is a 96% reduction compared to the old office [11, 47].

Several measures for improving energy efficiency of the building are implemented. The building envelope is well-insulated, a demand controlled ventilation with heat recovery, heat pump, and photovoltaic cells (PVs) are some of the solutions installed [48]. The installation of a sea water heat pump covers the cooling demand and 90 % of the building`s heating demand [49]. To reduce the emissions from building materials, low-carbon concrete and hollow-blocks are used [50].

To fulfil the requirement of a ZEB, PVs are installed on 340 m^2 of the roof to produce energy on-site [48]. From the account of energy calculations based on the climate in Bergen, the yearly production will be about 53 000 kWh or 26 kWh/m^2 to meet the energy requirements in NS 3031:1987 [48]. An efficiency of 17 % and a 25-degree gradient make the basis for the calculation. The delivered energy should, according to NS 3031:2007, be 84 730 kWh/year, energy from PVs not included in the calculation [49]. When electricity from the PVs are taken into account, the net delivered energy was estimated to 31 729 kWh/year [48]. Excess energy is delivered to the power grid at Haakonsvern for use in other buildings [48].

The energy target for the building is to cover: room heating, ventilation heating, fans, pumps, lighting, cooling, automechanisms, and energy demand directly connected to operation, by use of self-produced renewable energy [49]. Since the acquisition of the office, the present results from the operation are in line with the envisaged energy performance. After the first year in operation of the office, the real net delivered energy increased slightly to 34 778 kWh/year [51]. In the latest update of the energy calculations from December 2016, the actual net delivered energy per heated floor area is 17.1 kWh/m^2, which is a 7 % increase compared to the estimated 16 kWh/m^2[52].

Before the office was constructed, a climate gas budget was composed by use of the *klimagassregnskap.no*, which is a model for calculating carbon footprints of buildings. The climate gas emissions for the construction materials are estimated to be 5.8 kg CO_2-eq/m^2 per year, where the main contributor is the outer walls [53]. Estimated emissions from the operation of the office are 1.7 kg CO_2-eq/m^2 per year [53]. The heated BRA in these calculations was 2012 m^2, and the average emissions factor, 112 g CO_2-eq/kWh [53].

The expected lifetime of the building, from installation of the building components to the demolition of the building, is set to 60 years. Windows and roof covering have a lifetime of 20-40 years [54, 55] , thus a replacement of these are included in the LCI.

NDEA employed Building Information Modelling (BIM) in the planning of the office at Haakonsvern. This is a digital tool for modelling the essential information in a construction process to improve the survey, coordination and interaction between the disciplines, contractors, and sub-contractors [56]. Buildings with areas, building components, installations, and technical equipment can be simulated in both 2D, 3D, and 4D to facilitate the design and engineering as well as retrieving of material quantities and costs calculations before starting the construction [56].

3.3 Analysed alternatives

To assess how the building would perform if it was constructed different, five alternatives of the office with different material solutions were considered by LCA and LCC. The detailed information on the inventory for the different alternatives are included in the Appendix.

Alternative 1:

This alternative consists of the building as built with low-CO_2 emission concrete and hollow core blocks. For these materials, the environmental impact and energy use connected to low-carbon concrete and hollow-blocks are calculated from EPDs, Voss cement (B35 M45) and Nobi Voss AS (hollow core blocks).

Alternative 2:

The quantities with low-CO_2 emission concrete and hollow core blocks are replaced with normal concrete. The amount of reinforcement steel per m3 concrete for hollow core elements is based on average quantities common in Norway.

Alternative 3:

In this alternative, concrete in the bearing structures, hollow core blocks and roof has been replaced with timber structures. This consist of a beam-/pillar system, where the truss is made of beams and pillars in glue-laminated timber. The floor slabs and roof are made of tier of joists/framework? in wood with acoustic insulation in floor and extra insulation in roof.

Alternative 4:

More extended use of timber, in addition to the timber bearing structures, the external walls are replaced. The aluminium façade plates are replaced with timber and the windows changed to wooden ones.

Alternative 5:

Similar as built (Alternative 1), but there has been added additional PV panels on the façade facing south.

3.3.1 LCA: input data and assumptions

<u>*Construction phase*</u>

Data on main materials was extracted from BIM files and used as the basis for all alternatives. Missing data was calculated by use of technical drawings of the office and AutoCAD, information in documents from contractors and NDEA, and other assumptions were made in accordance with reports. For alternatives 3-5, building components that were replaced with other material options were dimensioned. The gross area (BTA) for the floors is 672.5 m^2 and 683 m^2 for the roof. The length of the building is 42 m and the width, 16.3 m.

Alternative 1

In the building as built, EPDs for low carbon concrete and hollow core blocks were used. The environmental performance and energy use for these materials were calculated by using the information in the EPDs multiplied with the quantities retrieved from BIM and AutoCAD. Concrete in floor slabs and roof were exchanged with the EPD for hollow core blocks (Figure 21), and the EPD for low-carbon concrete (Figure 20) were used in the other building parts with concrete; foundation, pillars, concrete walls and beams. The technical drawings and documents on the different building parts have been used to calculate the volume of pillars, beams and foundation. The materials quantities in the roof is extracted from BIM files and the data given in documents from the contractors.

Alternatives 2

In this alternative, all concrete is computed as standard concrete in SimaPro. The concrete in plinths, foundation, structures for elevator and shaft in the foundation were calculated by use of the technical drawings. The amount of reinforcing steel in concrete is assumed to be the same as in Norsk Prisbok, Table 2. In addition, these values have been used to compute the amount of steel in the beams, pillars, basement floor, concrete walls and floors. The material quantities in the basement floor and floors slabs are found by multiplying the BTA with the information from the contractors. while the amount of concrete and steel were computed by volumes and densities.

Table 2: Amount of reinforcements steel in concrete [57].

Plinths	120	kg/m^3
Pillars	160	kg/m^3
Structural beams	160	kg/m^3
Foundation plate	140	kg/m^3
Continuous foundation	80	kg/m^3
Structural concrete walls	80	kg/m^3
Concrete walls	70	kg/m^3

Alternative 3

Consist of the same construction elements with EPDs that Alternative 1. To replace the floor slabs and roof with timber, the loads for the different components must be determined. This was done by use of SINTEF`s database on constructions and materials. The dead load for acoustic floor slabs is found in Byggdetaljer in SINTEF Byggforsk 471.031, to be 1.0 kN/m^2 and the live load 3.0 kN/m^2 [2]. Glue laminated timber is used for the beams, pillars, floors and roof.

The wooden beams are dimensioned by use of table 21c in Byggdetaljer in SINTEF Byggforsk 520.222, and the dimension determined to 140x495 mm to achieve the span width of 4m, which is the longest span that holds the load (~32 kN/m) [58]. Because of the span width, it is decided to have 4 lengths in each floor. An assumption of using the same concrete walls and concrete structures for elevator and shaft, make it not necessary to cover these lengths.

The dimension load for the pillar, calculated by SINTEF Byggforsk 520.233, is the dimensioned load per m^2 multiplied by the span width of the beam, divided by 2 [59]. This gives a load of 63.9 kN, and a cross-sectional area for the pillar of 17 000mm^2. From figure 242 in 520.233, the pillar dimension 140x135mm bear this load. The buckling length of 3.3 m is the storey height (3.8m) minus the beam height. After subtracting the concrete structures which function as bearing structures, the number and volume of pillars is determined.

Based on the SINTEF report; «Life cycle GHG Emissions from a wooden load-bearing alternative for a ZEB office concept» [40], nail plates are added to the beams and pillars. The amount is calculated as a percentage of the volumes of the beams and pillars.

The maximum load for the floor slabs is 3.4 kN/m^2, selecting a dimension of 73x300 mm for the tier of beams with beam space c/c of 600 mm, giving a span of 6.16 m [60]. 70 beams are needed to cover the 2 floors, covering 96 % of the BRA area (area for concrete structures excluded). Mineral wool surrounds the beams. The construction for the tier of beams is based on figure 722. in Byggdetaljer in SINTEF Byggforsk 522.511 [61]. 30x48 mm wood lathing from the same guideline is chosen, beam space c/c of 600 mm. To reach the sound requirements in class B for offices in NS8175 in table 42a in SINTEF Byggforsk 522.513, noise reduction insulation is added [62]. The sound reduction number, R_w, is minimum 40dB, and the maximum step sound level is 58 dB [62]. The insulation consists of a layer of mineral wool (table 832 in 522.511) [61] , particle board and fibreboard, as illustrated in the Appendix. Two layers of gypsum make the ceiling.

The construction of the roof is based on figure 21 in Byggdetaljer in SINTEF Byggforsk 525.324. with a layer of mineral wool, rood board [63]. The thickness of mineral wool is determined by obtain the same U-values required for building. Beams and wood lathing are calculated in the same way as for the floor. For vapour barrier and air barrier, the same quantities as for the building as built are used (from BIM files).

When using timber in the bearing structure, the weight of the building is reduced. This reduces the demand of concrete and steel in the foundation. From the SINTEF report « Life Cycle GHG emissions from a wooden load-bearing alternative for a ZEB office concept», a reduction factor of 0.35 is used for the concrete plinths to calculate the new material quantities [40].

Alternative 4

The same floor slabs, foundation, roof, beams and pillars as in Alternative 3 are employed.

The windows which originally have aluminium coating were replaced with wooden windows.

Timber cladding is replacing the aluminium façade plates, calculations for the new external walls are made to achieve the original U-value of 0.12. The assumptions for the materials used in the walls are based on figure 23 in Byggdetaljer in SINTEF Byggforsk 523.255 [64]. A share of 25 % wood vertical and horizontal studs included insulation is assumed, with c/c 600 mm and 125 mm beam width. The other materials included in the walls are: wood lathing, air barrier, fibre board, insulation, vapour barrier and gypsum plates. For the barriers and gypsum plates, the thicknesses retrieved from the contractors are use. The quantities of the different layers are found in the appendix. The areas of the timber cladding, insulation, fibre board and the barriers amounts to the building area minus the areas for windows and doors. For the 36x48 mm lathing, a wood share of 15 % is considered (table 33 in SINTEF Byggforsk 523.255) [64]. The thermal conductivities (wood= 0.12 W/mK and glava=0.035 W/mK) and thickness for studs and mineral wool, together with the internal surface resistance comprise the U-value. For more details on dimensioning of timber structures, see Appendix.

Alternative 5

The same EPDs as in Alternative 1 are used.

For the supplemented PVs on the facade, information on technical specifications and generic values is received from a conversation with GETEK AS, a company offering BIPV and BAPVs. Standard PVs on facades consist of PVs assembled by 60 solar modules of, giving an effect of 260 W, with an estimated lifetime of 25 years. Typical efficiency for a panel is 16 % with a total system loss of ~15 %. The PVs are attached to the aluminium facade plates on the wall facing south, the BAPVs solution. The attachment rails are not included in the inventory as it is the PVs that constitute the greatest use of material. It is possible to replace facade plates with PVs, but this is not done in this report as this must be taken into consideration when projecting a building to achieve the building requirements. It is emphasised that all values are averages as it is necessary to make detailed calculation for each case to optimise the energy production.

All alternatives

For some buildings parts, the materials or amounts are the same as for the building as built. This applies for the windows, outer and internal doors, basement floors, floor coverings, roof cover, wind and air barriers, PV panels on the roof and the inner walls. The concrete walls are included in all alternatives too, as these function as important load bearing structures in the building. Floor coverings and ceramic tiles in the floor slabs, doors and inner walls were exported from BIM.

Transport phase

The impacts from transport of all materials to the construction site and the replacements have been analysed. The standard unit for transportation is ton km (tkm), which is equal to the material quantities in tons multiplied by the distance for the transport. For some materials the supplier was given in the documentation of the building and made it possible to calculate the transport distance for these to Haakonsvern. To compute the impacts from the rest of the materials, it is made an assumption for a typical transport route of Bergen – Oslo, which sets the reference transport distance to 450 km. Since the quantities need to be in tons, conversion factors have been calculated from similar products and information on different processes given in SimaPro, to determine weight of material volumes.

The analyses have been conducted with freight transport on road by trucks of the size class 16-32 metric tons gross vehicle weight, within the emissions class EURO5 (170g CO_2/tkm) [65].

Operation phase

Replacements

During the lifetime (LT) of a building, materials in some building parts must be replaced due to wear and tear. For this analysis, replacements are based on the intervals for maintenance actions in the directions from SINTEF`s Byggforskserien 700.320 [66]. Materials replaced in the alternatives are shown in Table 3.

Table 3: Overview of materials replaced in the different building alternatives.

Alternatives 1-3	**Alternative 4**	**Alternative 5**
Bitumen roofing, LT= 30years	Bitumen roofing, LT= 30years	Bitumen roofing, LT= 30years
Windows, LT= 40 years	Windows, LT= 40 years	Windows, LT= 40 years
Outer doors, LT= 40 years	Outer doors, LT= 40 years	Outer doors, LT= 40 years
Floor covering; tiles and linoleum, LT= 30 years	Floor covering; tiles and linoleum, LT= 30 years	Floor covering; tiles and linoleum, LT= 30 years
PVs on roof, LT= 25 years	PVs on roof, LT= 25 years	PVs on roof, LT= 25 years
Aluminium facade plates, LT=40 years	Timber cladding, LT=50 years	Aluminium facade plates, LT=40 years
	Paint on external walls, LT= 50years	PVs on façade, LT= 25 years (assume longer LT after the first replacement)

The materials replaced in alternative 1-3 are the same, alternative 4 has different windows and external walls, and alternative 5 has PVs on roof in addition to the same changes as in the first alternatives. All materials in the table are replaced one time during the life time of 60 years of the office.

Only electricity for the space heating in the operation phase is analysed.

Calculation of electricity production from the PVs on the south facade is executed by use of Photovoltaic Geographical Information System (PVGIS), see Apendix. The calculator estimates the performance of Grid-connected PVs based on location and specification for the PVs, provided by Institute for Energy and Transport in the European Commission. Installed peak power derives from the area of PVs multiplied by the efficiency. In a year, the office will gain an extra production of electricity of 23 800 kWh, Table 4 [67].

Table 4: Data for BAPVs on the south facade.

Area facade [m2]	Efficiency	Peak power [kWp]	Production [kWh]
286	16 %	45.8	23 800

The electricity mix chosen in this thesis is medium voltage electricity in the market. This voltage level should be used for the service sector and public buildings [68]. The dataset in SimaPro includes inputs produced in the countries, imports, transmission networks, direct emissions to air and losses during transmission [65]. The electricity mix is composed of non-renewable and renewable energy resources. Non-renewable energy consists of energy produced from fossil, nuclear and biomass sources. The renewable energy is made up of power from biomass, wind, solar, geothermal and hydropower.

The electricity mix used in SimaPro is based on the energy delivered in the Northern region. It is composed of electricity produced in Norway, Sweden, Denmark and Finland. One kWh of the mix is calculated from the share of electricity from the different countries contributing to the total Nordic production (except Island, which is not included in SimaPro). This gives a CO_2-emission factor of 163 g CO_2-eq/kWh.

Most of the materials are analysed with environmental data from materials inputs in the Ecoinvent database version 3 in SimaPro. This means that the emission factor is specific for the different materials based on the production site. It is assumed that the CO_2-emission factor for electricity in Ecoinvent will remain constant throughout the lifetime of the building, as it is hard to predict how regional electricity production will develop.

3.3.2 LCC: Input data and assumptions

The chosen real rate for the LCC is taken from the predefined real discount rate in difi`s guide for LCC on public buildings. The real discount rate set to 4 % for the calculation period of 60 years, the lifetime of the building, [69].

Construction phase

Prices for the various construction materials are found in Norsk Prisbok. This is a reference book for the Norwegian construction sector, containing prices for materials and building projects, and information regarding LCC and carbon footprints values [57]. The app version 2017-01 was used in this report, with the price database from 2016. A value-added tax of 25 % is added to the material costs. For the materials not included in Norsk Prisbok, contractors were known and have provided or commented the prices. The price of low-carbon concrete delivered for the office is the same as for standard concrete, as most contractors offer low-carbon concrete now.

The costs for the PV panels on the south façade derives from a phone call with GETEK AS, which had an approximately installation costs of 20 NOK/W.

Transport phase

The costs for transportation of construction materials and replacements are not included.

Operation phase

Replacements costs are calculated for the materials replaced, which is expected to be about 2.75 % of the investment costs. This percentage is assumed by the annual operation costs (energy excluded) divided by the investment costs.

The operation costs take basis in an electricity cost of 0.845 NOK/kWh. The assumption for this is that the electricity costs will fluctuate year by year, choosing a period for representing an average. The fixed cost is an average price of the electricity price, fees and grid rent of the last 5 years (2012-2016).

For Alternative 5, the extra energy production from the PV panels reduces the delivered energy demand to 7927 kWh.

The thesis does not investigate the end-of life phase for the building. Because of this, the last part of the equation for calculating NPV is excluded, which means that the disposal and residual value is not taken into consideration.

3.4 Performed analyses

In this project, the LCA of the case building has been analysed in SimaPro considering the construction phase, use phase and transport. The attributional approach with partitioning (allocation) is preferred as the system model, which attributes inputs and outputs to the functional unit of the product system [70]. By use of the Allocation Cut-Off by classification model, environmental impacts and emissions connected to a product are distributed among materials and processes, whether they are by-products or not, linked to the production [70]. The unit process version is chosen to include all upstream processes connected to the supply chain of the production system for the evaluated processes [71]. There is no cut-off for recycled materials, only the impact from the recycling process is taken into account, excluding burdens from primary production of the material [70]. This means that any potential benefits from recycling construction components is not taken into account.

The LCC is performed by use of data from Norsk Prisbok and the material quantities that differ the different alternatives. The investment costs and operation costs for the building as built are given in documents from NDEA.

3.4.1 Goal and scope

The goal of these analyses is to estimate the largest impact of the GHG- emissions and primary energy use connected to the materials including transport and replacements, and the operation for the different building alternatives. LCAs make the basis for computing the environmental impact for the construction and use phase, and the associated costs for the different alternatives are calculated by the principles of LCC.

3.4.2 Functional unit

The functional unit is $1m^2$ of heated floor area (BRA) in the office building over an estimated lifetime of 60 years. The heated floor area is 2035.7 m^2, calculation based on the BIM-files. Results from the life cycle analyses are mainly presented with the annualized emissions and energy use, where the functional unit is divided on the lifetime.

3.4.3 Boundaries

The system boundaries for the analyses have been limited to the extraction of raw materials (A1), manufacturing of products and materials (A2-A3) and the transport of construction materials (A4). The operational energy use stage (B1) and replacements over the life time (B2) is also included.

Materials and components have been analysed using the EcoInvent database. The exceptions are low-carbon concrete and hollow core blocks, which have been calculating by use of EPDs. The Expected life times used for the materials, which are replaced in accordance with SINTEFs recommendation for replacements, are listed in the appendix.

Technical installations have not been included in this thesis.

Inventory analysis

The inventory consists of the material quantities in the pre-use phase, net delivered energy, the expected spare parts for replacement components and transport of all materials during the construction and use phase.

LCA inputs

The SimaPro edition made use of in this thesis is 8.1.1, in which the Ecoinvent Life Cycle Inventory (LCI) database version 3 is integrated. LCA methodology forms the basis of the ecoinvent database covering economic activities and their impact on the environment at a unit process level, and links intermediate goods and service inputs to other relevant unit processes supplying them [70].

The chosen localisation for the production is Europe (RER) or Switzerland (CH), with an exception for normal concrete. Normal concrete produced in Europe had a lower value for climate change than normally considered in Norway, so the average production for the rest of the world (ROW) was used. (371 kg CO_2-eq/m^3).

The length, area and volume of the different materials and components included in the construction assembly derives from the BIM files used in the software Revit 2017. Material take-offs for the different parts of the building have been exported to Excel, and then used as inputs in SimaPro. The material quantities for the different building alternatives analysed can be found in the Appendix.

For the LCA calculations, the time horizon in IPCC, GWP 100-year scenario for CO_2-emissions is used in SimaPro 8.1. Integrating the environmental impacts from the different building alternatives over a period of 100 years.

4 Results

In this chapter, the results from the LCA and LCC analyses are presented.

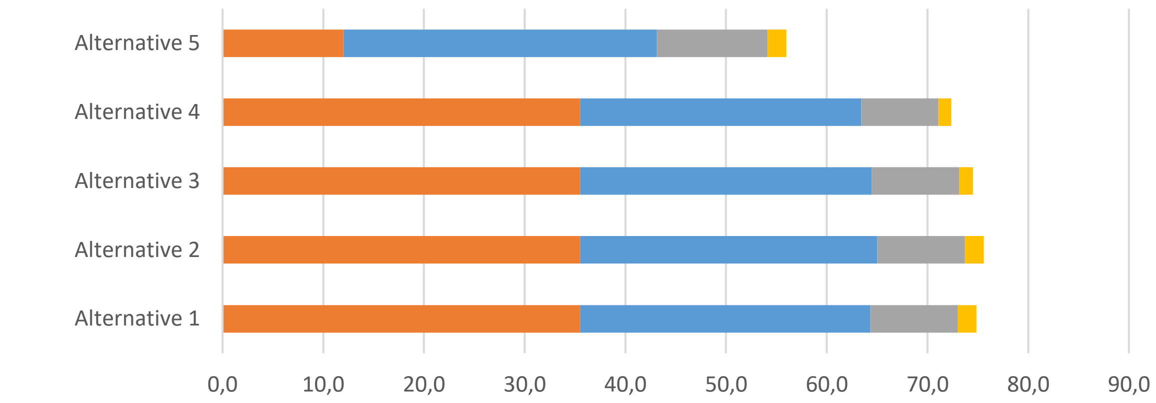
1) As built with low-carbon concrete
2) Hypothetical use of normal concrete
3) As built, but with timber bearing structures
4) As built, but Timber bearing structures, timer facades and wooden windows
5) As built with PVs on the south façade

4.1 Cumulative energy demand (CED)

Figure 9 illustrates the CED indicator, normalized per gross internal floor area and year, for the five alternatives. The alternative that uses the most electricity is Alternative 2, where most energy is needed to produce materials. This gives an increase in CED by 7 % compared to as built in Alternative 1. CED in the construction phase for the other alternatives is very similar, which entails no big difference in choosing wood or low carbon concrete with a view on saving energy. The presence of PV panels on the façade, in Alternative 5, leads to the lowest electricity demand in the use phase, 12 kWh/m^2 per year, which is almost one third of the electricity use in Alternative 1, with PV panels only on the roof; this is due to the more PV panels installed, which reduces the demand for delivered energy, although it slightly increases CED in the construction phase. With respect to the other life phases, transport uses the lowest amount of energy, and the replacements constitute about 13 % of CED for the alternatives without PVs on the façade (Alternatives 1-4), and about 27 % for the alternative with PV panels on the façade (Alternative 5).

Figure 10 shows the distribution of CED in the different life phases, for the five alternatives. By looking at the different life phases analysed, the construction and use phases consume the greatest part of CED. Transport constitutes only 2-4 % of CED, while the replacements about 12 %. The distribution of CED during the life cycle is very similar for Alternatives 1- 4, where the proportion of the energy for building operation is greater than for the other phases. The highest use of energy for Alternative 5 is related to materials (construction phase and replacements).

Figure 11 shows the allocation of renewable and non-renewable energy for the whole building life cycle, in the five alternatives.



	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Use phase	35,48	35,48	35,48	35,48	12,02
Construction phase	28,83	29,55	28,98	27,95	31,12
Replacements	8,68	8,68	8,68	7,65	10,97
Transport	1,88	1,88	1,37	1,26	1,90

kWh/ m^2 per year

Use phase   Construction phase   Replacements   Transport

Figure 9: Annual cumulative energy demand per m^2 for the five alternatives.

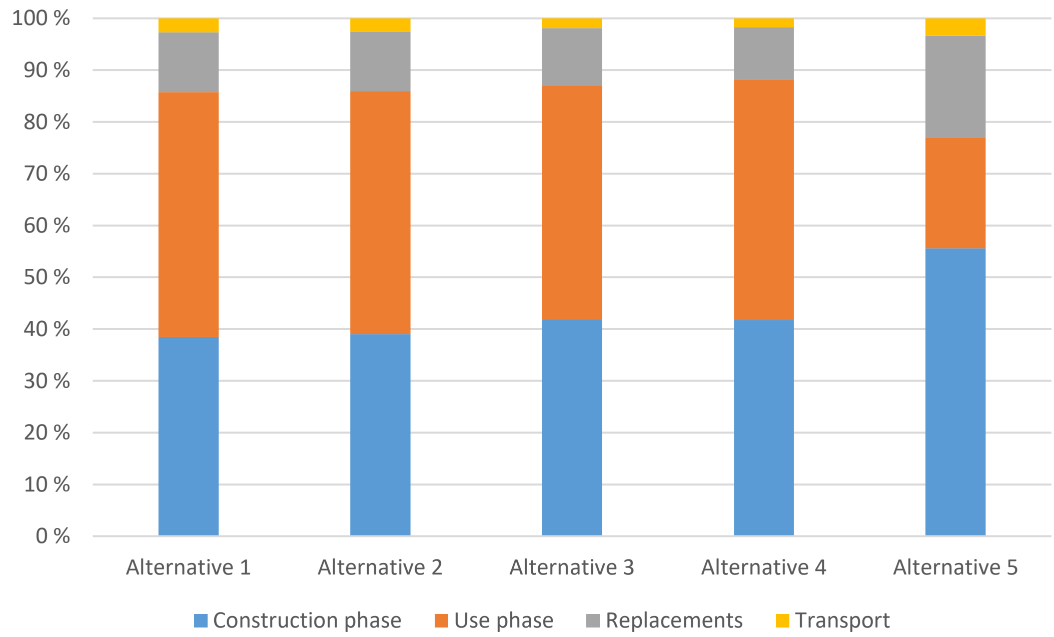


Figure 10: Distribution of CED during the building life cycle.

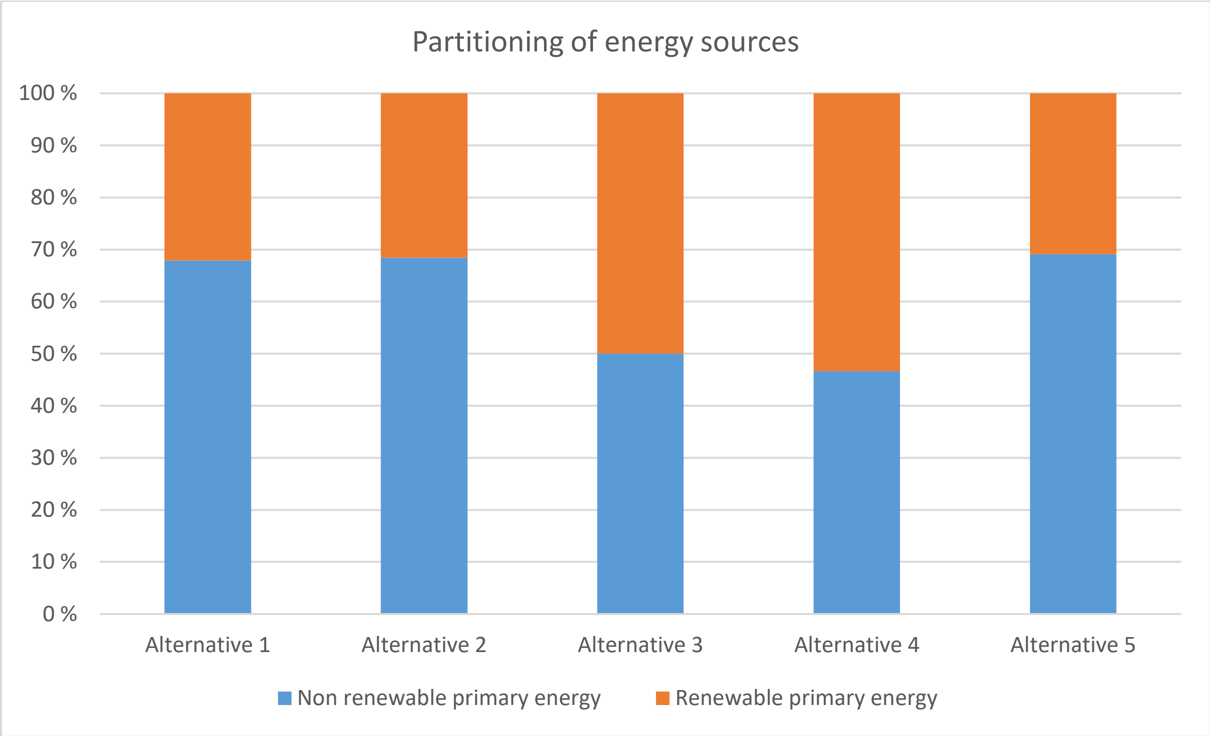


Figure 11: Partitioning of energy sources for the different material alternatives and the operation of the building.

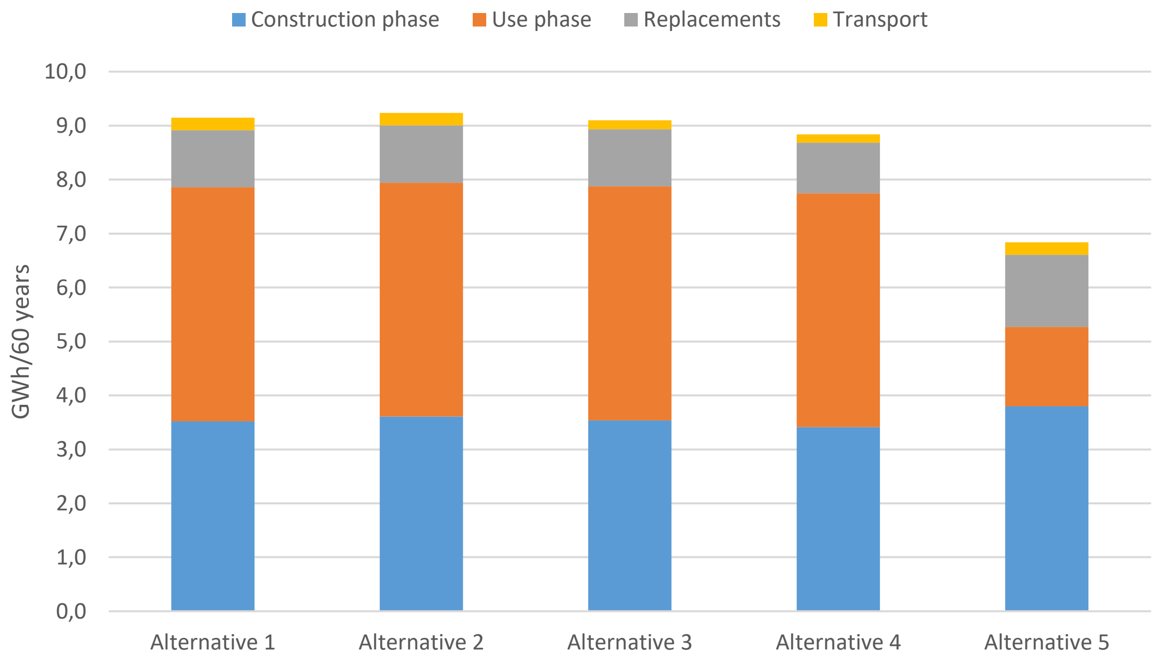


Figure 12: CED over the building life time.

The highest use of non-renewable CED is in Alternatives 1, 2 and 5, and it is mainly related to the operation of the office as shows Figure 11. The partitioning for alternatives 3 and 4 is about half renewable energy sources and half non-renewable sources.

In Figure 4 Figure 12, CED over the total duration of the building is shown for the five alternatives. The differences between alternatives 1,3 and 4 are small as they consume about 9 GWh. Alternative 2 still has the highest CED, while alternative 5 show that there is potentially a lot of energy to save over time.

4.2 Global warming potential (GWP)

In Figure 5, GWP is shown for different life phases in the five alternatives. As visible, the CO_2 emissions associated with Alternative 2 are the highest ones, which is mainly related to the CO_2 intensity from the production of normal concrete. Reducing the amount of concrete by making use of timber allows an advantage with respect to CO_2 emissions. The alternative with timber in bearing construction, cladding and wood windows, Alternative 4, emits 3.4 kg CO_2 per m^2 per year, which means a reduction of 34 % in proportion to Alternative 1 (as built).

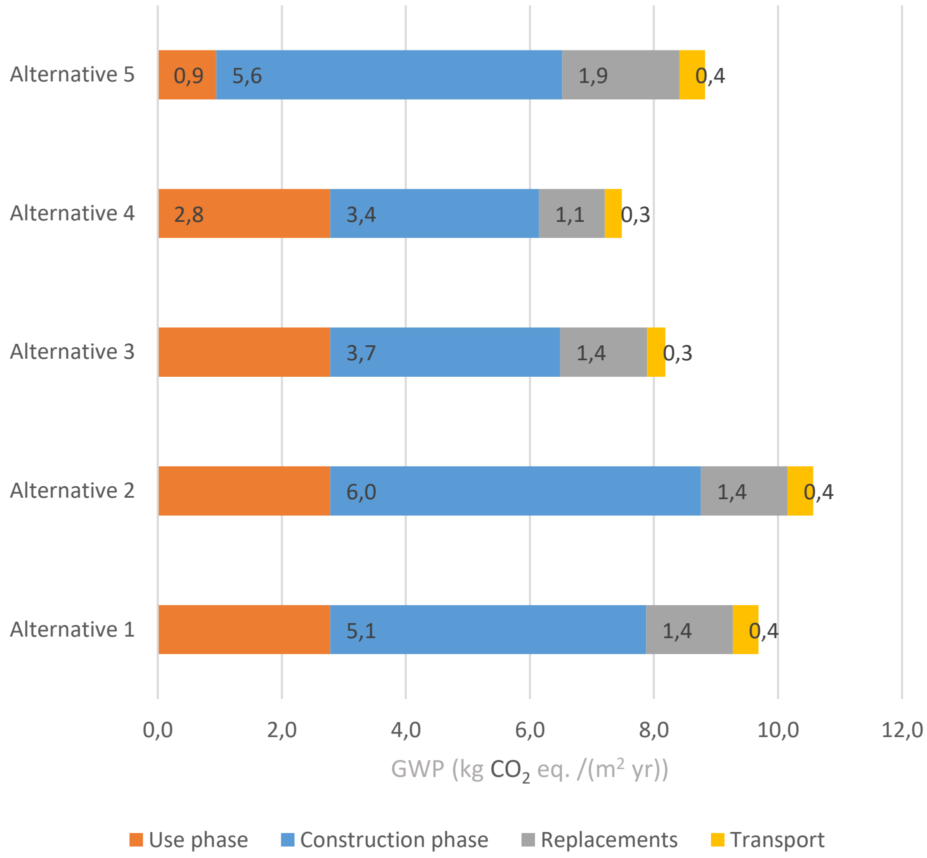
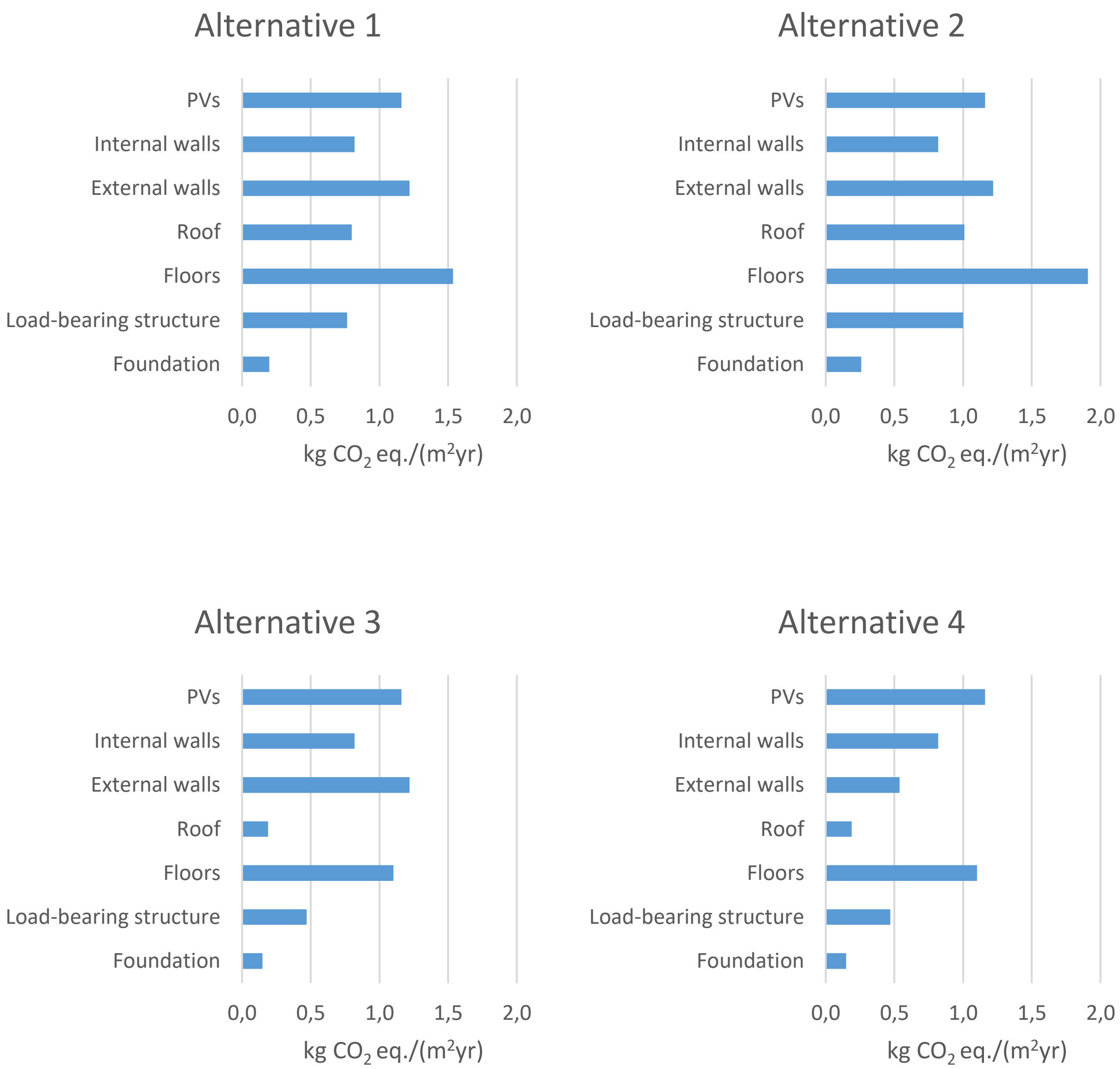


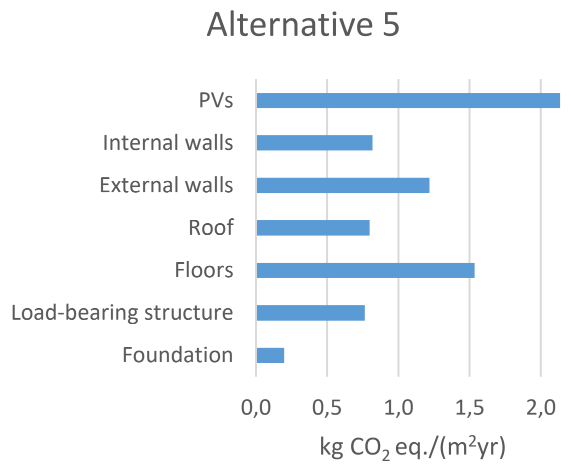
Figure 13: Annual CO_2 emissions for the five alternatives in kg CO2 eq. per m^2.

The share of CO_2 emissions per m^2 from transport, materials, energy use and replacements for the various alternatives is shown in Figure 6 for the various alternatives. For all alternatives, the emissions from the construction phase amounts to about half of the total emissions. The shares for the alternatives with timber replacements are smallest here. Due to the more energy, demanding process of producing PV panels, 63 % of the emissions in Alternative 5 comes from the construction phase. The second largest contributor is the use phase for Alternatives 1-4 (26-37 %) and the replacements in Alternative 5 (21 %). The contribution from transport is not very significant compared to the other stages, only about 4%.

GWP from the differing building components are illustrated in Figure 7. By looking at the different components of the building, the highest GWP is from the floors for all options. Depending on the alternatives, there is some variety in the other important components for CO_2 emissions. Roof and load-bearing structures are the other dominant emitters for Alternative 1 and 2, together with PV panels for Alternative 5. For Alternative 3, external and internal walls are the next important contributors, and the internal walls and PV panels for Alternative 4.

Table 5: Annual GWP per m2 for building components, including replacements in the different alternatives.





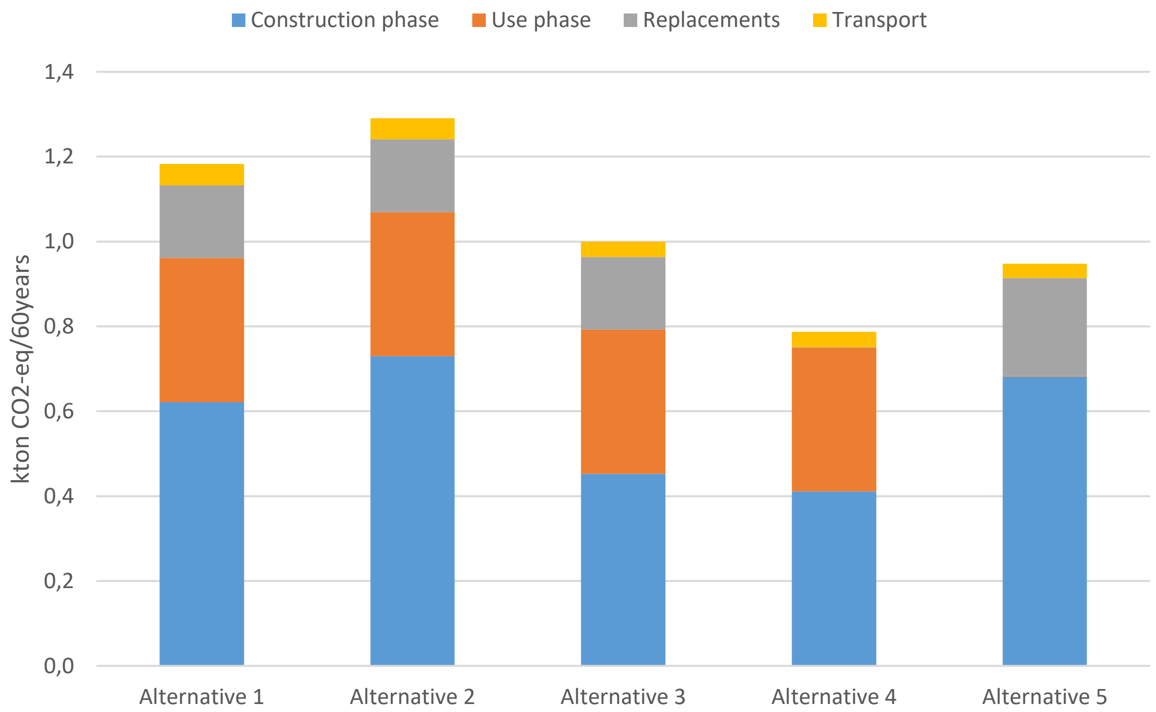


Figure 14: The global warming potential in kton CO2 eq. for the various material alternatives.

The alternatives with the highest share of concrete, Alternative 1 and 2, have the highest contribution to climate gas emissions. The exception is for Alternative 5, which has the second lowest emissions, -20 % compared to Alternative 1. The best option with respect to GWP is

Alternative 4, which reduces the emission by 4000 tons of CO_2 (-33 %) compared to Alternative 1.

4.3 Other environmental indicators

In Figure 15 the results from further impact categories in the LCA analysis are shown. This can be used as picture for all alternatives, as it reflects the main construction materials in the different building parts.

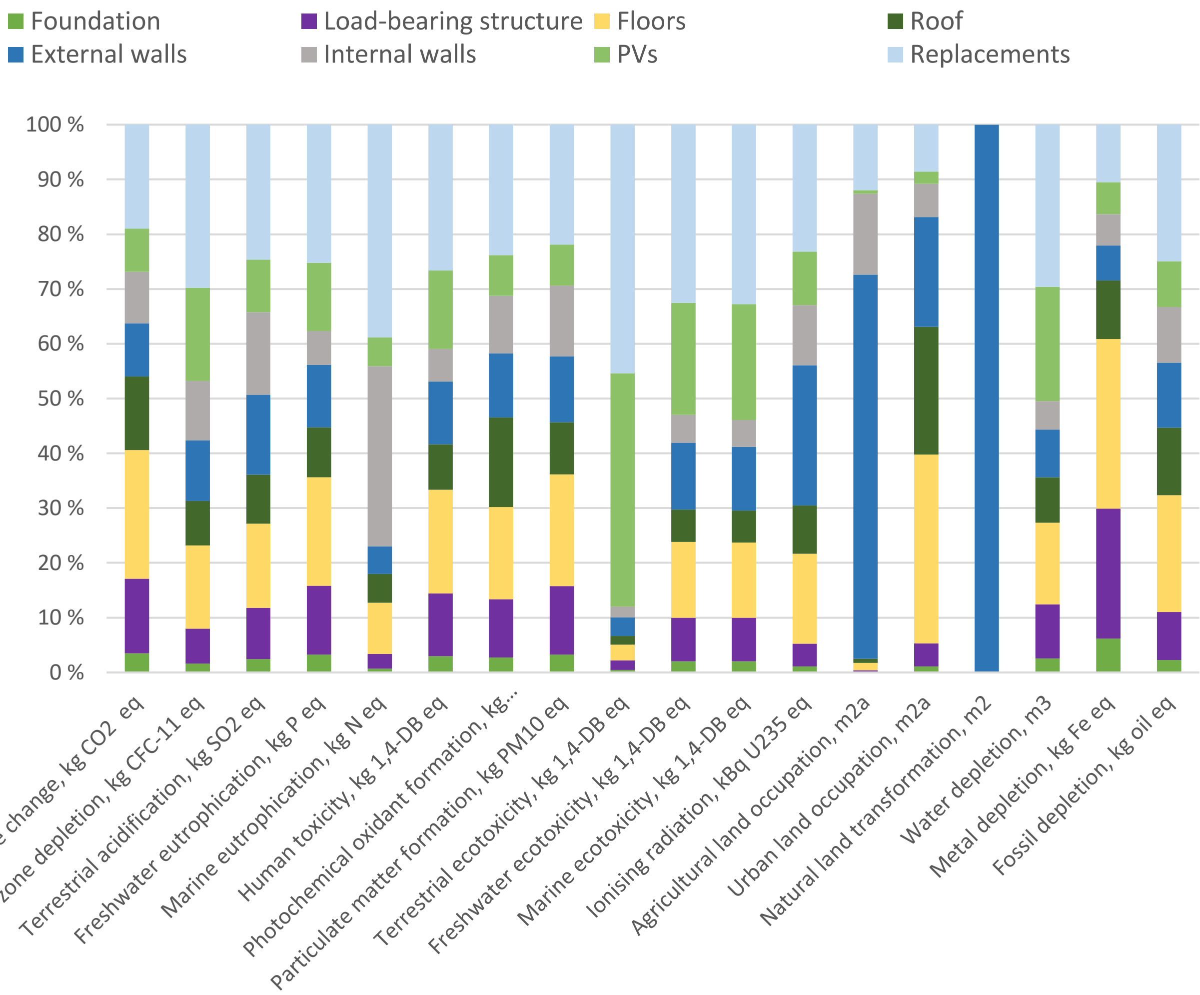


Figure 15 Environmental impacts from different construction parts in alternative 2.

The most important construction elements contributing to climate change are the floor slabs (~23 %) and replacements (~19 %), the rest of the construction parts have about the same contribution. For the ozone depletion, 30 % of the impact comes from replacements, and the next highest contributions come from floors and PV (~15 % each). The highest impact from internal walls is found in marine eutrophication, otherwise they have low influence in the other impact categories.

Replacements have sizeable contribution to most impact categories, especially in marine eutrophication and terrestrial ecotoxicity. There are three impact categories that stands out from the others; terrestrial ecotoxicity where PV panels and replacements amounts to most of the emissions, and agricultural occupation and natural land transformation with external walls as the main contributor.

4.4 Net present cost

Table 6: Investment costs and calculated annual costs for the different materials options.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Investment costs (NOK)	94 000 000	94 000 000	91 469 000	91 736 000	94 915 000
NOK/m^2	46 000	46 000	45 000	45 000	47 000
Maintenance costs (NOK)	2 583 000	2 576 000	2 513 000	2 521 000	2 608 000
NOK/(m^2 yr)	1 300	1 300	1 200	1 200	1 300
Electricity costs	29 400	29 400	29 400	29 400	10 000
NOK/(m^{2}yr)	14	14	14	14	5

The investment costs are the same for Alternative 1 and 2, as the price for the low carbon concrete used in the project (category B) is considered to be equal to that of normal concrete. The lowest investment costs are in Alternative 3, as the timber bearing structure is around 70 % cheaper than the concrete one. The next lowest investment costs are in Alternative 4, due to the additional timber facade and wooden windows. These alternatives also have the most moderate maintenance costs. By adding extra PV panels on the facade of the building as built, the investment and maintenance costs increases by 1 %. The operation costs are the same for Alternatives 1-4, while the PV panels on the facade gives an annual saving of 64 %. However, the electricity costs are negligible in the NPC of the building as visible in Figure 16. The differences between the NPCs for the alternatives are very small, with a deviation of 228 000 NOK.

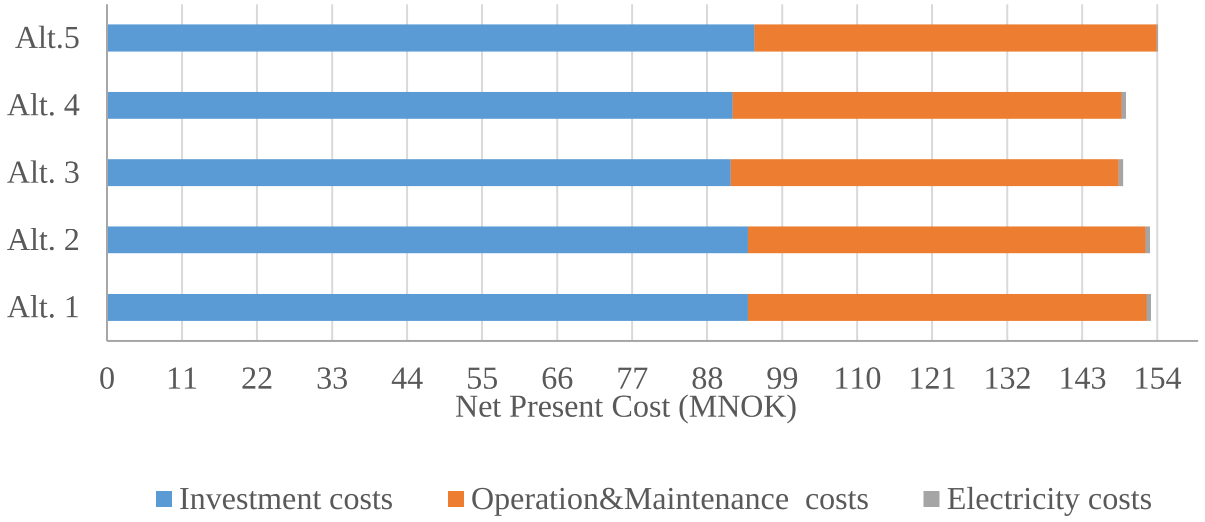


Figure 16: Net present costs for a calculation period of 60 years

EAC per m^2 is shown in Figure 17 for all the alternatives. The investments costs for the construction of the building represent 60 % of the total costs. Operation and maintenance costs constitute the other main component of the total costs.

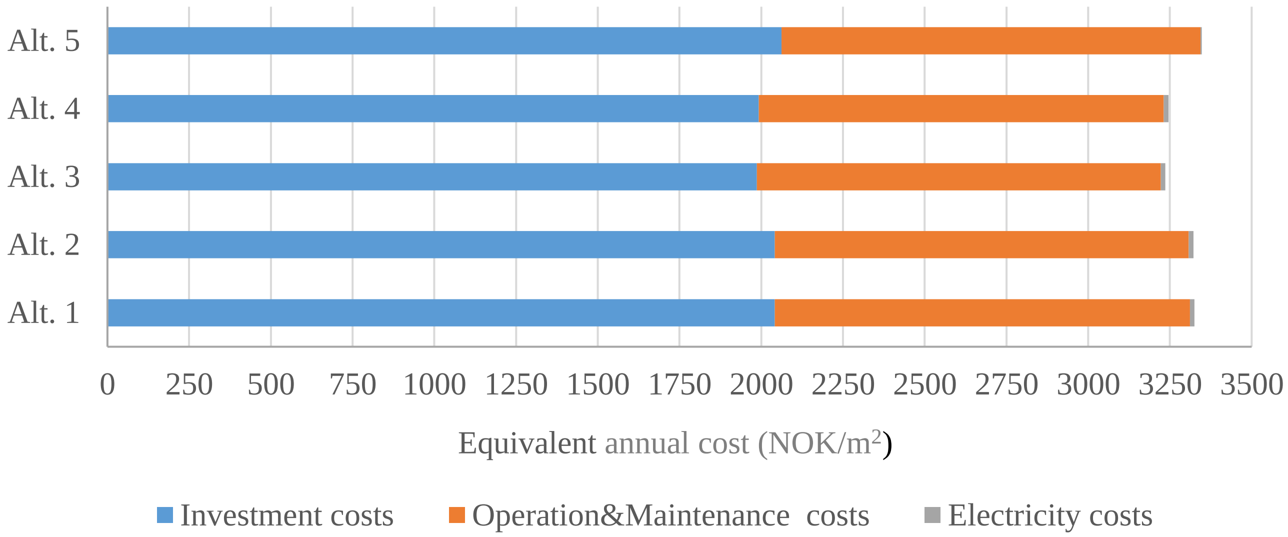


Figure 17: Annual costs per m2 for investment, operation and maintenance and electricity costs.

4.5 Combined LCA and LCC results

The chosen indicators; GWP, CED and NPC have been normalised to a scale (1-5) based on the alternative with the highest impact for each indicator. There are small differences between the various alternatives, especially for the NPC, which is more or less equal, as can be seen in Figure 18. The main differences are related to the GWP. Alternative 4 performs best in two of the indicators, GWP and CED, while Alternative 2 is worst.

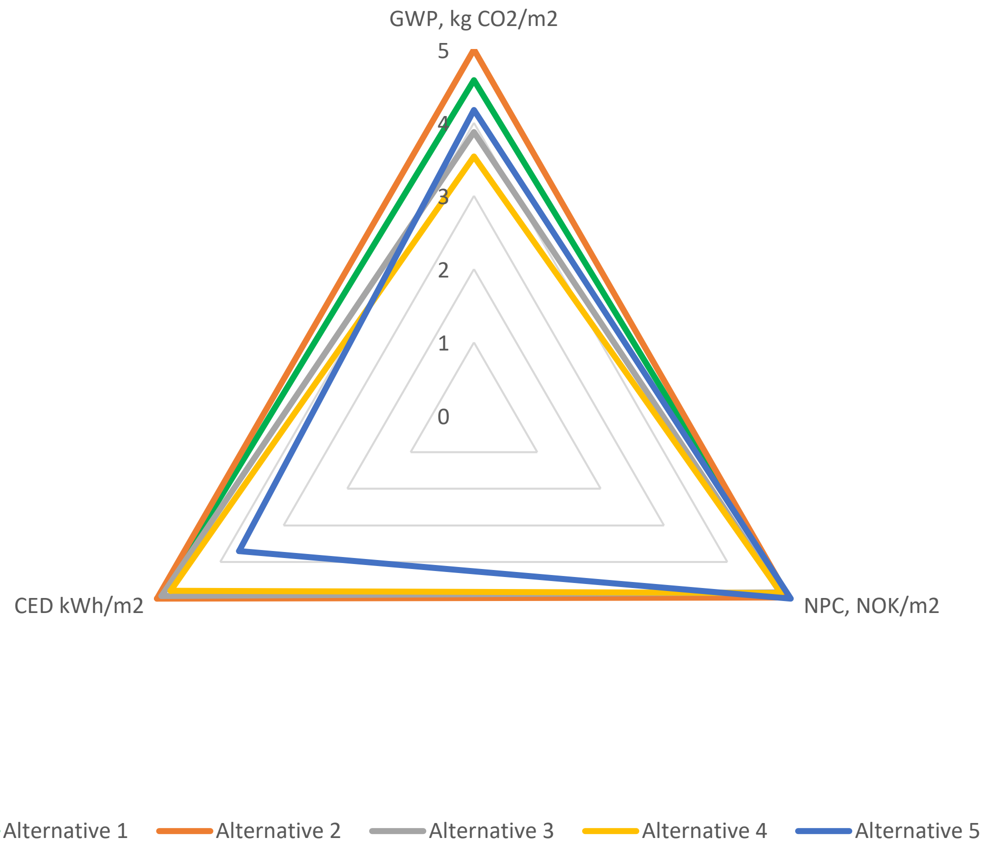


Figure 18: Normalised scores for the GWP, EAC and CED over the lifetime of the building.

To separate the indicators by emphasising important factors in a decision-making process, the normalised scores of the indicators should be weighted. Figure 19 illustrates the weighted scores, where GWP has been set as the most important one due to its significance in the current scientific discourse, weighted 0.5, while CED is weighted 0.3 and NPC as 0.2; as the results for the various alternatives for NPC are similar in the present thesis, the weight for this category is decided to be lower than the one for CED. The graph displays that the differences in the GWP indicator would be the main argument when choosing the best alternative for the building. The alternatives farthest away from the centre of the diagram have the worst sustainability performance, making alternative 2 the least option. Alternative 5 performs best when it comes to CED and in the middle for GWP, so the preferable solutions would be either Alternative 5 or alternative 4, which is best for the GWP.

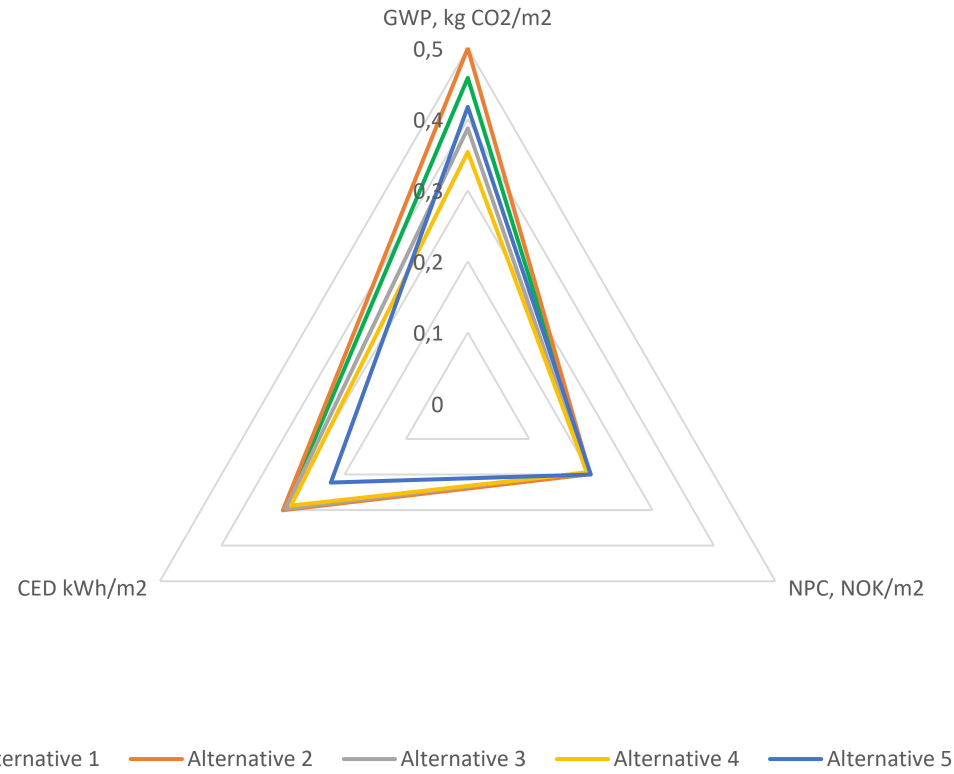


Figure 19: Weighted scores of the indicators. GWP= 0.5, CED= 0.3, NPC= 0.2.

5 Sensitivity analyses

In Figure 20, the EAC are checked for different life times of the building. With a longer life span, the EAC will be reduced compared to the used calculation period of 60 years. If the calculated period would have been 110 years, the investment costs for Alternative 1 would increase by about 8 %, increasing the EAC by 5.1 %. The electricity costs are so small that they are barely visible, not affecting the total EAC. The operation and electricity costs stays the same for all life spans.

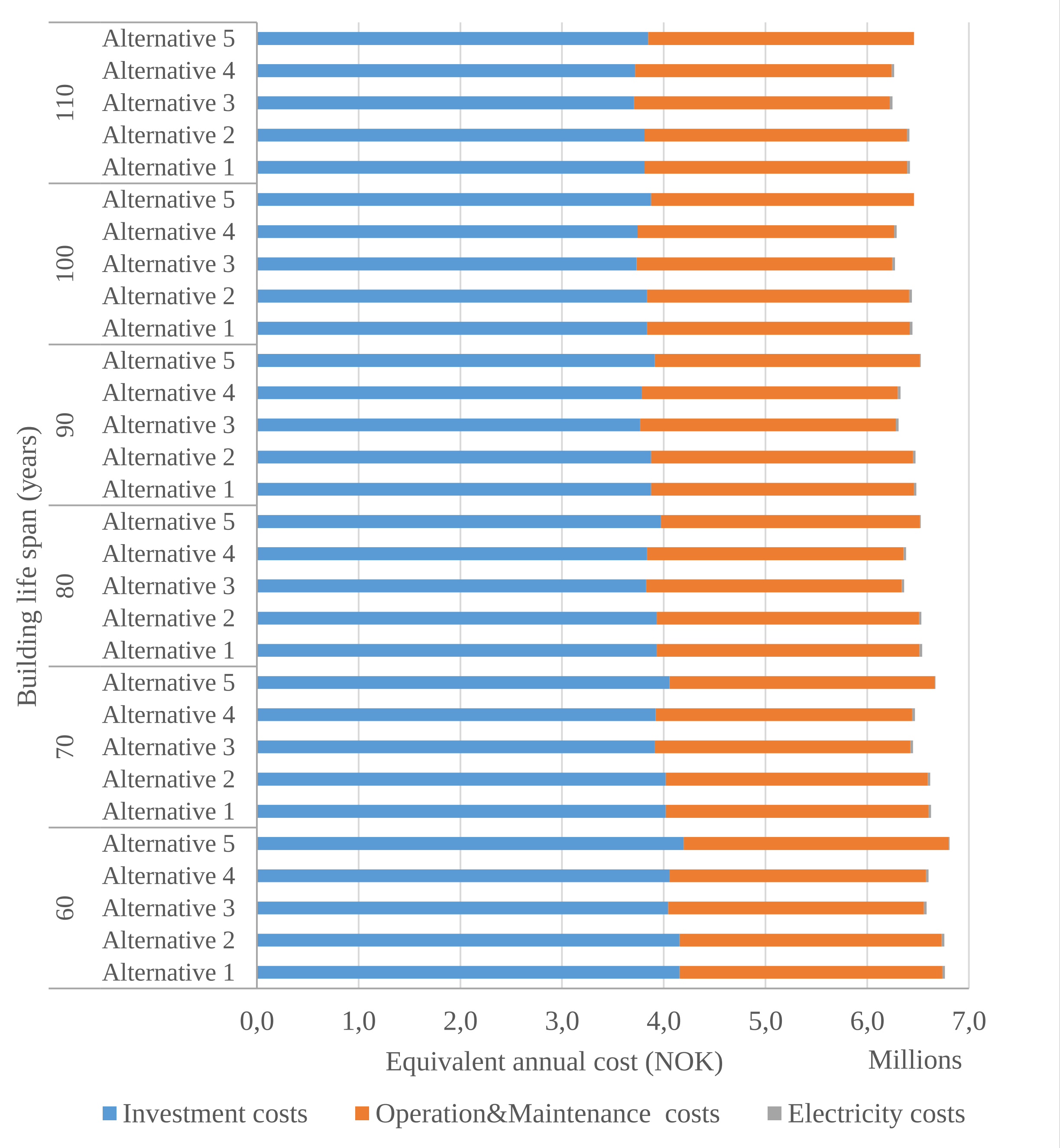


Figure 20: Sensitivity analyses of EAC for different building life spans.

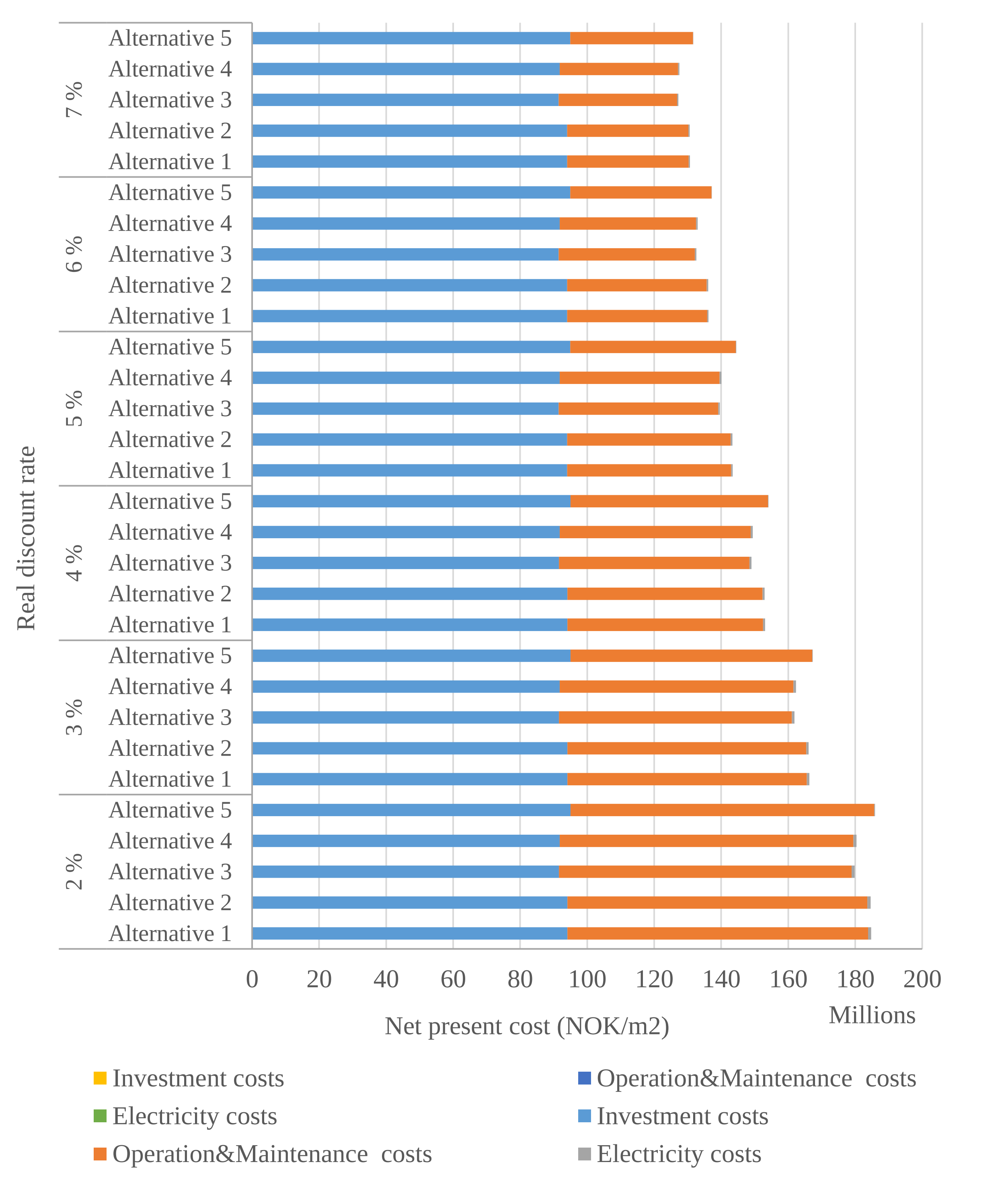


Figure 21: Sensitivity analyses for different real discount rates.

By using a lower real discount rate, the NPC increases, and opposite by use of a higher one. A real discount rate of 2% increases the NPC by 21 %, while a real discount rate of 7% reduces the NPC by 15 %. The investment costs are not affected by a change in the discount rate.

Table 7: Sensitivity analysis of CO_2-emissions for electricity mixes.

Electricity EU [g CO_2/kWh]	Electricity NO [g CO_2/kWh]	Electricity Nordel [g CO_2/kWh]
508,1	22,8	162,8
212 %	-86 %	

The results for GWP depend on the electricity mix used in the analyses. By using a Norwegian electricity mix, the CO_2-emissions would have been reduced by 86 % compared to the Nordel mix used in this project. If an European electricity mix were considered, this would have led to an 212 % increase of the GWP results

6 Discussion

6.1 Important findings

The results from the CED for the different life stages show that there are small variations between the energy demand for most of the alternatives. The difference is principally in the operation phase, where Alternative 5 has a 66 % reduction in energy demand compare to the other alternatives. The installation of extra PC panels gives a large energy- savings for the use phase, but has the highest energy demand when it comes to the other phases. The production of PV panels is energy intense, which becomes visible when comparing it to the other alternatives. For the other alternatives, there are no real distinctions. Alternative 4 reduces the CED by 4 % compared to Alternative 1, as the production of timber needs a little less energy. The difference of using low-carbon concrete and hollow core blocks compared to standard concrete yields only 1 % improvement in the energy demand in the construction phase. The transport phase only employ a minimum of the CED for the analysed phases.

Both the construction phase and the operation phase are energy demanding during the lifetime of the building, construction amounts to about 40 % of the CED and the operation to 45-47 % (when not taking Alternative 5 into account). This means that largest energy savings potential is to use materials with less energy intense production and by reducing the electricity for operation of the building.

The distribution of the energy sources for the production of the materials shows that CED for the alternatives with timber contain higher shares of renewable energy than the other alternatives. Alternatives 1,2 and 5 uses more energy from non-renewable sources, 70 % of the total CED.

When it comes to GWP, the results vary more between the different alternatives. The main differences here are still found in the use phase and the construction phase, but it is slightly more variations in the replacements too. Transport has an insignificant contribution to GWP. The alternative with extra PV panels has significantly lower GHG-emissions in the use phase than the other alternatives. This is due to the smaller amount of delivered electricity needed, which has considerable associated emissions, leading to an emission reduction of 70 %. The highest CO_2-emissions are detected in construction phase, where Alternative 2 performs clearly worse than the others (6 kg CO_2 per m^2 per year). This gives 43 % more emissions in the operation phase than the best, Alternative 4. These findings indicate the gain by replacing concrete and steel with timber. By use of low-carbon concrete, a reduction of 15 % is achieved compared to use of normal concrete.

The building components that influence the GWP the most are the floors slabs, PV panels and the external walls. This is mainly due to the large amount of materials included here, and that these also requires a high share of energy in the manufacturing. The annual GWP per m^2 per year is highest for the alternatives with more concrete and steel (Alternatives 1,2 and 5), which underlines the impacts from usage of these materials. By replacing building parts with timber, one can attain a CO_2- emissions reduction of 20-30%. There is a significant reduction in GWP for the building elements replaced with wood, Alternatives 3 and 4. Shifting the aluminium coated windows with wooden windows reduces the emissions by 34 %. The total emissions reduction of having a timber façade as in Alternative 4 is 60 %. Over the lifetime of the building, the order of the alternatives performance with respect to GWP are; 4, 3 ,5, 1 and 2, where the first one emits the least.

For other impact categories, the floors slabs, internal walls and replacements have greater impact in many impact categories. Focusing on ozone depletion, acidification, eutrophication and photochemical oxidant formation, which are included in EPDs, replacements, floors, internal and outer walls are the main contributors. In the last category mentioned, the impacts are distributed among most of the building parts, excluded the foundation and the PVs. The replacements consist of amongst other, bitumen, windows, PVs and aluminium plates, which means these materials have significant impacts on the environment.

The NPCs for the various alternatives reveal that there are small differences in the profitability by choosing one alternative in relation to another. Alternative 3 is the most reasonable, but only about 3 % cheaper than Alternative 1. The costs for Alternative 1 and 2 are about the same, as the costs for the low-carbon concrete and normal concrete are equal. Adding PV panels on the façade increases the costs by 1 % compared to the existing building. From these results, the choice of the preferred alternative would depend more on the sustainability indicators.

Timber: lightweight material – eases transport, construction work. With a lighter bearing structure, due to timber buildings elements, the reinforcements in foundation can be reduced. Reducing the amount of concrete by making use of timber allows an advantage with respect to CO_2 emissions. On the contrary, a light building can face more challenges in restricting forces and vibration under strong wind.

The long-term energy and cost savings benefit of choosing alternatives with wood must be considered.

6.2 Consistency with literature

The results for the study in terms of GWP have similarities with other LCAs on nZEB. This is the case for the construction phase, which is the phase with the highest contribution to GWP for all alternatives. For a study with an office about the same size as the one analysed in this project and with similar CO_2 factor for the electricity mix (132 g CO_2-eq/kWh, in this study: 163 g CO_2-eq/kWh), the embodied emissions in construction materials were larger than the emissions from the operation of the building, which is true for the thesis.

By evaluating which building parts that influence the GWP the most, the PV panels, external walls and floors were identified as the main contributors. This is in accordance with the study of Georges Haase et al. The study also mentioned that the emission reduction achieved by installation PVs did not exceed the emissions in the construction phase. For Alternative 5, the emissions due to installation of additional PC panels increased by 0.5 kg CO2/(m^2 yr), but the reduction in the use phase was 1.9 kg CO2/(m^2 yr), differentiating it from the other study.

In Alternative 5, the additional PV panels minimises the net delivered energy demand, making it easier to sustain the low energy requirements for ZEBs. Extra installation of PVs might make it possible to fulfil even higher ZEB ambition levels as ZEB-O, defined by the Norwegian Research Centre on ZEB. Compared with the findings from Dokka et.al., where the embodied emissions related to the installation of the PVs increased, this applies also in this case.

The difference of the life cycle impact of Alternative 1 in concrete/steel with Alternative 3 with load bearing structures of wood is 182 t CO_2-eq., which gives an emission reduction of 15 %. In the study of Hofmeister et al. the emission reduction by replacing the concrete/steel load-bearing structure with wood was about 50 %. The study was performed for a four-story office building, where some of the reduction obtained derives from the extra floor, since the more concrete/steel that are replaced, the more emissions can be saved. When comparing Alternative 3 to Alternative 2, an emission reduction of 40 % is achieved, illustrating that low-carbon concrete performs better than normal concrete.

6.3 Strengths and limitations within the study

It should be noted that the service lifetime for PV panels is uncertain and is highly dependent on the quality of the actual PV panels used. CO_2-emission factors if the grid becomes more decarbonised, the emissions related to the operation of the building will decrease.

The results from the NPV analyses are sensitive to the choice of discount rate. By increasing the rate to 7 %, the NPC were reduced by 15 %. Using a higher discount rate will make the costs of potential project look more profitable. The discount rate of 4 % is the standard in LCC for public buildings, so the calculation should be in line with assumptions in other projects.

The material quantities originate from the BIM-files, assuming this minimises the uncertainties for the material use in the building, but there are some uncertainties with use of BIM regarding the quantities and which type of materials that have been used. This is due to the incomplete information in the description of the BIMs. To deal with this, comparisons between material take offs in Revit, technical drawings and use of AutoCAD have been made to complete the material inventory.

Use of both the Ecoinvent database and EPDs give some challenges in respect of different functional units and lack of information for executing conversions. Different units as; kg, m^2, m^3, unequal content of reinforcement in concrete and standardised sizes of e.g. windows and doors, makes it necessary to adapt the processes by using the processes that are most similar. This is the case for the windows, which are given in total area of windows in BIM, but needs to be converted to glass and window frames since whole windows are not available in SimaPro. Missing information on densities, life times and assumptions makes it harder to find real conversion factors.

Not all the associated materials for the building exist in SimaPro, which means that some processes create less/more impact than the actual materials used. This will give different results than the one performed with Klimagassregnskap.no before the building was use. Another reason for the difference in CO_2-emissions from the construction phase, is the use of European datasets for technology levels and energy mix in the ecoinvent database.

Span width - problem with wood.   Hollow core blocks are good for large span widths and to fulfil acoustic requirements in office buildings, with a lower carbon footprint than normal concrete.

Because of the long life-time of a building, the uncertainties related to LCC are several. Future price on electricity is hard to predict as this is dependent on the energy production and trade with other countries, which gives uncertainties in the operation costs.

The output from the installed PV panels fluctuates with the weather conditions, potentially resulting in a different net production than estimated. After the first year, the electricity delivered is higher than expected, but this may change from year to year, sometimes giving a surplus and other times a deficiency. Since the operation costs are determined by the office own electricity production, changes in the efficiency of the PV panels will influence these. With projection of larger changes in the climate in the future, the number of days with high solar power supply and hydropower production may become affected.

The potentially sustainable gain of using LCC is highest by implementing it in an early stage, in the project and design phase, before the choice of materials and building components.

As the building sector moves toward towards reduced GHG-emissions and ZEB goals, the use of timber in constructions are more likely to become more widespread. With the increased demand of wood due to emission reductions, development in technology and industrialised industry would make it more affordable and improve the efficiency on the construction site. In recent years, massive wood in public building has increased in popularity because of its environmental and constructional features. If it will pricewise be the same as traditional building materials as concrete and steel, the probability of having a greater share of timber buildings in the future will increase.

Development in low-carbon concrete – if the related emissions continue to decrease, this will be a good material option in the scope of reducing emissions within the building and construction industry.

There will always be some uncertainties when performing LCAs because of the enormous amount of data included in the calculations. Thousands of data sources connect the processes and underlying flows connected to them, and every data has a certain uncertainty. It is also a possibility of incomplete chains, which means that some processes or products included in the building and its operation may not be accounted for.

The database integrated in SimaPro uses average values for Europe, which will in some cases differ from production located in Norway. This is taken into consideration for the electricity mix used in the analyses, making a mix of the Nordic electricity production as Norway trades electricity with the other countries. However, the emission factor in this project was greater than the one used in the estimated calculations based on Norwegian electricity mic. When comparing this study with studies based on the Norwegian electricity mix, one should be aware of this regarding the result for the GWP.

7 Conclusion

In this project, LCA and LCC were used to calculate the sustainability performance and life cycle costs of a nZEB office building. The analyses were conducted for five different material alternatives to evaluate how the building performs and for comparisons with alternative material solutions, which can be used in future buildings.

The life cycle stages investigated were the construction phase, transport, replacement, and operation phase, to determine how the different phases performed with respect to the selected indicators: cumulative energy demand, CO_2-emissions, and net presents costs.

The results from the study have led to the following conclusion:

- The CED is lowest for the alternative with additional PV panels on the south façade. By installing more PVs, there is a great potential for reducing the energy demand in the operation phase, thus saving electricity costs.

Calculations show that CED for Alternative 5 are lower, with the total reduction in CED being 25 % and 66 % lower in the use phase, compared to the building as built. The installation increases energy use in the construction and replacement phase, but this does not exceed the total energy savings. In periods where the energy production is higher than the need of the building, there is an extra gain of sending the electricity to other buildings nearby or selling it on the grid.

- Alternative 4 performs best in terms of GWP, with a total CO_2-emissions of 7.5 kg CO_2-eq per m^2 per year. Using wooden elements in building parts reduces the emissions by 29 % compared to as built.

By replacing building parts with high contents of concrete and steel with timber, a significant reduction in CO_2-emissions is achieved. Both alternatives with wood structures have lower emissions than Alternative 1 with low-carbon concrete. By replacing the load bearing structures (Alternative 3), the GWP is reduced by 15 % compared to as built. This indicates, that the more wood, the higher emission reductions are obtained. Floors, external walls, and PVs are main contributors to GWP.

- When it comes to costs, there are small differences separating the different alternatives. Only a difference of 112 NOK per m^2 per year separates the cheapest alternative, i.e. Alternative 3, from the most expensive one, i.e. Alternative 5.

Regarding the differences in the NPC, the variations in the costs for the different material alternatives were insignificant. The most reasonable choice would be Alternative 3, but the NPC over 60 years is only 3 % less than Alternative 1. Use of timber in the building gives the lowest costs.

Concluding, taking the here examined perspectives into account, i.e. CED, GWP, and NPC, Alternative 5 is best with regards to CED, but Alternative 4 performs best with respect to GWP. Regarding NPC, all alternatives are about equal. Moreover, according to the here chosen weighting, Alternative 2 performs worst, followed by Alternative 1. Thus, timber and other wooden structures are recommended for the use in nZEBs in general, although the final decision strongly depends on an emphasis on either one of the three indicators.

For future work, more material alternatives can be assessed for LCA and LCC of the case study, e.g. use of solid wood as this improves the efficiency at the construction site by shorten the times of construction. This was not done in this project due to the lack of information on dimensioning buildings with solid wood.

There can also be included more life stages in the LCA, such as the end-of life stage, which would most likely make a difference in the environmental performance of wood due to GWP reduction in relation to biogenic carbon storage.

More environmental and economic indicators as e.g. global costs, indoor quality, etc. can also be included in such a case study. Further development of the weighting process of the indicators can be considered in the analyses by use of e.g. specific mathematical techniques common in multi-criteria decision analysis.

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9 Appendix

LCA: Resultater

System boundaries (X=included, MND=module not declared, MNR=module not relevant)

Product stage			Construction installation stage		User stage							End of life stage				Beyond the system bondaries
Raw materials	Transport	Manufacturing	Transport	Construction/ installation stage	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction/ demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4	A5	C1	C2
GWP	kg CO_2 -eqv	2,21E+002	4,45E+000	3,29E+000				
ODP	kg CFC11 -eqv	3,36E-006	0,00E+000	4,05E-007				
POCP	kg C_2H_4-eqv	5,05E-001	5,43E-003	2,16E-002				
AP	kg SO_2 -eqv	1,78E-001	2,65E-002	5,33E-003				
EP	kg PO_4^{3-} -eqv	3,43E-002	5,21E-003	3,86E-003				
ADPM	kg Sb -eqv	4,56E-005	0,00E+000	1,42E-006				
ADPE	MJ	9,18E+002	5,95E+001	4,28E+001				

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

Ressursbruk (Resource use)

Parameter	Unit	A1	A2	A3	A4	A5	C1	C2
RPEE	MJ	5,93E+001	6,54E-002	1,86E-001				
RPEM	MJ	3,01E-001	2,56E-002	1,61E-001				
TRPE	MJ	5,96E+001	9,11E-002	3,47E-001				
NRPEE	MJ	1,16E+003	5,94E+001	4,33E+001				
NRPEM	MJ	7,65E+000	0,00E+000	0,00E+000				
TNRPE	MJ	1,17E+003	5,94E+001	4,33E+001				
SM	kg	1,91E+002	0,00E+000	0,00E+000				
RSF	MJ	0,00E+000	0,00E+000	0,00E+000				
NRSF	MJ	5,83E+002	0,00E+000	0,00E+000				
W	m^3	2,27E+002	4,61E-001	1,09E+000				

RPEE Fornybar primærenergi brukt som energibærer; **RPEM** Fornybar primærenergi brukt som råmateriale; **TRPE** Total bruk av fornybar primærenergi; **NRPEE** Ikke fornybar primærenergi brukt som energibærer; **NRPEM** Ikke fornybar primærenergi brukt som råmateriale; **TNRPE** Total bruk av ikke fornybar primærenergi; **SM** Bruk av sekundære materialer; **RSF** Bruk av fornybart sekundære brensel; **NRSF** Bruk av ikke fornybart sekundære brensel; **W** Netto bruk av ferskvann

Figure 22: EPD for low-carbon concrete from Voss cement [1].

LCA: Resultater

System boundaries (X=included, MND=module not declared, MNR=module not relevant)

Product stage			Construction installation stage		User stage							End of life stage				Beyond the system bondaries
Raw materials	Transport	Manufacturing	Transport	Construction/ Installation stage	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction/ demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	MNR	MNR	MNR	MNR	MNR	MNR	MNR	X	X	MNR	MNR	MNR

Miljøpåvirkning (Environmental impact)

Parameter	Unit	A1	A2	A3	A4	A5	C1	C2
GWP	kg CO_2 -eqv	5,15E+001	1,30E+000	3,77E+000	2,06E+000	9,00E+000	1,71E+000	2,06E+000
ODP	kg CFC11 -eqv	1,20E-006	0,00E+000	7,67E-007	0,00E+000	5,99E-007	3,08E-007	0,00E+000
POCP	kg C_2H_4-eqv	1,58E-001	6,87E-003	2,75E-002	9,53E-003	3,55E-002	1,29E-002	9,53E-003
AP	kg SO_2 -eqv	6,49E-002	1,52E-003	7,41E-003	2,23E-003	8,68E-003	2,92E-003	2,23E-003
EP	kg PO_4^{3-} -eqv	1,35E-002	2,79E-004	8,14E-004	4,38E-004	1,27E-003	3,45E-004	4,38E-004
ADPM	kg Sb -eqv	1,85E-004	0,00E+000	1,53E-005	0,00E+000	4,61E-006	5,57E-007	0,00E+000
ADPE	MJ	2,93E+002	1,96E+001	5,13E+001	3,31E+001	6,41E+001	2,42E+001	3,31E+001

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

Ressursbruk (Resource use)

Parameter	Unit	A1	A2	A3	A4	A5	C1	C2
RPEE	MJ	8,84E+000	3,08E-001	2,20E+001	7,26E-001	9,49E+000	1,35E-001	7,26E-001
RPEM	MJ	1,40E+000	8,98E-002	1,37E-001	2,16E-001	2,90E+000	2,24E-002	2,16E-001
TRPE	MJ	1,02E+001	3,98E-001	2,21E+001	9,42E-001	1,24E+001	1,57E-001	9,42E-001
NRPEE	MJ	3,86E+002	2,00E+001	7,34E+001	3,40E+001	6,72E+001	2,44E+001	3,40E+001
NRPEM	MJ	5,64E-001	0,00E+000	0,00E+000	0,00E+000	6,70E-002	0,00E+000	0,00E+000
TNRPE	MJ	3,87E+002	2,00E+001	7,34E+001	3,40E+001	6,73E+001	2,44E+001	3,40E+001
SM	kg	1,93E+001	0,00E+000	0,00E+000	0,00E+000	1,13E+000	0,00E+000	0,00E+000
RSF	MJ	0,00E+000	0,00E+000	0,00E+000	0,00E+000	2,70E-004	0,00E+000	0,00E+000
NRSF	MJ	9,60E+001	0,00E+000	0,00E+000	0,00E+000	1,02E+000	0,00E+000	0,00E+000
W	m^3	1,24E+002	8,90E-002	3,45E-001	1,03E-002	9,20E-002	4,17E-003	1,03E-002

RPEE Fornybar primærenergi brukt som energibærer; **RPEM** Fornybar primærenergi brukt som råmateriale; **TRPE** Total bruk av fornybar primærenergi; **NRPEE** Ikke fornybar primærenergi brukt som energibærer; **NRPEM** Ikke fornybar primærenergi brukt som råmateriale; **TNRPE** Total bruk av ikke fornybar primærenergi; **SM** Bruk av sekundære materialer; **RSF** Bruk av fornybart sekundære brensel; **NRSF** Bruk av ikke fornybart sekundære brensel; **W** Netto bruk av ferskvann

Figure 23: EPD for hollow core blocks produced by NOBI [72] .

Table 8: Density for construction materials

Construction material	**Density [kg/m^3]**	**Basis weight [kg/m^2]**
Steel	7800	
Concrete	2400	
Insulation: XPS	29	
Sika radon membrane		1.2
Insulation EPS	15	
Glue laminated timber	470	
Cross laminated timber	500	
Particle board	730	
Fibre board	500	
Mineral wool, acoustic plate	125	
Mineral wool; floor,roof	16.5	
Gypsum	720	

Table 9: Dimensioning table for wooden beam layer in glue laminated timber, from Moelven Limtre AS .[60]

Tabellen angir lysåpning i meter

Antall felt								
C/C avstand	0,30 m		0,60 m		0,30 m		0,60 m	
Limtre - dimensjoner	**Lysåpning meter**	Max nyttelast kN/m²	**Lysåpning meter**	Max nyttelast kN/m²	**Lysåpning meter**	Max nyttelast kN/m²	**Lysåpning meter**	Max nyttelast kN/m²
36 x 200	**4,11**	2,5	**3,32**	2,3	**4,32**	4,1	**3,49**	3,0
36 x 225	**4,69**	2,4	**3,81**	2,1	**4,92**	4,0	**4,00**	2,9
36 x 250	**5,13**	2,6	**4,30**	2,0	**5,39**	4,2	**4,52**	2,8
36 x 270	**5,42**	2,8	**4,66**	2,0	**5,69**	4,4	**4,94**	2,7
36 x 300	**5,84**	3,2	**5,16**	2,1	**6,13**	4,8	**5,42**	2,8
36 x 315	**6,04**	3,3	**5,35**	2,2	**6,34**	4,9	**5,61**	2,9
36 x 350	**6,51**	3,8	**5,77**	2,5	**6,83**	5,3	**6,06**	3,1
36 x 360	**6,64**	3,9	**5,89**	2,5	**6,97**	5,4	**6,18**	3,2
36 x 400	**7,16**	4,3	**6,36**	2,9	**7,52**	5,8	**6,67**	3,4
48 x 200	**4,77**	2,7	**3,87**	2,4	**5,00**	5,1	**4,06**	3,7
48 x 225	**5,24**	3,0	**4,43**	2,3	**5,50**	5,4	**4,65**	3,5
48 x 250	**5,64**	3,3	**4,97**	2,2	**5,92**	5,8	**5,21**	3,5
48 x 270	**5,96**	3,6	**5,25**	2,4	**6,26**	6,1	**5,51**	3,7
48 x 300	**6,42**	4,1	**5,67**	2,7	**6,74**	6,5	**5,95**	3,9
48 x 315	**6,65**	4,3	**5,87**	2,9	**6,98**	6,7	**6,17**	4,1
48 x 350	**7,18**	4,8	**6,34**	3,2	**7,53**	7,2	**6,66**	4,4
48 x 360	**7,32**	4,9	**6,47**	3,3	**7,69**	7,3	**6,80**	4,4
48 x 400	**7,90**	5,5	**6,99**	3,7	**8,29**	7,8	**7,34**	4,7
48 x 450	**8,60**	6,2	**7,61**	4,2	**9,03**	8,4	**8,00**	5,1
48 x 495	**9,21**	6,7	**8,16**	4,6	**9,67**	8,9	**8,57**	5,4
73 x 200	**5,23**	3,2	**4,42**	2,5	**5,49**	6,6	**4,64**	4,4
73 x 225	**5,69**	3,7	**5,00**	2,5	**5,97**	7,1	**5,25**	4,4
73 x 250	**6,14**	4,1	**5,39**	2,8	**6,44**	7,6	**5,66**	4,7
73 x 270	**6,48**	4,5	**5,70**	3,0	**6,81**	8,0	**5,99**	4,9
73 x 300	**6,99**	5,0	**6,16**	3,4	**7,34**	8,6	**6,47**	5,3
73 x 315	**7,25**	5,2	**6,38**	3,6	**7,61**	8,8	**6,70**	5,4
73 x 350	**7,82**	5,8	**6,89**	4,0	**8,21**	9,4	**7,24**	5,8
73 x 360	**7,98**	6,0	**7,03**	4,1	**8,38**	9,6	**7,39**	5,9
73 x 400	**8,61**	6,6	**7,60**	4,6	**9,04**	10,2	**7,98**	6,3
73 x 450	**9,38**	7,4	**8,28**	5,1	**9,85**	10,9	**8,69**	6,8
73 x 495	**10,05**	8,1	**8,88**	5,6	**10,55**	11,6	**9,32**	7,2

Dimensioning of timber structures

The building components are dimensioned in accordance with NS-EN 1995-1-1, climate class 1, as this applies for bearing structures in heated and ventilated buildings. To determine the needed strength of the timber components, load-duration classes were computed in accordance with SINTEF’s database on building directions.

The snow load for Bergen is found to be 2.0 kN/m^2 in NS 3491-3 [73]. To achieve the intended level of reliability when calculating loads, partial factors are used to compute loads in the breaking point state. The partial factors for permanent loads (dead loads) γG= 1.2 and for the variable loads as snow and live loads, γQ = 1,5 from NS-EN1990 in Byggdetaljer in SINTEF Byggforsk [58]. By multiplying these with the dead load and live load, it resulted in a dimensioned load of 5.70 kN/m^2, which give a dimensioned load per meter of 31.96 kN/m.

Thermal properties of building components

Heat transfer coefficients, U-values, are standardised measurements describing the characteristic of a building`s heat loss [74]. It measures the amount of heat [W] per unit of time flowing through an area of 1 m^2 under a constant temperature difference of 1 °C, between the surface of the warm and cold side of the structure [74]. The better insulation, the lower U-value. The value can be measured or calculated by use of the equation in NS-EN ISO 6946 [74].

$$U = \frac{1}{R_T} + \Delta U \quad \left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right]$$

R_T = total heat resistance [m^2K/W]
ΔU = plus possible addition because of design, performance, etc

The U-values of the building elements describes the heat loss through walls, floors, roof, external doors and windows. Heat resistance in materials and external and internal surface resistance determine the U-values. The minimum U-values performance criteria for the building elements contribute to an energy efficient building envelope, reducing the demand for heating during winter and cooling in summer. The U-values are necessary when calculating the energy demand for the operation of the building.

To maintain the same level of thermal performance as the actual building, floor slabs, roof and external walls in alternative 3 and 4, were dimensioned to obtain the same U-values. The calculations are made in accordance with NS-EN ISO 6946, found in Byggforsk 471.008 [74].

Table 8: Inventory - EPD

Construction	Material input (if otherwise unclear)	Amount	Unit	Process used
Foundation				
Plinths, plates	Reinforcement steel	5,682.70	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Plinths, plates, beams	Concrete	52.54	m3	EPD
Bearing construction				
Pillars	Concrete	25.99	m3	EPD
	Reinforcement steel	4,158.96	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Walls	Concrete	118.16	m3	EPD
	Reinforcement steel	8,271.40	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Beams	Concrete	59.23	m3	EPD
	Reinforcement steel	9,476.64	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Outer walls				
Non-bearing outer walls		15,422.40	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Lathing		159.89	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Insulation		10,205.26	kg	Glass wool mat {CH}| production | Alloc Rec, U
Air-, windbarrier		315.90	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Facade plates		5,992.80	kg	Aluminium facade plate
Window frames		51.67	m2	Window frame, wood-metal, U=1.6 W/m2K {RER}| production | Alloc Rec, U

Window glass		4,316.27	kg	Flat glass, coated {RER}| production | Alloc Rec, U
Window glass		2,158.13	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Doors	Wood	14.50	m2	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Doors		8.10	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Inner walls				
Gypsum plates		17,533.60	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Tiles		5,342.10	kg	Ceramic tile {CH}| production | Alloc Rec, U
Insulation		2,087.60	kg	Glass wool mat {CH}| production | Alloc Rec, U
Glass		58,350.00	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Lathing		19.19	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Doors		221.49	m2	Door, inner, wood {RER}| production | Alloc Rec, U
Doors		25.29	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Slab structures				
Insulation		3,900.50	kg	Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U
Insulation		1,008.75	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U

Concrete	Concrete	67.25	m3	EPD
Steel		5,380.00	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Floor cover		5,365.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Floor cover		1,813.35	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Air-, windbarrier		807.00	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
slabstructures		6,541.30	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Hollow block floor	Hollow block floor	481,138.22	kg	EPD
Floor cover		4,238.52	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Floor cover		1,305.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Steel		1,408.50	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Ceiling		3,098.70	kg	Glass wool mat {CH}| production | Alloc Rec, U
Roof				
Roof cover		5,805.50	kg	Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U
Insulation		4,589.76	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Insulation		3,175.95	kg	Rock wool {CH}| production | Alloc Rec, U

Vapour barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Hollow block floor	Hollow block floor	344,511.58	kg	EPD
Reinforcement steel		4,501.42	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Ceiling		2,128.17	kg	Glass wool mat {CH}| production | Alloc Rec, U
Steel		967.35	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
PV panels		340.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U

Table 10: Inventory - Ecoinvent

Construction	Material input (if otherwise unclear)	Amount	Unit	Process used
Foundation				
Plinths, plates		5,682.70	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Plinths, plates, beams		52.54	m3	Concrete, normal [75]| production | Alloc Rec, U
Bearing construction				
Pillars		25.99	m3	Concrete, normal [75]| production | Alloc Rec, U
		4,158.96	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Walls		118.16	m3	Concrete, normal [75]| production | Alloc Rec, U
		8,271.40	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Beams		59.23	m3	Concrete, normal [75]| production | Alloc Rec, U

		9,476.64	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Outer walls				
Non-bearing outer walls		15,422.40	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Lathing		159.89	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Insulation		10,205.26	kg	Glass wool mat {CH}| production | Alloc Rec, U
Air-, windbarrier		315.90	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Facade plates		5,992.80	kg	Aluminium facade plate
Window frames		51.67	m2	Window frame, wood-metal, U=1.6 W/m2K {RER}| production | Alloc Rec, U
Window glass		4,316.27	kg	Flat glass, coated {RER}| production | Alloc Rec, U
Window glass		2,158.13	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Doors	Wood	14.50	m2	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Doors		8.10	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Inner walls				
Gypsum plates		17,533.60	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Tiles		5,342.10	kg	Ceramic tile {CH}| production | Alloc Rec, U
Insulation		2,087.60	kg	Glass wool mat {CH}| production | Alloc Rec, U
Glass		58,350.00	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Lathing		19.19	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Doors		221.49	m2	Door, inner, wood {RER}| production | Alloc Rec, U

Doors		25.29	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Slab structures				
Insulation	XPS	3,900.50	kg	Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U
Insulation	EPS	1,008.75	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Concrete		67.25	m3	Concrete, normal [75]| production | Alloc Rec, U
Steel		5,380.00	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Floor cover		5,365.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Floor cover	Linoleum	1,813.35	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Air-, windbarrier	Membrane	807.00	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Slabstructures	Reinforcement steel	6,541.30	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Hollow block floor		481,138.22	kg	Lightweight concrete block, pumice {DE}| production | Alloc Rec, U
Floor cover	Linoleum	4,238.52	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Floor cover		1,305.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Steel		1,408.50	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Ceiling		3,098.70	kg	Glass wool mat {CH}| production | Alloc Rec, U
Roof				
Roof cover		5,805.50	kg	Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U
Insulation	EPS	4,589.76	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Insulation		3,175.95	kg	Rock wool {CH}| production | Alloc Rec, U

Vapour barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Hollow block floor		344,511.58	kg	Lightweight concrete block, pumice {DE}| production | Alloc Rec, U
Reinforcement steel		4,501.42	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Ceiling		2,128.17	kg	Glass wool mat {CH}| production | Alloc Rec, U
Steel		967.35	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
PV panels		340.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U

Table 11: Inventory - Timber bearing structure

Construction	Material input (if otherwise unclear)	Amount	Unit	Process used
Foundation				
Plinths, plates	Reinforcement steel	4,171.66	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Plinths, plates, beams	Concrete	39.94	m3	EPD
Bearing construction				
Pillars	Timber	6.62	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
	Nail plates	942.21	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Walls	Concrete	118.16	m3	EPD
	Reinforcement steel	8,271.40	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Beams	Timber	28.14	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
	Nail plates	942.21	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Outer walls				

Non-bearing outer walls		15,422.40	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Lathing		159.89	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Insulation		10,205.26	kg	Glass wool mat {CH}| production | Alloc Rec, U
Air-, windbarrier		315.90	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Facade plates		5,992.80	kg	Aluminium facade plate
Window frames		51.67	m2	Window frame, wood-metal, U=1.6 W/m2K {RER}| production | Alloc Rec, U
Window glass		4,316.27	kg	Flat glass, coated {RER}| production | Alloc Rec, U
Window glass		2,158.13	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Doors		14.50	m2	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Doors		8.10	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Inner walls				
Gypsum plates		17,533.60	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Tiles		5,342.10	kg	Ceramic tile {CH}| production | Alloc Rec, U
Insulation		2,087.60	kg	Glass wool mat {CH}| production | Alloc Rec, U
Glass		58,350.00	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Lathing		19.19	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Doors		221.49	m2	Door, inner, wood {RER}| production | Alloc Rec, U
Doors	Metal	25.29	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Slab structures				

Insulation	XPS	3,900.50	kg	Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U
Insulation	EPS	1,008.75	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Concrete	concrete	67.25	m3	EPD
Steel		5,380.00	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Floor cover		5,365.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Floor cover	Linoleum	1,813.35	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Air-, windbarrier	Membrane	807.00	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Lathing		3.27	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Isolation		8,996.42	kg	Glass wool mat {CH}| production | Alloc Rec, U
Floor cover	Linoleum	4,238.52	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Floor cover		1,305.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Timber work		48.28	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
Particle board		28.92	m3	Particle board, for indoor use {RER}| production | Alloc Rec, U
Fibreboard		47.32	m3	Fibreboard, soft {Europe without Switzerland}| fibreboard production, soft, from wet & dry processes | Alloc Rec, U
Ceiling	Gypsum plates	12,303.72	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Roof				
Roof cover		5,805.50	kg	Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U

Particle board		10.93	m3	Particle board, for indoor use {RER}| production | Alloc Rec, U
Lathing		2.03	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Air barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Board		2.52	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Insulation		4,946.32	kg	Glass wool mat {CH}| production | Alloc Rec, U
Beams		25.03	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
Vapour barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Lathing		1.98	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Gypsum plates		6,392.88	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
PV panels		340.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U

Table 12: Inventory - Timber facade

Construction	Material input (if otherwise unclear)	Amount	Unit	Process used
Foundation				
Plinths, plates	Reinforcement steel	4,171.66	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Plinths, plates, beams	Concrete	39.94	m3	EPD
Bearing construction				
Pillars	Timber	6.62	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U

	Nail plates	942.21	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Walls	Concrete	118.16	m3	EPD
	Reinforcement steel	8,271.40	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Beams	Timber	28.14	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
	Nail plates	942.21	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Outer walls				
Gypsum plates		10,535.52	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Lathing		3.52	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Insulation		5,571.67	kg	Glass wool mat {CH}| production | Alloc Rec, U
Air barrier		219.49	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Vapour barrier		157.58	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Studs		112.56	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Fibreboard		13.51	m3	Fibreboard, soft {Europe without Switzerland}| fibreboard production, soft, from wet & dry processes | Alloc Rec, U
Paint, primer		53.63	kg	Alkyd paint, white, without solvent, in 60% solution state {RER}| alkyd paint production, white, solvent-based, product in 60% solution state | Alloc Rec, U
Wooden lagging		21.39	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U

Window frames		51.67	m2	Window frame, wood, U=1.5 W/m2K {RER}| production | Alloc Rec, U
Window glass		4,316.27	kg	Flat glass, coated {RER}| production | Alloc Rec, U
Window glass		2,158.13	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Doors	Wood	14.50	m2	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Doors		8.10	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Inner walls				
Gypsum plates		17,533.60	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Tiles		5,342.10	kg	Ceramic tile {CH}| production | Alloc Rec, U
Insulation		2,087.60	kg	Glass wool mat {CH}| production | Alloc Rec, U
Glass		58,350.00	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Lathing		19.19	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Doors		221.49	m2	Door, inner, wood {RER}| production | Alloc Rec, U
Doors	Metal	25.29	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Slab structures				
Insulation	XPS	3,900.50	kg	Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U
Insulation	EPS	1,008.75	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Concrete	Concrete	67.25	m3	EPD
Steel		5,380.00	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Floor cover		5,365.00	kg	Ceramic tile {CH}| production | Alloc Rec, U

Floor cover	Linoleum	1,813.35	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Air-, windbarrier	Membrane	807.00	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Lathing		3.27	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Isolation		8,996.42	kg	Glass wool mat {CH}| production | Alloc Rec, U
Floor cover	Linoleum	4,238.52	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Floor cover		1,305.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Timber work		48.28	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
Particle board		28.92	m3	Particle board, for indoor use {RER}| production | Alloc Rec, U
Fibreboard		47.32	m3	Fibreboard, soft {Europe without Switzerland}| fibreboard production, soft, from wet & dry processes | Alloc Rec, U
Ceiling		12,303.72	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Roof				
Roof cover		5,805.50	kg	Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U
Particle board		10.93	m3	Particle board, for indoor use {RER}| production | Alloc Rec, U
Lathing		2.03	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Air barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Board		2.52	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Insulation		4,946.32	kg	Glass wool mat {CH}| production | Alloc Rec, U

Beams		25.03	m3	Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U
Vapour barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Lathing		1.98	m3	Sawnwood, softwood, kiln dried, planed {RER}| market for | Alloc Rec, U
Gypsum plates		6,392.88	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
PV panels		340.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U

Table 13: Inventory - PV facade

Construction	Material input (if otherwise unclear)	Amount	Unit	Process used
Foundation				
Plinths, plates	Reinforcement steel	5,682.70	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Plinths, plates, beams	Concrete	52.54	m3	EPD
Bearing construction				
Pillars	Concrete	25.99	m3	EPD
	Reinforcement steel	4,158.96	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Walls	Concrete	118.16	m3	EPD
	Reinforcement steel	8,271.40	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Beams	Concrete	59.23	m3	EPD
	Reinforcement steel	9,476.64	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Outer walls				
Non-bearing outer walls		15,422.40	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Lathing		159.89	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Insulation		10,205.26	kg	Glass wool mat {CH}| production | Alloc Rec, U

Air-, windbarrier		315.90	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Facade plates		5,992.80	kg	Aluminium facade plate
Window frames		51.67	m2	Window frame, wood-metal, U=1.6 W/m2K {RER}| production | Alloc Rec, U
Window glass		4,316.27	kg	Flat glass, coated {RER}| production | Alloc Rec, U
Window glass		2,158.13	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Doors	Wood	14.50	m2	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Doors		8.10	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
PV panels		286.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U
Inner walls				
Gypsum plates		17,533.60	kg	Gypsum plasterboard {CH}| production | Alloc Rec, U
Tiles		5,342.10	kg	Ceramic tile {CH}| production | Alloc Rec, U
Insulation		2,087.60	kg	Glass wool mat {CH}| production | Alloc Rec, U
Glass		58,350.00	kg	Flat glass, uncoated {RER}| production | Alloc Rec, U
Lathing		19.19	m3	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U
Doors		221.49	m2	Door, inner, wood {RER}| production | Alloc Rec, U
Doors	Metal	25.29	m3	Door, outer, wood-aluminium {RER}| production | Alloc Rec, U
Slab structures				
Insulation	XPS	3,900.50	kg	Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U
Insulation	EPS	1,008.75	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U

Concrete	Concrete	67.25	m3	EPD
Steel		5,380.00	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Floor cover		5,365.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Floor cover	Linoleum	1,813.35	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Air-, windbarrier	Membrane	807.00	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
slabstructures		6,541.30	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Hollow block floor		481,138.22	kg	EPD
Floor cover	Linoleum	4,238.52	kg	Synthetic rubber {RER}| production | Alloc Rec, U
Floor cover		1,305.00	kg	Ceramic tile {CH}| production | Alloc Rec, U
Steel		1,408.50	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U
Ceiling		3,098.70	kg	Glass wool mat {CH}| production | Alloc Rec, U
Roof				
Roof cover		5,805.50	kg	Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U
Insulation	EPS	4,589.76	kg	Polystyrene foam slab {RER}| production | Alloc Rec, U
Insulation		3,175.95	kg	Rock wool {CH}| production | Alloc Rec, U
Vapour barrier		126.36	kg	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U
Hollow block floor		344,511.58	kg	EPD
Reinforcement steel		4,501.42	kg	Reinforcing steel {RER}| production | Alloc Rec, U
Ceiling		2,128.17	kg	Glass wool mat {CH}| production | Alloc Rec, U
Steel		967.35	kg	Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U

PV panels		340.00	m2	Photovoltaic panel, multi-Si wafer {RER}| production | Alloc Rec, U

Table 14: EPD - Alternative 1, low emission concrete

Alternative 1, low emission concrete	GWP (kg CO2 eq/m2 *year)	Total primary energy (MJ/m2*yr)	Total primary energy (kWh/m2*yr)	% of total CO2-emission	% of total primary energy
Construction phase	5.09	102.97	28.83	52.56%	38.51%
Use phase	2.78	126.72	35.48	28.72%	47.39%
Replacements	1.40	30.99	8.68	14.47%	11.59%
Transport	0.41	6.72	1.88	4.25%	2.51%
Sum	9.69	267.40	74.87	100.00%	100.00%

Table 15: EPD - Alternative 2, normal concrete

Alternative 2, normal concrete	GWP (kg CO2 eq/m2 *year)	Total primary energy (MJ/m2*yr)	Total primary energy (kWh/m2*yr)	% of total CO2-emission	% of total primary energy
Construction phase	5.97	105.53	29.55	56.53%	39.09%
Use phase	2.78	126.72	35.48	26.32%	46.94%
Replacements	1.40	30.99	8.68	13.26%	11.48%
Transport	0.41	6.72	1.88	3.89%	2.49%
Sum	10.57	269.96	75.59	100.00%	100.00%

Table 16: EPD - Alternative 3, timber structure

Alternative 3, timber structure	GWP (kg CO2 eq/m2 *year)	Total primary energy (MJ/m2*yr)	Total primary energy (kWh/m2*yr)	% of total CO2-emission	% of total primary energy
Construction phase	3.70	103.50	28.98	45.25%	38.90%
Use phase	2.78	126.72	35.48	33.98%	47.62%
Replacements	1.40	30.99	8.68	17.12%	11.65%
Transport	0.30	4.88	1.37	3.65%	1.83%
Sum	8.19	266.10	74.51	100.00%	100.00%

Table 17: EPD - Alternative 4, timber structure+facade

Alternative 4, timber structure+facade	GWP (kg CO2 eq/m2 *year)	Total primary energy (MJ/m2*yr)	Total primary energy (kWh/m2*yr)	% of total CO2-emission	% of total primary energy
Construction phase	3.36	99.83	27.95	44.96%	38.64%
Use phase	2.78	126.72	35.48	37.18%	49.05%
Replacements	1.06	27.32	7.65	14.18%	10.57%
Transport	0.28	4.50	1.26	3.68%	1.74%
Sum	7.48	258.37	72.34	100.00%	100.00%

Table 18: EPD - Alternative 5, PV facade

Alternative 5, PV facade	GWP(kg CO2 eq/m2 *year)	Total primary energy (MJ/m2*yr)	Total primary energy kWh/m2*yr)	% of total CO2-emission	% of total primary energy
Construction phase	5.58	102.97	28.83	63.22%	53.68%
Use phase	0.94	42.92	12.02	10.68%	22.37%
Replacements	1.89	39.17	10.97	21.41%	20.42%
Transport	0.41	6.77	1.90	4.69%	3.53%
Sum	8.82	191.82	53.71	100.00%	100.00%

Table 19: EPD - Global warming potential

GWP (ton CO2 eq)	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Construction phase	0.62	0.73	0.45	0.41	0.68
Use phase	0.34	0.34	0.34	0.34	0.12
Replacements	0.17	0.17	0.17	0.13	0.23
Transport	0.05	0.05	0.04	0.03	0.05
Sum	1.18	1.29	1.00	0.91	1.08

Table 20: EPD - Total primary energy

Total primary energy (GWh)	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Construction phase	3.52	3.61	3.54	3.41	3.52
Use phase	4.33	4.33	4.33	4.33	1.47
Replacements	1.06	1.06	1.06	0.93	1.34
Transport	0.23	0.23	0.17	0.15	0.23
Sum	9.15	9.23	9.10	8.84	6.56

Table 21: Transport - Products, suppliers, and distances

Product	**Supplier**	**Produced**	**Distance to Bergen, km**
Aluminium plates 3003 H44	Alumeco Norge AS	Lørenskog	486
Window	NorDan AS	Åsnes kommune	562
Concrete	Norbetong AS	Oslo	465
Concrete B35 M45	Voss Cementfabrikk AS	Voss	115
Hollow core blocks	NOBI Voss AS	Voss	115
Insulation Kraftunderlag	Fløysand Tak AS	Os	41
Insulation Mestertekk			41
EPS s80	Vartdal	Vartdal	360
Rockwool			360

Table 22: Transport - Ecoinvent, EPD, Timber bearing structures

Ecoinvent, EPD, Timber bearing structures	Value	Unit	Conversion factor	Tons	tkm	tkm, replacements
Concrete, normal [75]| production | Alloc Rec, U	323.17	m3	2380	769.14	88,451.63	
Reinforcing steel {RER}| production | Alloc Rec, U	38,632.42	kg		38.63	17,384.59	
Gypsum plasterboard {CH}| production | Alloc Rec, U	32,956.00	kg		32.96	14,830.20	
Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U	179.08	m3	500	89.54	40,293.00	
Glass wool mat {CH}| production | Alloc Rec, U	17,519.73	kg		17.52	7,883.88	
Polyethylene, high density, granulate {RER}| production | Alloc Rec, U	1,249.26	kg		1.25	562.17	
Aluminium facade plate	5,992.80	kg		5.99	2,912.50	2,912.50
Windows	267.50	m2	39.0	10.43	5,863.43	5,863.43
Door, outer, wood-aluminium {RER}| production | Alloc Rec, U	47.89	m2	38.8	1.86	836.16	441.74
Ceramic tile {CH}| production | Alloc Rec, U	12,012.10	kg		12.01	5,405.45	3,001.50
Door, inner, wood {RER}| production | Alloc Rec, U	221.49	m2	27.6	6.11	2,750.91	2,750.91
Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U	3,900.50	kg		3.90	1,755.23	
Polystyrene foam slab {RER}| production | Alloc Rec, U	5,598.51	kg		5.60	2,015.46	
Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U	7,755.85	kg		7.76	3,490.13	
Synthetic rubber {RER}| production | Alloc Rec, U	6,051.87	kg		6.05	2,723.34	2,723.34
Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U	5,805.50	kg		5.81	238.03	238.03
Lightweight concrete block, pumice {DE}| production | Alloc Rec, U	825,649.80	kg		825.65	94,949.73	
Rock wool {CH}| production | Alloc Rec, U	3,175.95	kg		3.18	1,143.34	

Table 23: Transport – PV's facade

PVs facade	Value	Unit	Conversion factor	Tons	tkm	tkm, replacements
Concrete, EPD	323.17	m3	2380	769.14	88,451.63	
Reinforcing steel {RER}| production | Alloc Rec, U	38,632.42	kg		38.63	17,384.59	
Gypsum plasterboard {CH}| production | Alloc Rec, U	32,956.00	kg		32.96	14,830.20	
Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U	55,626.81	m3	500	89.54	40,293.00	
Glass wool mat {CH}| production | Alloc Rec, U	71,948.16	kg		17.52	7,883.88	
Polyethylene, high density, granulate {RER}| production | Alloc Rec, U	88,269.50	kg		1.25	562.17	
Aluminium facade plate, Alumeco	5,992.80	kg		5.99	2,912.50	2,912.50
Windows	267.50	m2	39.00241705	10.43	5,863.43	5,863.43
Door, outer, wood-aluminium {RER}| production | Alloc Rec, U	47.89	m2	38.8	1.86	836.16	441.74
Ceramic tile {CH}| production | Alloc Rec, U	12,012.10	kg		12.01	5,405.45	3,001.50
Door, inner, wood {RER}| production | Alloc Rec, U	221.49	m2	27.6	6.11	2,750.91	2,750.91
Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U	3,900.50	kg		3.90	1,755.23	
Polystyrene foam slab {RER}| production | Alloc Rec, U	5,598.51	kg		5.60	2,015.46	
Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U	7,755.85	kg		7.76	3,490.13	
Synthetic rubber {RER}| production | Alloc Rec, U	6,051.87	kg		6.05	2,723.34	2,723.34
Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U	5,805.50	kg		5.81	238.03	238.03
Hollow block floor	825,649.80	kg		825.65	94,949.73	
Rock wool {CH}| production | Alloc Rec, U	3,175.95	kg		3.18	1,143.34	
Pv_roof	340.00	m2	16.8	5.71		2,570.40

PV_facade	286.00	m2	16.8	4.80		2,162.16

Table 24: Transport - Timber facade, structure

Timber facade, structure	Value	Unit	Conversion factor	Tons	tkm	tkm, replacements
Concrete, EPD	225.35	m3	2380	536.33	61,678.30	
Reinforcing steel {RER}| production | Alloc Rec, U	12,443.06	kg		12.44	5,599.38	
Gypsum plasterboard {CH}| production | Alloc Rec, U	46,765.72	kg		46.77	21,044.57	
Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U	145.07	m3	500	72.54	32,641.06	10.70
Glass wool mat {CH}| production | Alloc Rec, U	21,602.01	kg		21.60	9,720.90	
Polyethylene, high density, granulate {RER}| production | Alloc Rec, U	1,436.79	kg		1.44	646.56	
Windows	267.50	m2	39.00241705	10.43	5,863.43	5,863.43
Door, outer, wood-aluminium {RER}| production | Alloc Rec, U	47.89	m2	38.8	1.86	836.16	441.74
Ceramic tile {CH}| production | Alloc Rec, U	12,012.10	kg		12.01	5,405.45	3,001.50
Door, inner, wood {RER}| production | Alloc Rec, U	221.49	m2	27.6	6.11	2,750.91	2,750.91
Polystyrene, extruded {RER}| polystyrene production, extruded, CO2 blown | Alloc Rec, U	3,900.50	kg		3.90	1,755.23	
Polystyrene foam slab {RER}| production | Alloc Rec, U	1,008.75	kg		1.01	363.15	

Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Rec, U	7,264.42	kg		7.26	3,268.99	
Synthetic rubber {RER}| production | Alloc Rec, U	6,051.87	kg		6.05	2,723.34	2,723.34
Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U	5,805.50	kg		5.81	238.03	238.03
Glued laminated timber, for indoor use {RER}| production | Alloc Rec, U	108.07	m3	470	50.79	22,857.63	
Particle board, for indoor use {RER}| production | Alloc Rec, U	39.85	m3	730	29.09	13,090.07	
Fibreboard, soft {Europe without Switzerland}| fibreboard production, soft, from wet & dry processes | Alloc Rec, U	47.32	m3	250	11.83	5,323.50	
Alkyd paint, white, without solvent, in 60% solution state {RER}| alkyd paint production, white, solvent-based, product in 60% solution state | Alloc Rec, U	53.63	kg		0.05	24.13	24.13
PV roof						2,570.40

Performance of Grid-connected PV

NOTE: before using these calculations for anything serious, you should read [this]

PVGIS estimates of solar electricity generation

Location: 60°20'19" North, 5°13'45" East, Elevation: 0 m a.s.l.,

Solar radiation database used: PVGIS-classic

Nominal power of the PV system: 45.8 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 5.8% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 4.0%
Other losses (cables, inverter etc.): 15.0%
Combined PV system losses: 23.1%

Fixed system: inclination=90°, orientation=0°				
Month	E_d	E_m	H_d	H_m
Jan	19.40	601	0.50	15.5
Feb	48.40	1360	1.27	35.6
Mar	78.70	2440	2.12	65.8
Apr	101.00	3030	2.83	84.9
May	98.70	3060	2.88	89.4
Jun	102.00	3050	3.04	91.3
Jul	92.20	2860	2.78	86.1
Aug	82.30	2550	2.43	75.3
Sep	74.80	2240	2.12	63.7
Oct	46.30	1430	1.27	39.2
Nov	24.10	723	0.64	19.1
Dec	13.20	408	0.34	10.7
Yearly average	**65.1**	**1980**	**1.85**	**56.4**
Total for year		**23800**		**677**

E_d: Average daily electricity production from the given system (kWh)
E_m: Average monthly electricity production from the given system (kWh)
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)
H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

Figure 24: Performance of grid-connected PV

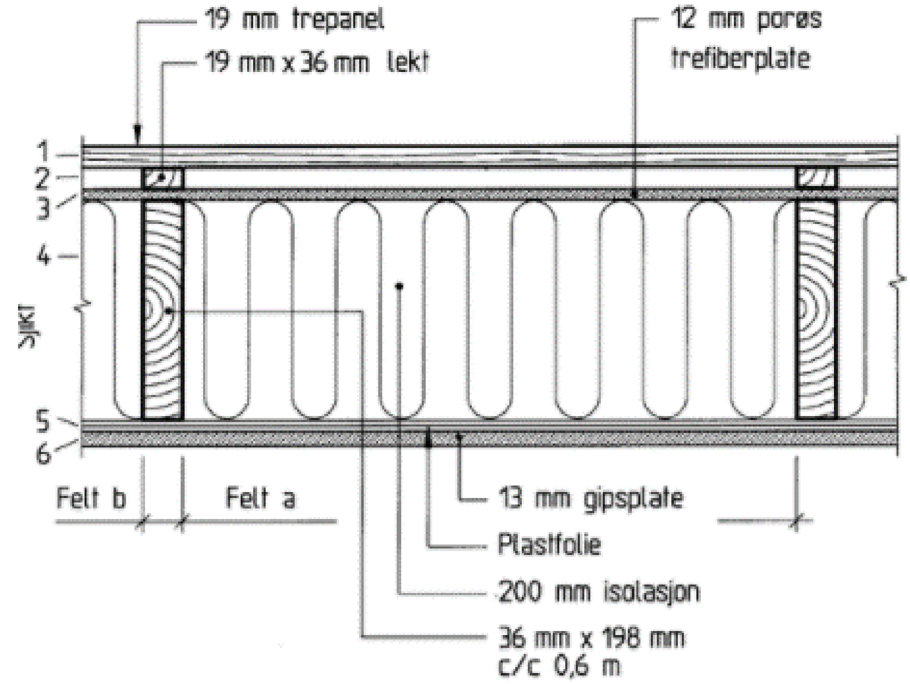

Figure 25: Wall structure

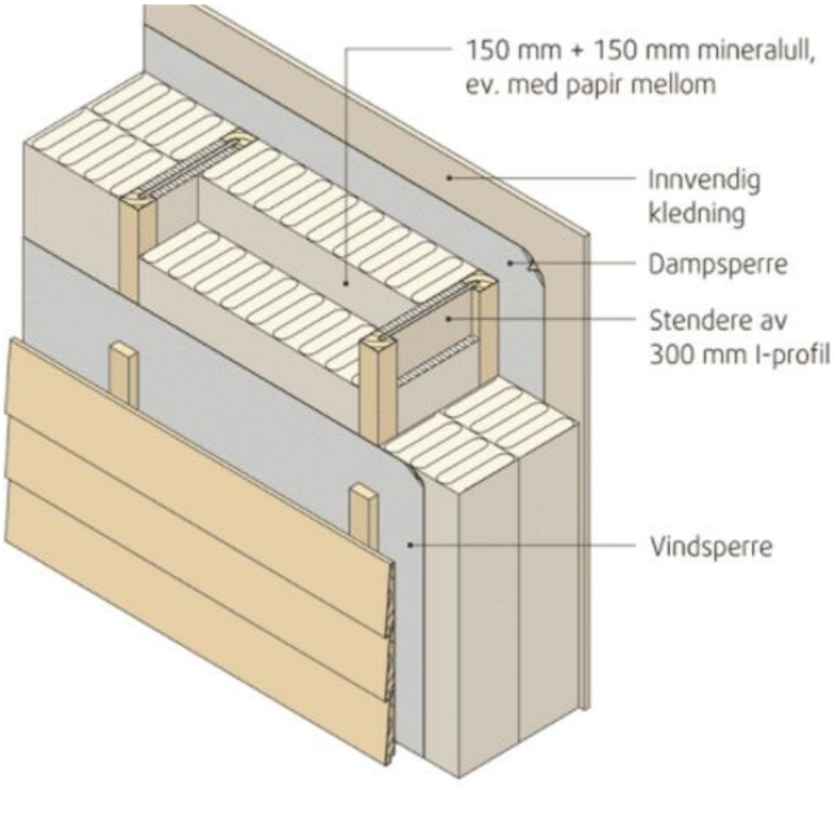

Figure 26: Outer wall with I-profile

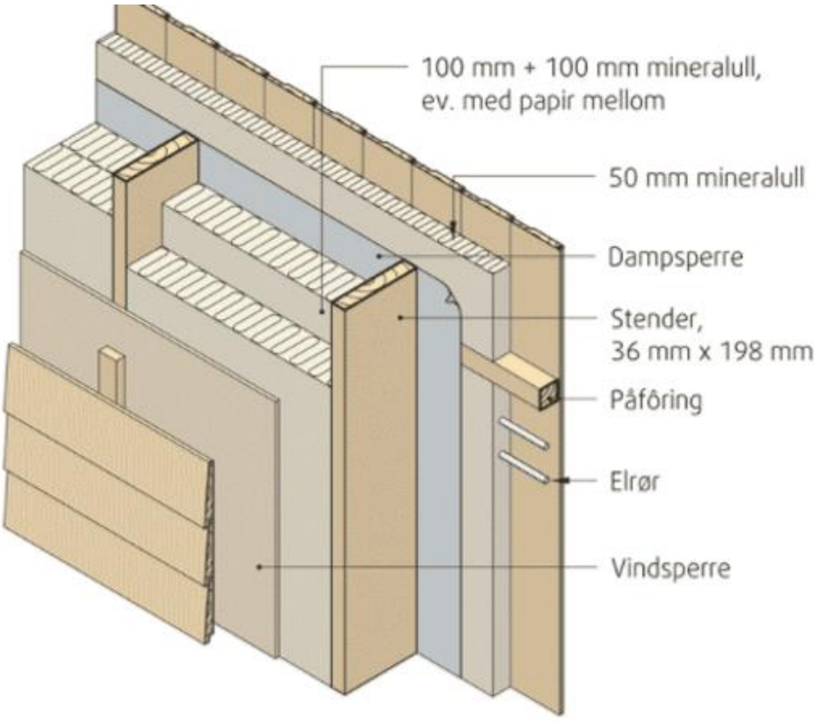

Figure 27: Outer wall with internal horizontal lining and retracted vapor barrier

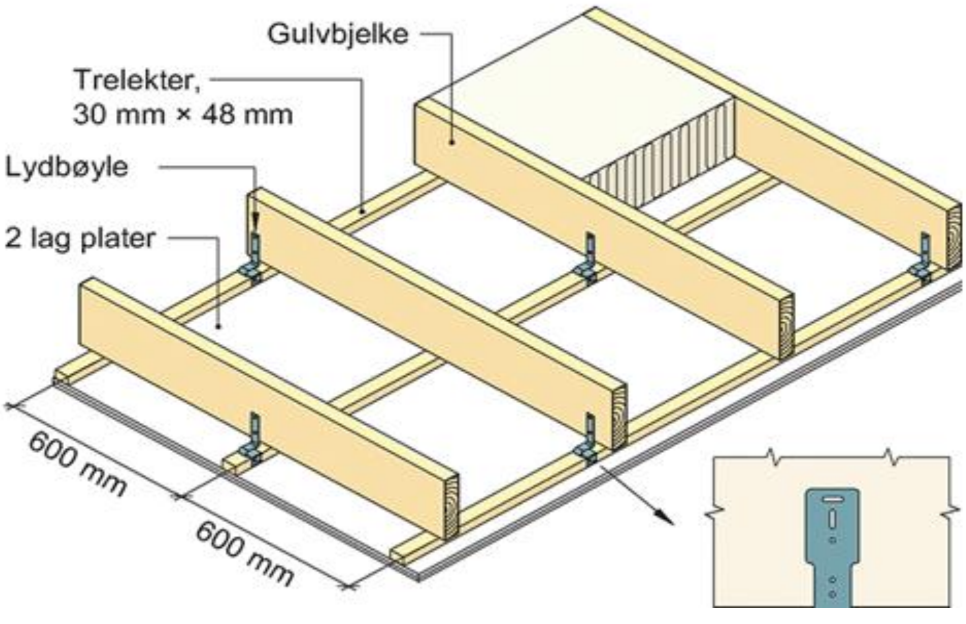

Figure 28: Floor slabs structure

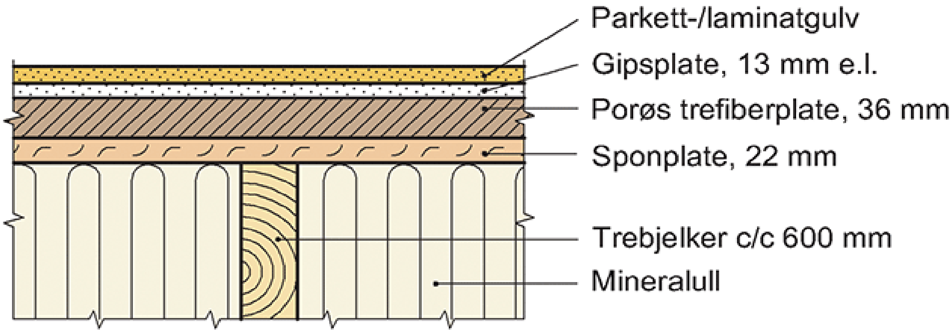

Figure 29: Floor slabs, sectional view

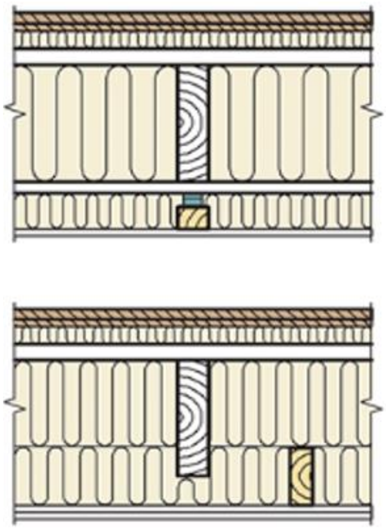

Figure 30: Floor slabs – possibilities of vibration isolation, sectional view

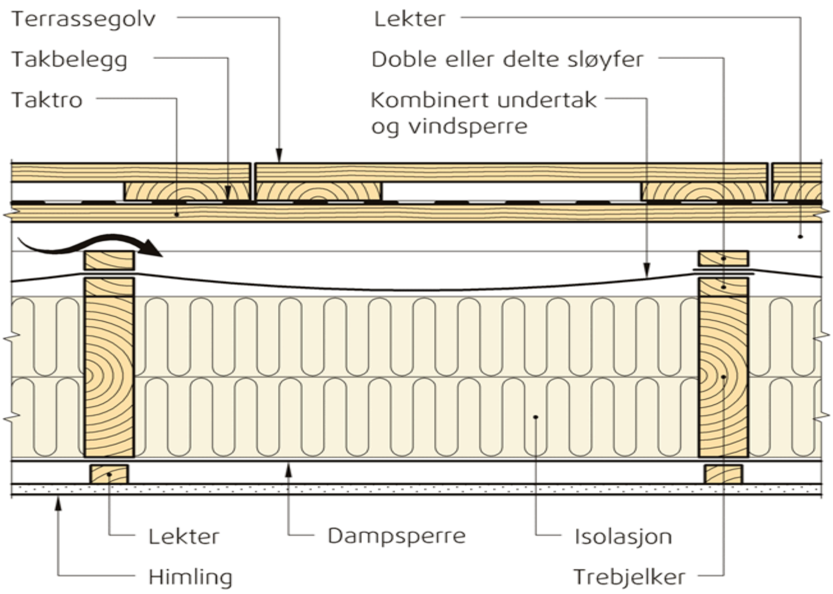

Figure 31: Roof, sectional view

Table 25: Costs of bearing system, floors and roof, external walls, and the PV system

Category number		Category	Incl. VAT	Unit
02.2		**Bearing system**		
	0.2.2.A	**Cast-in-situ concrete beams and pillars**		
		Total price, pillar 300*400	2859.20	NOK/m
		Precast concrete pillar, 300x400	3440.89	NOK/m
	02.2.A.012	Total price, beam 300*500	2863.75	NOK/m
		Precast concrete beam, rectangular, 300x500	2859.06	NOK/m
		Precast concrete shelf beam, 500/300x600	3491.67	NOK/m
	02.2.D	**Timber beams and pillars**		
		Laminated wood beam, 140x495	1230.63	NOK/m
	02.1.F.09	Plinth, 0.6*2*2	8477.08	NOK/m3
02.3		**External walls**		
	02.3.D	**Climate walls above ground**		
	02.3.D.006	Climate wall, 300 mm insulation	1606.25	NOK/m2
		Climate wall, 400 mm insulation	1741.25	NOK/m2

	02.3.G	**Lightweight facades**		
		Alucobond plates	572.13	NOK/m2
	02.3.F	**Solid wood (structural walls)**		
	02.3.F.014	Solid wood elements in outer wall, t= 240 mm	11338.54	NOK /m3
02.5		**Ceilings**		
	02.5.D	**Timber floor**		
	02.5.D.001	Separating floors with timber structure	1087.50	NOK/m2
		Fibreboard	346.25	NOK/m2
		Insulation, 150 mm	187.50	NOK/m2
		Insulation, 200 mm	250.00	NOK/m2
		Insulation, 250 mm	321.25	NOK/m2
		Bjelkelag	446.25	NOK/m2
		Bjelkelag	511.25	NOK/m2
		Bjelkelag, 4200 mm distance	501.25	NOK/m2
		Bjelkelag	588.75	NOK/m2
		Merkostnad for bjelkelag av helttre	54.31	NOK/m2
	02.5.4.019 0	Subfloor system, c/c 600 mm, steel	357.50	NOK/m2
	02.5.B	**Cast-in-situ concrete floor**		
	02.5.C	**Precast concrete floors**		
	02.5.C.003	Hollow-core slab, 265 mm	1251.25	NOK/m2
		Hollow-core HD 265 mm	1103.75	NOK/m2
		Ghosting and grouting	147.50	NOK/m2
		Levelling	327.50	NOK/m2
	02.5.7.020 0	Ceiling system, mineral wool, 20 mm	396.25	NOK/m2
	02.5.C.024	Solid wood elemets in ceilings, 210 mm	2169.00	NOK/m2
	02.5.C.025	Solid wood elemets in ceilings, 160 mm	1681.00	NOK/m3

02.6		Roof		
	02.6.A.008	Hollow-core slab, 365 mm	1335.42	NOK/m2
		single-ply roofing+ insulation, 450 mm	1183.04	NOK/m2
		single-ply roofing+ insulation, 500 mm	1254.46	NOK/m3
		single-ply roofing	300.00	NOK/m2
04.9		**PV system**		
		Standard	20.00	NOK/W

Table 26: Quantities of bearing system and external wall elements; the latter without windows and external doors

QUANTITIES		
Bearing system		
Wood pillars	350.33	m
Wood beams	406.02	m
Plinths, concrete structure	30.96	m3
Plinths, wooden structure	18.37	m3
External walls		
External walls	1125.59	m2

Table 27: Investment costs - Cost statement at first level

Cost statement at 1st level		
	NOK	**NOK/m2**
General expenses	8482202	4168.158231
Building construction	26828350	13183.46437
HVAC installations	4663750	2291.769042
Electric power installations	4684250	2301.842752
Telecommunications and automation installations	4120500	2024.815725
Other installations	820000	402.9484029
Outdoor works	2121750	1042.628993

General costs		
Early phase (including preliminary project)	5125181	2518.516462
Designing	5765483	2833.161179
Administration	4000000	1965.601966
Design Management	1000000	491.4004914
Client Ombudsman	1000000	491.4004914
Incidental expenses	425210	208.9484029
Insurance, Fees	100000	49.14004914
Plot		
VAT	15002874	402.9484029
Demolition	500000	402.9484029
Temporary solutions		
Artistic decoration	455000	402.9484029
Warranty follow-up	300000	402.9484029
Operating expenses, furnishing phase	240000	402.9484029
Expected addition	8365450	402.9484029
Total	94000000	46191.64619

Table 28: Investment costs - New costs for new elements for each alternative

New elements_New investment costs		
	NOK	**NOK/m2**
Alternative 1_Project as built (low carbon concrete)		
Initial investment costs	94000000	46191.64619
Alternative 2_Normal concrete		
Initial investment costs	94000000	46191.64619
Normal concrete cost	5826932.196	2863.357345
Low carbon concrete cost (Class A)	6059166.293	2977.477294
Low carbon concrete cost (Class B)	5826932.196	2863.357345
New investment cost	93767765.9	46077.52624
New investment cost_1	94000000	46191.64619

Alternative 3_Timber bearing structure		
Initial investment costs	94000000	46191.64619
Concrete/Steel bearing structure cost (low carbon concrete)	6059166.293	2977.477294
Timber bearing structure cost	3528211.04	1733.764639
New investment cost	91469044.75	44947.93354
Alternative 4_Timber bearing structure+timber facade+timber windows		
Initial investment costs	94000000	46191.64619
Concrete/Steel bearing structure cost (low carbon concrete)	6059166.293	2977.477294
Timber bearing structure cost	3528211.04	1733.764639
Alucobond facade cost	643984.7801	316.4544374
Timber facade cost	1108706.15	544.8187469
Aluminium-wood windows	1537121.875	755.3424447
Wooden windows	1339506.25	658.2340295
New investment cost	91736150.49	45079.18943
Alternative 5_PV panels on facade		
Initial investment costs	94000000	46191.64619
PV system on facade cost	915200	449.7297297
New investment cost	94915200	46641.37592

Table 29: Operation and maintenance costs

Alternative 1 (as built)		
	NOK per year	**NOK/m2 per year**
Depreciation	1566667.00	769.86
Management	81069.00	39.84
Continuing operations	389000.00	191.15
Maintenance	860631.00	422.91
Replacement		
Development	35350.00	17.37
FDVU total	1366050.00	671.28
FDVU / investment costs at first level	1.45%	

Cleaning	768950.00	377.86
Energy	31857.00	15.65
Water and wastewater	162578.00	79.89
Waste	24167.00	11.88
Security and protection	100000.00	49.14
Outside	10985.00	5.40
Complements	150000.00	73.71
Tot exl energy	2582730.00	
Tot exl energy / investment costs at first level	2.75%	
Unit electricity cost	0.845	NOK/kWh
Total electricity use	34778.00	kWh
Total electricity cost	29387.41	NOK

Table 30: Operation and maintenance costs for different alternatives based on the built-in alternative

	NOK	**NOK/m2**
Alternative 1_Project as built (low carbon concrete)		
Annual operation and maintenance cost (excluding energy costs)	2582730.00	1269.15
Annual energy cost	29387.41	14.44
Total	2612117.41	1283.60
Alternative 2_Normal concrete		
Annual operation and maintenance cost (excluding energy costs)	2576349.17	1266.02
Annual energy cost	29387.41	14.44
Total	2605736.58	1280.46
Alternative 3_Timber bearing structure		
Annual operation and maintenance cost (excluding energy costs)	2513189.85	1234.98
Annual energy cost	29387.41	14.44
Total	2542577.26	1249.42
Alternative 4_Timber bearing structure+timber facade		
Annual operation and maintenance cost (excluding energy costs)	2520528.81	1238.59
Annual energy cost	29387.41	14.44

Total	2549916.22	1253.03
Alternative 5_PV panels on facade		
Annual operation and maintenance cost (excluding energy costs)	2607875.90	1281.51
Annual energy cost	9276.41	4.56
Total	2617152.31	1286.07

Table 31: Net present cost - Alternative 1

Alternative 1_Project as built, low carbon concrete				
Calculation Period [years]	60			
Real discount rate	**4.00%**	https://www.anskaffelser.no/verktoy/tidliglcc +Årskostnader-LCC		
	Total, year 0	**Discount rate**	**Present value factor**	
Investment costs				
Investment costs for all materials, works, and other expenses	NOK 94,000,000.00		1.00	**NOK 94,000,000.00**
Operation and maintenance cost (excluding energy costs)				
Annual cost for operation/maintenance /replacement	NOK 2,582,730.00	4.00%	22.62	**NOK 58,430,366.26**
Energy costs				
Electricity (annual cost)	NOK 29,387.41	4.00%	22.62	**NOK 664,845.78**
Net present cost				**NOK 153,095,212.04**
			NOK/m2	75231.06243

Table 32: Net present cost - Alternative 2

Alternative 2_Normal concrete				
Calculation Period [years]	60			
Real discount rate	**4.00%**	https://www.anskaffelser.no/verktoy/tidliglcc +Årskostnader-LCC		
	Total year 0	**Discount rate**	**Present value factor**	
Investment costs				
Investment costs for all materials, works, and other expenses	NOK 94,000,000.00		1.00	**NOK 94,000,000.00**
Operation and maintenance cost (excluding energy costs)				
Annual cost for operation/maintenance /replacement	NOK 2,576,349.17	4.00%	22.62	**NOK 58,286,009.63**
Energy costs				
Electricity (annual cost)	NOK 29,387.41	4.00%	22.62	**NOK 664,845.78**
Net present cost				**NOK 152,950,855.41**
			NOK/m2	75160.12551

Table 33: Net present cost - Alternative 3

Alternative 3_Timber bearing structure				
Calculation Period [years]	60			
Real discount rate	**4.00%**	https://www.anskaffelser.no/verktoy/tidliglcc +Årskostnader-LCC		
	Total, year 0	**Discount rate**	**Present value factor**	
Investment costs				
Investment costs for all materials, works, and other expenses	NOK 91,469,044.75		1.00	**NOK 91,469,044.75**
Operation and maintenance cost (excluding energy costs)				
Annual cost for operation/maintenance /replacement	NOK 2,513,189.85	4.00%	22.62	**NOK 56,857,125.38**
Energy costs				
Electricity (annual cost)	NOK 29,387.41	4.00%	22.62	**NOK 664,845.78**
Net present cost			NOK/m2	**NOK 148,991,015.91** 73214.25843

Table 34: Net present cost - Alternative 4

Alternative 4_Timber bearing structure+timber facade/windows				
Calculation Period [years]	60			
Real discount rate	**4.00%**	https://www.anskaffelser.no/verktoy/tidliglcc +Årskostnader-LCC		
	Total, year 0	**Discount rate**	**Present value factor**	
Investment costs				
Investment costs for all materials, works, and other expenses	NOK 91,736,150.49		1.00	**NOK 91,736,150.49**
Operation and maintenance cost (excluding energy costs)				
Annual cost for operation/maintenance /replacement	NOK 2,520,528.81	4.00%	22.62	**NOK 57,023,158.22**
Energy costs				
Electricity (annual cost)	NOK 29,387.41	4.00%	22.62	**NOK 664,845.78**
Net present cost				**NOK 149,424,154.49**
			NOK/m2	73427.10294

Table 35: Net present cost - Alternative 5

Alternative 5_PV panels on facade				
Calculation Period [years]	60			
Real discount rate	**4.00%**	https://www.anskaffelser.no/verktoy/tidliglcc +Årskostnader-LCC		
	Total, year 0	**Discount rate**	**Present value factor**	
Investment costs				
Investment costs for all materials, works, and other expenses	NOK 94,915,200.00		1.00	**NOK 94,915,200.00**
Operation and maintenance cost (excluding energy costs)				
Annual cost for operation/mainten ance /replacement	NOK 2,607,875.90	4.00%	22.62	**NOK 58,999,254.25**
Energy costs				
Electricity (annual cost)	NOK 9,276.41	4.00%	22.62	**NOK 209,864.77**
Net present cost				**NOK 154,124,319.02**
			NOK/m2	75736.7661