UNESCO World Heritage Centre in Aurlandsvangen: Balancing Energy Efficiency, CO_2 Emissions and Costs when Remodeling the Building Structure

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Master Thesis in Climate Change Management

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Sogndal

June 2021

I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 10.

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Master thesis in Climate Change Management

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Thesis submitted:
Spring 2021

Open thesis

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Keywords:
Remodeling, energy efficiency, CO_2 emissions, cost estimates, u-value calculation, energy simulation, life cycle assessment.

Number of pages: 68
+
Appendix: 42

Sogndal, 24/06, 2021

This thesis is a part of the master's program in Climate Change Management (Planlegging for klimaendringer) at the Department of Environmental Sciences, Faculty of Engineering and Science at the Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented and the conclusions in the thesis.

Preface

This master's thesis marks the end of a two-year education in Climate Change Management at the Western Norway University of Applied Sciences, campus Sogndal. The work of this thesis has been demanding, instructive, and it has provided a deeper understanding on the complexity of implementing sustainability in the construction industry.

First of all, I would like to thank my internal supervisor Marte Lange Vik. Thank you for tackling every draft text with admirable thoroughness, for familiarizing yourself with unknown subject matter to better help me, and for always making me leave our meetings with new motivation.

Furthermore, I would like to thank my external supervisor Anders-Johan Almås at Western Norway Research Institute. Thank you for all your help with the shaping of the thesis, for useful discussions and valuable input during this process. As supervisors, you two have contributed with useful constructive feedback during the master's writing. Having two supervisors with different professional backgrounds has been both necessary and helpful.

I would also like to draw attention to project manager Gøran Johansen who started the collaboration that shaped this thesis. Without him, I would not have been able to work with this exciting project. Good luck with the project, I look forward to seeing the result!

Finally, I would like to thank mom and dad for always giving me motivational words, Katrine for all the moral support throughout this process, and, last but not least, Jonas, for providing hugs and candy when needed. I could not have done this without you guys!

It is strange to set a final period to this thesis. I have learned so much and would not be without the experience and insight this thesis has given me. This is my master's thesis, it's finally done!

Sogndal, June 5, 2021

Berit Johanne Skogvang

Abstract

Greater focus on energy-efficient buildings made of low-emission material has potential to reduce large amounts of greenhouse gas emissions, thus creating a more sustainable construction industry. Since cost is often decisive for construction projects, it is essential to include this aspect. This thesis thus intended to find a balance between energy consumption, CO_2 emissions and cost for the remodeling of the UNESCO World Heritage Centre in Aurlandsvangen and investigate how such a balancing impact the concept choices. The concepts are intended to suit the architectural design made by MAD Architects, and they have been chosen based on inspections of the case building, technical building assessment of the existing building carried out by MultiConsult and discussions with the project manager.

The thesis focuses on the remodeling of the building structure itself, including wall, roof, slab on ground, windows, and doors. Three concepts have been developed for each building part, and four methods were implemented for the 15 concepts. The methods included u-value calculations to find the u-value of the concepts, energy simulation in SIMIEN to quantify the amount of saved energy compared to a TEK17 remodeling, as well as saved money and emissions from saved energy. Furthermore, life cycle assessment in One Click LCA were conducted, to quantify CO_2 emissions, and cost estimates were produced. The results laid the foundation for the balancing.

Choices were made to weight all factors equally. For other project it may be sufficient to weight differently, however, it is important to emphasize that cost should not be prioritized above the remaining factors. Nevertheless, the balancing process is most affected by the choices made in advance of the balancing. All recommended concepts are used in at least one of the extreme concept combinations, which indicates that the chosen concepts represent a thorough balancing, and that the choices made prior have been carefully completed.

The project itself meets several of the Sustainable Development Goals, however, for the detailed engineering, efforts should be made to ensure a more sustainable building design. This because the glass façade will result in high energy consumption, high emissions, and a large cost.

Sammendrag

Større fokus på energieffektive bygninger laget av materialer med lavt utslipp har potensiale til å redusere store mengder klimagassutslipp, og dermed skape en mer bærekraftig bygge industri. Kostnad er ofte avgjørende for mange byggeprosjekt, og det er derfor viktig å inkludere dette aspektet. Denne masteroppgaven har som hensikt å finne en balanse mellom energieffektivitet, CO_2-utslipp og kostnad for ombyggingen av UNESCOs verdensarvssenter i Aurlandsvangen, og videre undersøke hvordan en slik balansering påvirker konseptvalgene. Konseptene er ment å passe for den arkitektoniske utformingen laget av MAD Architects, og de er valgt på bakgrunn av befaringer av casebygningen, byggeteknisk vurdering av eksisterende bygg utført av MultiConsult og samtaler med prosjektlederen.

Oppgaven fokuserer på ombyggingen av selve bygningsskallet, inkludert vegg, tak, plate på mark, vinduer og dører. Tre konsepter er utviklet for hver bygningsdel, og fire forskjellige metoder ble gjennomført for de 15 konseptene. Metodene inkluderte u-verdiberegninger for å finne u-verdien til konseptene, energisimulering i SIMIEN for å kvantifisere mengden spart energi sammenlignet med en TEK17-ombygging, samt sparte penger og utslipp fra spart energi, livssyklusvurdering i OneClickLCA for å kvantifisere CO_2-utslipp, og kostnadsberegning av de forskjellige konseptene. Resultatene fra metodene la grunnlaget for balanseringen.

I balanseringen ble det valgt å vekte faktorene likt. For andre prosjekter kan det være aktuelt å vekte annerledes, men det er viktig å understreke at kostnader ikke burde vektes tyngre enn de to energiforbruk og CO_2 utslipp. Balanseringsprosessen er likevel mest påvirket av valgene som er gjort i forkant av balanseringen. Alle anbefalte konsept brukes i minst en av de ekstreme konseptkombinasjonene, noe som indikerer at de valgte konseptene representerer en tilfredsstillende balansering, og at valgene som er gjort i forkant er nøye gjennomført.

Prosjektet i seg selv møter flere av FNs bærekraftsmål, men for detaljprosjekteringen bør det gjøres en innsats for å sikre et mer bærekraftig arkitektonisk design. Dette fordi glassfasaden vil resultere i høyt energiforbruk, høye utslipp og store kostnader.

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1. Introduction

This chapter explains the background for this thesis and defines the purpose of it, it specifies the research question, and it provides a delimitation of the scope of the thesis. An overview of the thesis' structure is presented, with a short description of each chapter.

1.1. Background

Societal and political development is increasingly influenced by the increased focus on climate impacts. Trough national and international obligations, Norway has committed to increasing its environmental efforts and reducing the national greenhouse gas emissions. In 2018, the building sector accounted for 39% of all energy and process-related carbon dioxide emissions in the world, where 11% resulted from producing building materials and the remaining 28% from operation of the buildings (Global Alliance for Buildings and Construction, 2019). This emphasizes the importance that state authorities increase the focus on reducing emissions from the building sector, both by increasing the energy efficiency of buildings beyond the minimum requirements, as well as utilizing more low-emission materials.

To achieve reduced energy consumption of buildings it is insufficient to focus only on new buildings. There must also be an increased focus on making existing buildings energy-efficient. A project run by the Research Center on Zero Emissions Neighborhoods in Smart Cities shows that rehabilitation projects can decrease emissions with an average of 63.5% compared to new constructions (Wiik, 2020). This highlights the great potential for improving the existing building stock regarding environmental considerations. Furthermore, 80% of today's buildings will still be operated in 2050 (Norwegian Ministry of Local Government and Regional Development, 2009). To reach the Norwegian Parliaments goal of reducing energy consumption in buildings by 10 TWh from 2015-2030 it is therefore necessary to increase the energy efficiency of existing buildings (Meld. St. 25 (2015-2016) Innst. 401 S (2015-2016); Stub & Brenna, 2017).

To enhance the greenhouse gas reduction, Norway has put considerable intellectual and financial capital into further development of knowledge on energy-efficient solutions and low emission materials (Berg & Fuglseth, 2018; Moschetti et al., 2019; Nord & Sjøthun, 2014). However, the most prominent challenge for environmentally sustainable remodeling is the economic aspect, as cost is the deciding factor for many projects (Hayles & Kooloos, 2008). Hence, for energy-efficient measures and low emission materials to be chosen, they must also be cost-effective. By balancing energy-efficient measures, low emission materials and cost-efficient solutions, a more sustainable construction industry will be promoted. This constitutes the background for this master thesis.

Further, the one-sided focus on the construction phase is not sufficient to ensure a sustainable construction industry. For that to be realized, a larger range of consequences must be considered, and particularly important is cost and emissions past the construction phase. These are two key factors important to include in the assessment, when solutions are to be chosen. By looking at the building in a long-term perspective, one will better be able to understand the long-term impact of the construction. To address this, the building will be seen in a 50-year perspective, and the thesis will include how much cost and emissions have been saved from reducing energy consumption by choosing the various concepts. This will be part of the foundation for the concept recommendation that is to be represented.

1.2. Aim

This thesis aims to find concepts that are balanced between the three aforementioned factors, namely, energy efficiency, CO_2 emissions, and cost, for the large remodeling project of the UNESCO World Heritage Centre in Aurlandsvangen. Saved cost and saved emissions from saved energy will be used in the balancing process. Looking at the concepts during a longer period will make it easier to assess what concepts are more suited in the long run. By doing this, the thesis wants to provide the project group with a full recommendation, including environmentally sustainable and cost-effective building measures that will increase the building's energy efficiency. Furthermore, the thesis will discuss whether the balancing process leads to sustainable concept choices, and how the balancing could be altered to ensure a more sustainable conclusion. All of this will be investigated to understand how this balancing affects the remodeling choices being made. Consequently, the research question is as follows:

How does balancing energy efficiency, CO_2 emissions, and costs
impact remodeling choices made for the building structure of
the UNESCO World Heritage Centre in Aurlandsvangen?

1.3. Scope and Delimitation

An old concrete building in Aurlandsvangen is to be converted into a comprehensive UNESCO World Heritage Centre for Nærøyfjorden. The project has great ambitions when it comes to environmental sustainability and energy efficiency and have a minimum goal to meet the energy requirements that arise from the regulations on technical requirements (TEK17). It is nevertheless desirable that the building exceeds the energy requirements of TEK17, in order to further promote energy efficiency in buildings and thus a sustainable construction industry. Materials with low emissions are preferred, in order to reduce the climate impact from the project as much as possible.

The thesis is part of a larger project including a total of three master's theses. This thesis will investigate the remodeling of the building structure itself, including window and door alternatives, slab on ground, roof, and wall composites. Eventually, all three theses will result in a joint comprehensive concept, with accompanying recommendations for the project team. Read more about this in 9. The other theses will address the following topics:

- Sylvi Brækken - *Weighing the Importance of Energy Savings, CO_2 Emissions and Costs When Implementing Renewable Energy Technologies. Case: Nærøyfjorden UNESCO World Heritage Centre*: Various combinations of renewable energy technologies consisting of several types of heat pumps, solar thermal collectors, and solar panels.
- Halldór Þrastarson - *Keeping Old Buildings Green with Relevant Technology - A Case Study of UNESCO World Heritage Center, Nærøyfjordområdet*: Energy sources for heating, ventilation, and air conditioning systems (HVAC), as well as relevant control methods for building management systems and HVAC.

Since the case building provides guidelines for concept choices, it is important to emphasize that the recommendations are intended directly for this building. The thesis can be used to obtain information on different concepts with the associated values of the three factors, energy efficiency, CO_2 emissions and costs, but the concepts must be adapted to suit each individual project. Furthermore, the thesis will focus only on a set of solutions that are relevant for the building, and it will not address all possible choices. A large part of the work is to select the concepts to be assessed, thus eliminating down to three concepts per building part. In other words, there are more solutions that suits the building, than what is being presented here.

1.4. Thesis structure

The further structure of the thesis consists of nine chapters:

Chapter 2 – Case Building: The concept and design for the project is illustrated. The condition of the existing building and recommendations for the remodeling is presented, in addition to how these recommendations will be implemented.

Chapter 3 - Theory: Theory that is relevant to answer the research question is presented. This forms the basis for interpretation and discussion of results, and it is a central part of the thesis. The chapter comprises sustainability in the construction industry, climate impact from the construction industry, building requirements for energy-efficient buildings, energy-efficient rehabilitation, and an explanation of the term u-value.

Chapter 4 - Methods: The methods used in the thesis are presented. This includes u-value calculation, energy simulation, life cycle assessment, cost estimates and balancing. The chapter also includes the weaknesses of the methods, and how these have been dealt with.

Chapter 5 - Building Concepts: Three concepts are presented for each building part, which includes roof, wall, windows, doors, and slab on ground.

Chapter 6 - Results: The results obtained from the methods are presented in tables and figures and described and analyzed in text.

Chapter 7 - Discussion: Results are compared, discussed, and put in context with the research question. The balancing process, sustainability, and the ability to implement the concept is also discussed.

Chapter 8 - Conclusion: The recommended and full-fledged concept combination is presented, and the research question is attempted answered.

Chapter 9 - The Full Concept Recommendation: The recommendations from all three associated theses are gathered and presented, in addition to advice when implementing the recommendations in the project.

2. Case Building: UNESCO World Heritage Centre in Aurlandsvangen

The UNESCO World Heritage West Norwegian Fjords was made a part of UNESCO's list of World Heritage Sites in 2005. The site consists of the fjords and areas around the Nærøyfjord and Geirangerfjord (Vestnorsk fjordlandskap, 2021b). This the only area in Norway that is inscribed for its remarkable nature. A World Heritage Centre connected to the Geirangerfjord has existed for several years, but the Nærøyfjord does not have this (Vestnorsk fjordlandskap, 2021a). A UNESCO World Heritage Centre for the Nærøyfjord is, therefore, to be established in Aurlandsvangen.

2.1. Concept and Building Design

The old Aurland Kjøle og Fruktlager (translated: Aurland Cold and Fruit Storage) in Aurlandsvangen is a four-story concrete building located by the fjord. It is owned by a collaboration of local farmers and other locals. For a period, there has been active work to expand and develop the building. In November 2019, a letter of intent was therefore made between Aurland Cold and Fruit Storage and Nærøyfjorden World Heritage Park to develop a World Heritage Centre. Simultaneously, architect Gøran Johansen was employed as project manager. He has office in the building and runs daily operations of Aurland Fruit and Cold Storage (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020). The project manager has ambitions when it comes to climate and energy, and thereby a connection was established between the project manager and three master students at Climate Change Management at Western Norway University of Applied Sciences, campus Sogndal.

The desire for the concept is to gather local resources with the dissemination of world heritage values, and the building will be converted to a comprehensive center containing a warehouse and outlet for local farmers, an art exhibition, offices, and a tourist center with an associated cafe. It will be a meeting point for local farmers, where they can store and sell products, for visitors and tourists, who can buy products and view exhibitions, in addition to various administrative bodies, such as Nærøyfjorden World Heritage Park (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020). In this way, historical value and culture will be combined in one building (see Figure 1).

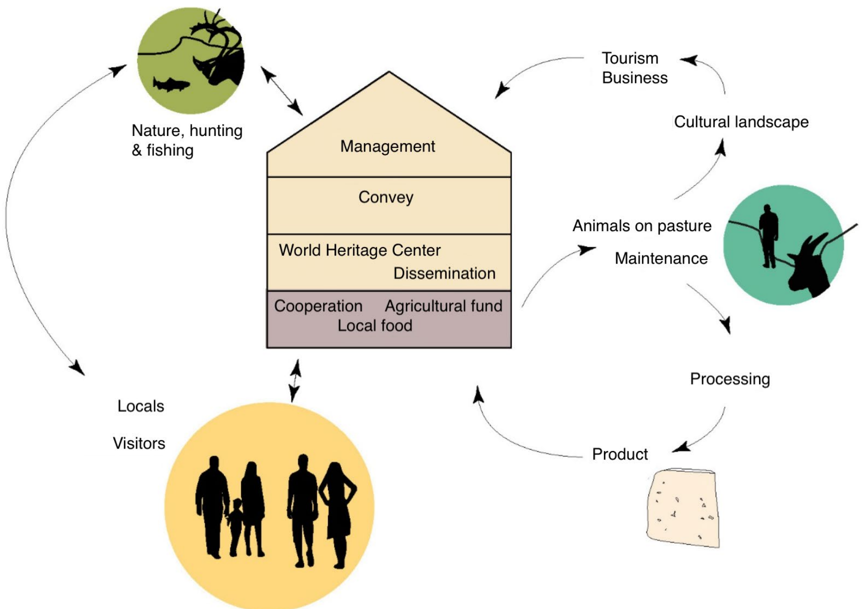

Figure 1: The concept for the center. The goal is to connect locals and tourists through historical and cultural values. Source: (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020) (Translated by the author)

At the request of the project group, MAD Architects have developed an architectural design for the center. The existing building will have a glass facade extension, to ensure that the facade of the existing building is communicated to the outside, see the concept design in Figure 2. This is especially important because the visual expression from the fjord has been a central point through the entire process. The desire is that many visitors come by boat, and it is therefore important that The World Heritage Centre appears as an inviting building, where the functions on each floor are clearly communicated. At the same time, it is important that the building does not stand out so much that it destroys the landscape expression (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020).

Figure 2: The architectural concept designed by MAD Architects. Source: (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020)

Figure 3 shows what functions the existing building will house for the center, and Figure 4 shows the functions in the new part of the building. On the ground floor there will be local industry, warehouse, toilet, and outlet. The first and second floors will contain an exhibition, café/restaurant, tourist information, cloakroom, and meeting rooms. On the top floor there will be offices for administrative and local dissemination bodies (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020).

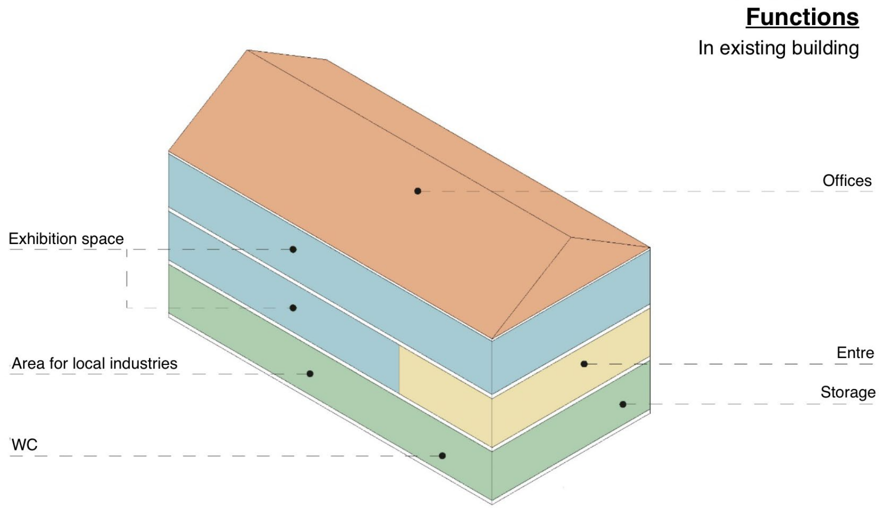

Figure 3: Functions that the existing building will house. Source: (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020) (Translated by the author)

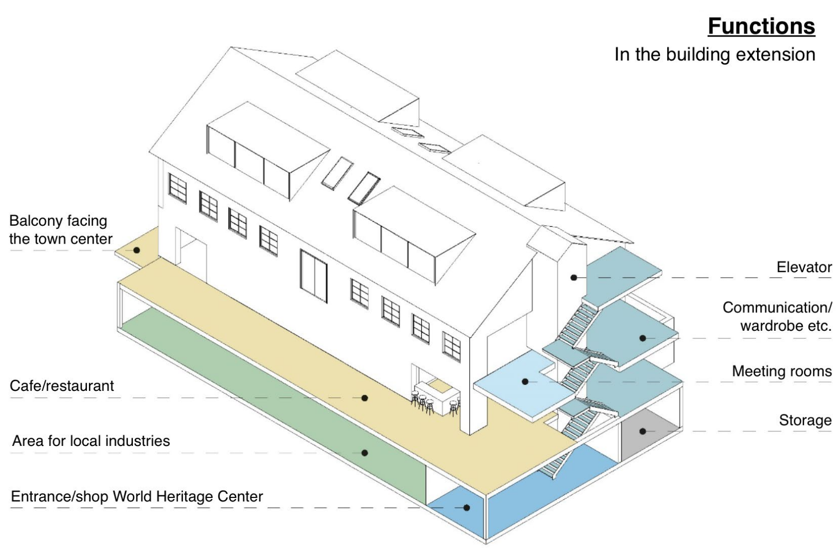

Figure 4: Functions in the building extension. Source: (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020) (Translated by the author)

More illustrations of the concept building can be found in Appendix A: Illustrations of the Concept Building.

2.2. Condition of the Existing Building and Recommendations for the Remodeling

The concept choices for the various building parts are made based on three sources of information. The first is personal inspections of the building, with all the impressions it entailed. The second is the wishes the project manager has expressed for the project. And the third is documents in connection to the project that were obtained by e-mail from the project manager. These include the preliminary project and the technical building assessment that has been carried out for the existing building by MultiConsult (G. Johansen, personal communication, October 10, 2020). The preliminary project has later been published. These three sources of information will provide the guidelines for the choices being made.

MultiConsult has evaluated the condition of the existing building and made recommendations for the remodeling. These will be presented, in addition to how the recommendations are implemented. The regulations on technical requirements for construction works (TEK17) are the minimum requirements for a building to be legally constructed in Norway, and these requirements only apply for new buildings (Byggteknisk forskrift (TEK17), 2017). Read more about TEK17 in 3.3.1. Although it is not necessary for a remodeling project to meet the energy requirements of TEK17, since they only apply to new buildings, this is still a wish of the project manager (G. Johansen, personal communication, April 16, 2021). Therefore, the minimum requirements will be used as a basis when the recommendations are implemented.

The existing building was built in 1956, and it is shown in Figure 5. It has four floors, where the basement has two partially backfilled walls, the first and second floors are above ground, and the third floor has a gable roof. It has a continuous support system in concrete.

Figure 5: The existing building (in beige) seen from the fjord. Source: (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020)

The current roof is an uninsulated salt roof, and it has rafters with ties and purlins in wood, but it lacks suspended ceilings. The roof, which is made of roofing sheets in a sine wave profile, can therefore be seen from the inside (see Figure 7).

Figure 7: The existing roof seen from the attic. Source: taken by the author January 26, 2021.

The roof does not meet today's technical requirements. Therefore, it is recommended that a completely new roof is built. MultiConsult proposes a ventilated roof consisting of ceiling, vapor barrier, insulation and rafters, wind barrier, ventilation, suspended ceilings, and roofing of, for example, slate or roof tiles (G. Johansen, personal communication, October 10, 2020). It is decided to accept this recommendation, and therefore use this construction for the three roof concepts.

The existing outer walls are made of concrete hole blocks with approx. 13 mm exterior plaster and paint (see Figure 6). The facades are in varying condition, and in some places both paint and plaster are peeling off. There have previously been carried out repairs of the plaster. Inside, the wall is of varying quality, and it is generally leaky and uneven. Around some of the windows there is damage to the hole blocks.

Figure 6: The existing building seen from north. Source: taken by the author January 26, 2021.

The existing walls do not satisfy today's technical requirements. Therefore, MultiConsult recommends for the wall to be insulated exterior, optionally with some internal insulation. According to the technical building assessment, if the insulation is attached mechanically, or if there is used external application, there will be no need to make major improvements to the current plaster layer, only repair loose or missing plaster, e.g., around some of the windows (G. Johansen, personal communication, October 10, 2020). From these recommendations, it has been decided that the concepts will consist of external insulation that is mechanically attached. Additionally, MultiConsult recommends an internal application for electrical wires, and a vapor barrier on the inside of the hole blocks to reduce moisture transport through the wall. These recommendations will be implemented in the concepts. Because a new roof is to be laid, there will be no problem with roof extensions when the wall is to be insulated. Therefore, it is not necessary to take this into account in the wall concepts. This could have affected the thickness of the insulation or required for some of it to be mounted internally.

Regarding the glass facade, MultiConsult states that such a solution is probably unsuitable for this building. This is because it will set high energy requirements for the remaining part of the facade. Additionally, MultiConsult believes that this glass facade system will add significant loads to the load-bearing system (G. Johansen, personal communication, October 10, 2020). Furthermore, such a solution will also create challenges when it comes to thermal climate, transmittance of daylight, external and internal condensation, and cost. Thus, further research must be done to investigate whether this is possible at all. Despite these recommendations, the glass facade will still be included as a part of the building design for this thesis. This is because it is a central part of the architectural concept of the project (G. Johansen, personal communication, October 9, 2020).

A glass facade is much less energy-efficient than a conventional wall (G. Johansen, personal communication, October 10, 2020). After several rounds of assessments and trials, it has been determined that if the building is to meet the requirements of TEK17 for maximum value of total net energy needs, the glass facade must be very energy-efficient. Therefore, it is assumed that the glass facade is predetermined, being one of the most energy-efficient solutions in the industry, with a u-value of 0.7 W/(m^2K). As a result, the glass façade concept will not be discussed, because it will be the same for all of the concepts. Read more about the definition of u-value in 3.5 and TEK17 requirements in 3.3.1.

The building has a total of 42 wooden windows with single glass and continuous bars, see Figure 8. Some of the windows also have an internal product window. Doors and gates are old and in varying condition.

Figure 8: Existing window on the north-east wall. Source: taken by the author January 26, 2021.

The technical building assessment recommends replacing all windows and doors with new triple glazing windows and well insulated doors. They state that some of the doors and windows probably can be repaired and reused. However, they do not recommend this, as it will be very costly and technically weaker than new windows and doors (G. Johansen, personal communication, October 10, 2020). Nevertheless, this thesis will include concepts for reuse of both windows and doors. That is because the project manager has expressed a great desire for this (G. Johansen, personal communication, January 26, 2021).

The foundation is made of concrete and it is insulated, but the dimensions are not known. No signs of settlement damage have been registered in the building. Slab on ground consists of 100 mm insulation of unknown type, vapor barrier and screed. It is assumed that the floor is from the year of construction, and the screed bears mark of this as it is uneven and has several holes.

The technical building assessment lists several reasons why the slab on ground should be replaced. Firstly, it has insufficient radon protection. There are several cases in Aurland where high radon levels have been registered in buildings, for instance in Heradshuset (NRK, 2015). Since it is planned for lasting stay in the basement, this must be considered, and a radon measurement must be carried out in the detailed engineering (Byggteknisk forskrift (TEK17), 2017, § 13-5). Secondly, the estimated thickness of insulation, 100 mm, does not satisfy the technical requirements. The insulation and vapor barrier have also reached their technical life and should be replaced. This also applies to any wires in the ground. Thirdly, the drainage in the ground is of unknown quality, but it is probably not sufficient, as it is the same age as the building (G. Johansen, personal communication, October 10, 2020).

MultiConsult recommends the new slab on ground to consist of draining masses with drainage pipes, radon membrane, 150 mm XPS insulation, vapor barrier and screed. This will be the basis for the slab on ground concepts. Other types of insulation will also be examined as part of the assessment.

Due to an increase in load, a capacity check should be also performed for the building. This goes beyond the scope of this thesis but must be implemented in the detailed engineering.

3. Theory

This chapter presents the theoretical basis for answering the research question. It includes the definition of sustainable development, sustainability in a building context, with indicators that will be used in the assessment of whether the concepts and the balancing process is sustainable or not. Furthermore, it will include information about climate impact in the construction industry, and how a life cycle assessment is carried out. Moreover, energy efficiency in buildings and building requirements for energy efficiency will be presented, in addition to various energy-efficient building concepts. Finally, rehabilitation and remodeling will be explained, with relevant measures for an energy-efficient result, in addition to a definition of u-value and why this is used in the thesis.

3.1. Sustainable Development

The concept of sustainable development was first introduced in the publication of the Brundtland Report, *Our Common Future*. It was defined as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987, p. 41). The definition of sustainable development has been further developed since then, and there is a common agreement among sectors that the term is built of three pillars; economic sustainability, social sustainability, and environmental sustainability (75th Economic and Social Council, n.d.). These include demands and interests across all sectors, and this broad variety of values often result in contradictory interests when decisions are made. Our Common Future stated that sustainable development should be an overall goal, rather than a sectoral interest (World Commission on Environment and Development, 1987). Only by balancing all three aspects can overall sustainable development be achieved.

The understanding of sustainable development is constantly evolving, and some events that have been important for this development are the Rio Conference in 1992 and the UN Millennium Development Goals in 2000. The Rio Conference was a major environmental conference where many heads of state prepared Agenda 21, a guide to sustainable development in the 21st century. The UN's Millennium Development Goals were a series of goals to fight poverty. These were to be reached by 2015 and are the history's most successful campaign to reduce poverty. Since poverty and sustainable development are strongly linked, this was an important breakthrough for the road towards a more sustainable world (The United Nations Association of Norway, 2019). Another large breakthrough happened in 2015, when the United Nations General Assembly published the Sustainable Development Goals (SDGs). These are 17 global goals intended to be achieved by 2030. These include all three aspects and are interlinked to ensure overall sustainable development. All the goals include specific targets, in addition to indicators used to measure the progress of each goal (Department of Economic and Social Affairs, n.d.-h).

In the preliminary project, it is highlighted that the project as a whole hits as many as 9 of the 17 Sustainable Development Goals, see Figure 9. SDG *3: Good health and well-being*, 4*: Quality education*, *14: Life below water*, *15: Life on* land and *17: Partnership for the goals* are highlighted because the center will convey the unique world heritage values of the West Norwegian fjord, and because it already has an existing collaboration at the bottom, which will act as a driving force for local farmers, local crafts and small-scale production. SDG *7: Affordable and clean energy*, *9: Industry, innovation, and infrastructure* and *11: Sustainable cities and communities* are highlighted because it is planned to use innovative energy solutions such as fjord heating, solar heating, natural ventilation, in addition to a mix of high-tech and low-tech solutions. Finally, SDG *12: Responsible consumption and production* is highlighted because the focus is on using an existing building rather than demolishing and building a new one (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020).

Figure 9: The Sustainable Development Goals that are presented in the preliminary project, as a part of the basis for the project.

This thesis focuses mainly on the building structure, and thus not all the SDGs that are relevant for the project are relevant for the thesis. The choices made in this thesis will be able to help the building meet SDG *9: Industry, innovation and infrastructure*, *11: Sustainable cities and communities* and *12: Responsible consumption and production* (Department of Economic and Social Affairs, n.d.-a). SDG 9 by developing a sustainable building, which can be done by carrying out a full-fledged balancing between energy efficiency, CO_2 emissions and cost (Department of Economic and Social Affairs, n.d.-e). Goal 11 by making choices that protect the worlds cultural and natural heritage, such as keeping the façade close to its original appearance (Department of Economic and Social Affairs, n.d.-f). Goal 12 by sustainable use of resources and reducing material footprint. This can be done by choosing low-emission materials that also are energy-efficient (Department of Economic and Social Affairs, n.d.-g).

3.1.1. The Concept of Sustainability in Buildings

When talking about sustainability, it is important to be aware of the difference between sustainability and sustainable development. Sustainable development is thought of as the process of achieving sustainability, while sustainability is considered a long term goal (UNESCO, n.d.). Sustainability in a construction context comprises several relevant perspectives. The planner, the developer, the owner, the user, and the society, all have their own desires and ambitions. These do not always align, and it is, therefore, necessary to have some general guidelines.

Through the White Paper 28 (2011-2012): *Good buildings for a better society*, Bygg21 was established. Bygg21 was a cooperation between the construction and real estate industry and state authorities, created to develop strategies to raise the industry's competence, innovation ability, and ability to communicate and share knowledge and experience. They also wished to facilitate better solutions to challenges connected to sustainability, productivity, and cost development within the industry. Bygg21 officially ceased in 2019, and the industry itself was challenged to continue the project. Rådgivende Ingeniørers Forening (translated: Consulting Engineers' Association) initiated a continuation of Bygg21, in what they defined as Bygg21 Phase 2 (Bygg21 Fase 2, n.d.).

In 2018, Bygg21 published a report called *10 quality principles of sustainable buildings and areas* (Bygg21, 2018a). The report was developed to make it easier for users to know how to make demands of sustainable qualities from developers. The report is thus an attempt of a recipe for how to get all the desired qualities to work with each other for a sustainable solution (Bygg21, 2019). This report includes recommended principles for the industry, to ensure sustainable areas and buildings. It states that "...sustainable buildings and areas means ensuring functionality and good user qualities, ensuring returns for the owner in a future market and at the same time achieving our national and international environmental goals." (Bygg21, 2018a, p. 6). The report emphasizes that the three aspects all need to be considered simultaneously because the pursuit of one quality principle should not be at the expense of the others (Bygg21, 2018a). This mindset runs concertedly with the principles from the Sustainable Development Goals. In addition, the report brings forward nine out of the 17 SDGs, among them SDG 9, 11 and 12 (Bygg21, 2018a).

The quality principles have been developed to cover the entire sustainability perspective and focus on everything from ensuring returns for future owners, functionality, and quality of use for the users of the building to the principle of achieving the national and international environmental goals (Bygg21, 2018a). For this thesis, the quality principles 8, 9 and 10 are particularly relevant. Table 1 shows what these quality principles imply in relevance for the thesis. These principles will provide guidelines for the discussion about whether the concepts are sustainable.

Table 1: Quality principles that are relevant for the thesis and what these principles implies (Bygg21, 2018a). The table and translations are produced by the author.

Quality principle	What the quality principle implies
8. Good buildings and areas utilize energy well	Good energy utilization: reducing the total need to buy energy through the year. First try to reduce energy needs, and then look for solutions to produce energy locally. Energy accounts for a large proportion of the lifetime costs of buildings and areas. By focusing on lifetime costs, we avoid poor energy solutions as a result of a pure focus on the lowest possible investment cost.
9. Good buildings and areas are built with good resource utilization and low greenhouse gas emissions	Choose building products that provide low greenhouse gas emissions during production and transport.
10. Good buildings and areas provide low operating and maintenance costs	Management, operation, and maintenance of buildings (abbreviated as FDV-costs in Norway) and areas include all related aspects, and all phases of the life cycle. Low FDV-costs are directly linked to the concept of sustainability through efficient operations, and by contributing to the highest possible economic value for all parties. Here, both resources and costs related to daily operations, and the long-term perspective are important.

Quality principle 8 goes hand in hand with SDG 9: by utilizing energy well this leads to more innovative and sustainable infrastructure. Quality principle 9 corresponds with SDG 12: when buildings are built with good resource utilization and low greenhouse gas emissions, this leads to more responsible consumption and production. Quality principle 10 goes coincides with SDGs 9, 11 and 12. By looking at a product through a life cycle perspective, and assessing the choices based on this, it will lead to more sustainable consumption, sustainable buildings, and innovative solutions.

In order to apply the quality principles, sufficient tools and methods are necessary. Through a survey of available tools that best fulfills the quality principles, it was found that none of the tools that are used in Norway today fully reflect the quality principles. Nevertheless, BREEAM is the tool of the

Norwegian market, that comes closest to fulfill the quality principles. This is because BREEAM is a high quality tool that has a comprehensive Norwegian adaptation, called BREEAM-NOR (Bygg21, 2018b).

BREEAM is one of many green building certification systems. These are rating systems used to evaluate a project's performance from a sustainability perspective, and they aim to promote the fulfillment of the Sustainable Development Goals through measurable indicators and criteria (Norwegian Green Building Council, n.d.-b). The most widely used certification system in Norway is BREEAM-NOR, a Norwegian adaptation of the British BREEAM. BREEAM-NOR reflects the “best practice” in Norway, and it is based on nine categories that include everything from management, energy, and transport to materials, pollution, and the indoor environment. These categories consist of several criteria, where points are awarded based on how many criteria the project meets. The system consists of five levels of certification based on the number of points: Pass, Good, Very Good, Excellent, and Outstanding (Norwegian Green Building Council, n.d.-a). The project manager has expressed interest in working towards a BREEAM-NOR certification, but this is not a set goal for the project (G. Johansen, personal communication, March 3, 2021). It is therefore decided not to let this lay direct guidance for the concept choices made in this thesis. Nevertheless, BREEAM-NOR will be used in the discussion as an evaluation of whether the concepts are sustainable or not.

BREEAM is very concerned about sustainability, and is constantly working to make designers, owners, users, and operation managers aware of the benefits of seeing sustainability in a life cycle perspective. A life cycle perspective means looking at the environmental impact through the life cycle of the product, not just for the materials used to make the product, read more about this in 3.2.1. In addition, BREEAM informs users about the benefits of creating buildings with lower environmental impact through the life cycle (Norwegian Green Building Council, 2016).

Furthermore, BREEAM promotes economic sustainability by encouraging the use of life cycle costs, i.e., all costs during a building's lifetime. They do this to create a suitable design, more precise specification of the project and a valuable overview of future operation and maintenance. They also promote economic sustainability by encouraging users to look at the costs through the building's life compared to the investment costs (Norwegian Green Building Council, 2016). An example is that if you spend more money on better insulating a building, the investment costs will go up, but on the other hand the operational costs will decrease. Seeing all the costs in a life cycle perspective is therefore important on the road to achieving a sustainability construction industry.

3.2. Climate Impact from The Construction Industry

Climate impact from the construction industry can be divided into three, based on where the greenhouse gas emissions occur during the construction process. The largest share of emissions is produced during the production and disposal of materials. This part is often not accounted for when discussing emissions from the construction industry, as it is often listed under other sectors. The second phase is the construction phase. This is when the construction is being built, and the emissions come from transportation, machinery, and energy use on the construction site. The last, and smallest, part comes from the operational phase. Emissions from the operational phase are small because of the ban on the use of fossil fuels for heating buildings and strict building regulations in Norway (Meld. St. 13 (2020-2021)). These make buildings in operation more energy-efficient today than before.

To lower the climate impact from the construction industry, there are various actions that can be taken. The Ministry of Local Government and Modernization published the report *Buildings for the future - Environmental action plan for the housing and construction sector 2009-2012* in 2009, to lay guidelines for a more environmentally friendly operation (Norwegian Ministry of Local Government and Regional Development, 2009). Here, they present five the following five focus areas to reduce the climate impact in the industry:

- Reduce greenhouse gas emissions
- Reduce the need for energy in buildings
- Map and minimize the use of substances that are hazardous to health and the environment in the construction industry
- Good indoor climate in buildings
- Prevent waste generation and increase the reuse and recycling of building materials

(Norwegian Ministry of Local Government and Regional Development, 2009)

These focus areas testify that reducing the climate impact from the construction industry has been on the authorities' agenda for years. This thesis will focus on the first two focus areas: reducing greenhouse gas emissions and reducing the need for energy in buildings.

3.2.1. Life Cycle Assessment

Life cycle assessment (LCA) is a method used to quantifying and evaluate the inputs and outputs of environmental impacts of a product through its lifetime. From that one can assess what processes can be environmentally improved. It is also used to compare products and processes with each other.

The overall goal of using a Life cycle assessment is achieving environmental sustainability (Muralikrishna & Manickam, 2017).

Life cycle assessment consists of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. The first phase, goal and scope definition, consists of determining the boundaries of the study, i.e., defining what processes will be considered in the assessment. The most comprehensive approach considers all the processes involved in a product. This is called a cradle-to-grave approach. This approach considers extraction of raw materials from nature, product design and manufacture, transportation, and distribution, use and maintenance of the product and the waste management, including recycling and final disposal (Muralikrishna & Manickam, 2017).

During the second phase, inventory analysis, data for input and output are quantified, focusing especially on the consumed raw materials and emissions to the environment. The third phase, impact assessment, the details from the inventory analysis are categorized by environmental impact, and then normalized and weighted. Examples of categories are resources, global warming, acidification, eutrophication, land use etc. During the final phase, interpretation, the results and conclusions from the second and third phase are reviewed, data sensitivity is determined, and the results of the LCA are summarized and presented (Muralikrishna & Manickam, 2017).

For this thesis, LCA will be used to find the greenhouse gas emissions from materials, including building materials, transport to the construction site, maintenance and material replacement, and recycling and disposal. The CO_2 emissions factor does not include the energy consumption of the building. The energy efficiency factor, on the other hand, concerns the amount of saved energy from one concept, compared to the energy consumption of a solution which only satisfies the minimum requirements of TEK17. Nevertheless, saved emissions from saved energy will be relevant when the concepts are compared against each other. Then, it will be sufficient to see how much emissions are saved from saved energy.

3.3. Energy Efficiency

Energy used in buildings accounts for 39% of Europe's total energy consumption (Global Alliance for Buildings and Construction, 2019). Many older buildings have high energy needs and do not satisfy the requirements of the current regulations on technical requirements. It is, therefore, a great need for rehabilitation that focuses on reducing energy needs and increasing energy efficiency. For Norway, the low electricity prices and its difficult climate have previously slowed down the development of energy-efficient buildings, when compared to other countries in Europe. However, in later years there has been a shift, where the authorities are setting stricter building regulations and companies are aiming to be more environmentally friendly (Norwegian Ministry of Local Government and Regional Development, 2009). Increasing the energy efficiency of buildings is one of the most effective actions to mitigate climate change (McKinsey & Company, 2009)

All buildings, new or old, can be built and remodeled to be more energy-efficient. However, social, and economic conditions set restrictions for this to happen. The main issue is that the industry and consumers do not choose this alternative. The investment cost for energy-efficient is greater than for traditional buildings (read more about these building concepts in 3.3.1). This type of construction is a long-term investment, where the owner will regain the investment after a longer period. This can be a hindrance for many, although, in the long run, it will be profitable due to reduced electricity costs or possible energy revenues. It is difficult to get homeowners to understand the importance of environmentally friendly buildings. I addition, there are perceptions that sustainable buildings are more expensive, even in the long run (Hayles & Kooloos, 2008). Hence, it is important to shed light on and create awareness around this topic.

3.3.1. Building Requirements for Energy Efficiency

The regulations on technical requirements consist of requirements for new buildings in Norway, and the aim of the regulations is to safeguard energy, the environment, health, and safety (Junker, 2018). In addition to technical requirements for the building itself, the regulation includes requirements for documentation, land use, nature impact, outdoor area and external environment, safety, fire, indoor climate, energy, installations, facilities and more (Byggteknisk forskrift (TEK17), 2017). The regulations on technical requirements are often referred to by the abbreviation TEK, followed by the year it was passed. The current regulations were passed in 2017 and is therefore called TEK17. For this thesis, the energy requirements in TEK17 are the most relevant part of TEK17. The project manager has expressed wishes that the existing buildings at least reaches TEK17 level as a result of the remodeling (G. Johansen, personal communication, April 16, 2021). Because energy efficiency is a key part, this thesis will also include concepts that goes beyond the energy requirements for TEK17.

The energy requirements of TEK17 can be met in two ways. Firstly, it can be done by meeting “the energy measures”, which are strict u-value requirements. Read more about u-value and u-value requirements in 3.5. Secondly, it can be done by meeting the minimum requirements of u-values, in addition to meeting “the energy framework”. The energy framework is a maximum value for total net energy need, and it differs for each building category (Direktoratet for byggkvalitet, 2018). In this thesis, the focus will be on the second method. The chosen building category is cultural building, and the requirement is 130 kWh/m^2 heated gross internal area per year (Byggteknisk forskrift (TEK17), 2017, § 14-2). The concept that meets these minimum requirements will be called the TEK17 concept, and the energy consumption of the various concepts will be compared to the TEK17 concept.

For building projects that wants to bypass the energy requirements of TEK17, there are more extreme types of energy-efficient requirements that can be reached. Low-energy building, passive building, net-zero building, and energy plus building are variations of buildings that are more energy-efficient than the average building. Although more energy-efficient buildings often require more energy to be made, they have a lower energy consumption compared to conventional buildings. Thus, the combined energy consumption is lower for energy-efficient buildings, when looking at it in a longer time perspective. It is therefore important to see energy consumption in a larger context.

The least ambitious energy-efficient building concept are low-energy buildings. They have a lower energy need for heating compared to conventional buildings. This is achieved through measures such as a well-insulated building body and recovery of heat from the ventilation system. Furthermore, passive building is a concept that has even lower energy needs than low-energy buildings. Net zero building is a concept where the building is designed to bring the building's total energy accounts as close to zero as possible. In practice, this means that the building must produce the same amount of energy as it consumes. There are different definitions of what time perspective should be used to measure energy consumption, either the operational phase or the entire life cycle of the building. This means that energy in connection with the production of building materials, transport, demolition, and disposal of the building is included in the energy budget. Energy plus building is the most ambitious energy-efficient building concept. These are buildings that produce energy and as the name implies, is on the plus side of consumption and produced energy. The time perspective discussion also applies for this concept (Norwegian Ministry of Local Government and Regional Development, 2010).

To illustrate how cost-effective an energy-efficient building is, UngEnergi have conducted a project where they investigated this. In their example, a detached house would cost NOK 100,000 more to build as a passive building instead of a conventional home. They calculated that this cost would be regained in 10 years, because of the reduced electricity cost. The same calculations also applied for a remodeling of an old building (UngEnergi, 2017). This shows how economically effective energy-efficient buildings can be in the long run.

For this thesis, there is no direct goal for the building to satisfy the requirements set for these energy-efficient building types. Rather, these requirements are used as an aid to find out if any of the concepts fit the requirements for these. Read more about the requirements in 3.5 and see the values in Table 2.

3.4. Rehabilitation and Remodeling

In the construction industry, the term rehabilitation is used for buildings that are being renovated for current purposes or to remedy neglected maintenance. This can include replacing or reinsulating building parts. If there is to be an expansion of the building itself, then it is called a remodeling. Both rehabilitation and remodeling aim to remove unwanted weaknesses in the building structure and reduce heat loss and air leakage (Evjenth et al., 2011).

Almost 80 percent of all existing buildings will still exist in 2050 (Norwegian Ministry of Local Government and Regional Development, 2009). Rehabilitation of these buildings are therefore highly important, seen from a climate perspective. A project conducted by SINTEF showed, by looking at life cycle assessments of over 120 Norwegian construction projects, that it is more climate-friendly to rehabilitate, rather than constructing new buildings (Ersfjord, 2020). Thus, efforts should be made to take care of and improve existing buildings. Further, the project found choosing environmentally friendly materials, implementing energy efficiency building measures, and the use of renewable energy to be the most important measures (Ersfjord, 2020). Nonetheless, the energy efficiency measures must be appropriate for the building in focus. It is important to ensure a balance between bound emissions from the materials and saved emissions from reduced energy use, so that the bound emissions do not outweigh the saved emissions. Hence, it is important to consider all aspects simultaneously.

Rehabilitation of existing buildings can lead to additional challenges compared to new buildings. Consideration must be given to ensure that the rehabilitation solutions fit the existing building and that there is a possibility of adjustments that must be made during the project period. To ensure that the rehabilitation is time-efficient and cost-effective, it is important that preparations are thoroughly carried out. Relevant preparations that are special for rehabilitation projects are condition assessment and examination of the building, in addition to measuring the building's sizes and angles as the building may no longer correspond to the initial drawings.

3.4.1. Energy-Efficient Rehabilitation of The Building Structure

SINTEF Building Research has developed UPGRADE, which is a guide for energy ambitious upgrading of commercial buildings. This includes guidance for all aspects of a rehabilitation process. In the part that deals with the building structure, it describes recommended measures for all building parts (SINTEF, 2014).

For the most energy-efficient upgrade of walls, exterior reinsulation is the most appropriate solution. This is because it reduces or eliminates cold bridges. For roofs, reinsulation is appropriate, or alternatively converting the roof into a compact roof. For the floor, the simplest measure is to build on top of the existing floor. In situations where maintaining the room height is a wish, existing floors should be removed and rebuilt. Windows are the part of buildings that often emits the most heat. Thus, windows have great potential for energy efficiency. Depending on the desired result, the alternatives are to improve existing windows or replace them. Facades with a large area of old windows can create cold drafts, which will affect the heat balance of the building (SINTEF, 2014).

Reducing energy consumption of existing buildings can lead to a poor indoor climate. It is estimated that poor indoor climate leads to a cost of NOK 8-12 billion for Norwegian society each year. This is due to illness, and in addition, lost income as a result of reduced productivity will come in addition (SINTEF, n.d.). The consequences of an energy-efficient improvement of the building will not be included in this thesis, but in the event of a remodeling, this should be investigated further.

3.5. U-value

The u-value, also called the heat transfer coefficient, of a building component indicates the thermal insulation capacity. It is defined as the heat flux density that passes through a planar, stratified building part when the difference in air temperature above the building part is 1 kelvin, under stationary conditions. The u-value can be found by measuring in the laboratory or by calculation, and it is specified with the unit $W/(m^2K)$ (Thue, 2019). Calculation of u-value will be described in more detail in 4.2.

U-value is used in several contexts; finding the general characteristics of the thermal insulation performance of structures, to evaluate against TEK17's requirements, to calculate heat power requirements for rooms or buildings as a basis for dimensioning of heating systems and to calculate the energy need for heating. U-value can only be used in one-dimensional, stationary heat flow conditions, and thus cannot be used for calculating instantaneous values of the heat flow when the air temperature varies. Over a long period, however, the u-value gives a correct picture of the average conditions (Thue, 2019).

In TEK17, The Ministry of Local Government and Modernization sets maximum u-values for the all building parts. The u-value requirements have become stricter in recent decades due to the increased focus on energy efficiency and the development of technology. As a result, the insulation thickness has increased significantly in all parts of the building (Thue, 2019).

Table 2 shows the minimum u-value requirements for TEK17 according to NS 3701 (Standard Norge, 2012). There are no low-energy and passive building requirements for roof, wall, and foundation. However, NS 3701 presents some suggested u-values that are included in the table below. These values are the basis for assessments of whether the concepts are suitable for a low-energy or passive building. The concepts of net-zero and plus building have no requirements related to u-values, thus being more focused on energy consumption and energy production.

Table 2: Maximum u-value requirements for TEK17, low-energy buildings and passive buildings (Standard Norge, 2012). The table and translations are produced by the author.

Building part	TEK17	Low-energy building	Passive building
	W/(m²K)	W/(m²K)	W/(m²K)
Roof	≤ 0.18	≤ 0.10 - 0.12	≤ 0.08 - 0.09
Wall	≤ 0.22	≤ 0.15 - 0.16	≤ 0.10 - 0.12
Window	≤ 1.2	≤ 1.2	≤ 0.8
Door	≤ 1.2	≤ 1.2	≤ 0.8
Foundation	≤ 0.18	≤ 0.10 - 0.12	≤ 0.08

As mentioned, the TEK17 requirement only applies for new buildings. But since energy efficiency is a wish of the project manager, it is desired that the concepts at least meet these requirements, and that several of the concepts also meet the low-energy and passive building requirements (G. Johansen, personal communication, April 16, 2021).

4. Methods

This chapter describes the methods that have been conducted in order to answer the research question. In addition, weaknesses will be presented and discussed.

4.1. Preparatory Work

Before the structuring of the thesis and the research question, it was important to get a good overview of the existing theory dealing with the topic in question. Getting acquainted with existing knowledge also became important to adapt the thesis to the case. The thesis was first intended as a more general balancing of the three mentioned factors, energy consumption, CO_2 emissions, and cost for rehabilitation of the average home. After contact with the project manager had been established, decisions were made to focus on the case building in Aurlandsvangen. It was important to get familiar with the case, and all available literature concerning the case building was reviewed. A detailed inspection of the building was also carried out in collaboration with the project manager. Here, it was important to examine the condition of the building and get a real picture of how the building looks, as well as the surrounding areas.

A SIMIEN simulation was then made of a TEK17 upgrade of the existing building. This was first done with plans to use the results in the thesis, which was later ruled out as the focus of the thesis shifted. Nevertheless, it has been an important exercise for gaining better knowledge about the use of SIMIEN, prior to the creation of the SIMIEN simulation of the TEK17 concept. The simulation of the TEK17 concept has been important for the remainder of the thesis, and it has been used in comparison with the other concepts, to establish the results on saved energy.

After the SIMIEN simulation of the TEK17 concept was completed, the work of selecting concepts and materials for the various building parts began. Many different solutions were evaluated; thus, additional concepts have been tested than what appears in this thesis. Finally, three concepts were chosen per building part for in-depth studies and assessment. To obtain sufficient information, various programs have been used, in addition to direct contact with companies and producers. To determine quantities, the drawings from MAD Architects have been used, as well as personal observations from the inspection.

4.2. U-value Calculation

U-value calculation is a method used to find the u-value, also called the heat transfer coefficient, of various construction components, such as walls, roofs, and floors. U-value calculation is a method that allows the user to have control over what parts of the construction affect the results the most. In that way, one can easily adjust e.g., the amount of insulation to find the optimal solution.

The u-value calculations in this thesis have been performed according to the standard NS-EN ISO 6946, by using equations from The Building Research Design Guide *471.008 Calculation of u-values after NS-EN ISO 6946* (SINTEF Byggforsk, 2018). Microsoft Excel has been used as calculation tool. Furthermore, heat conductivity values have been obtained from SINTEF Building Research and manufacturers where needed. For this thesis, the method is chosen primarily because the results are needed as input values for energy simulations in SIMIEN.

4.2.1. Implementation of U-value Calculation

Building parts with homogeneous layers are building parts where the materials are the same vertically down the building part. However, usually, building parts are composed of several components vertically throughout the building part. An example is a wooden frame wall where the wooden framing and isolation alternate vertically down the wall, see Figure 10. These walls have inhomogeneous layers. U-value calculation can be carried out for walls with both homogeneous layers and inhomogeneous layers, but the methods are somewhat different. Both methods are described below.

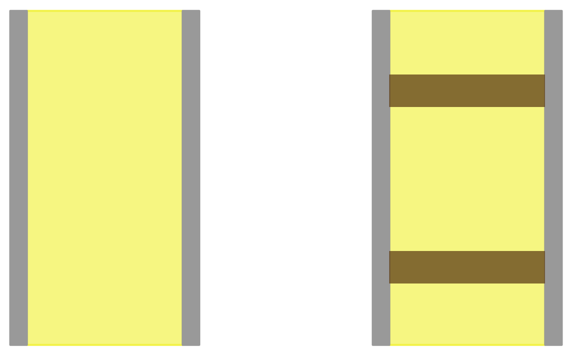

Figure 10: A wall with homogeneous layers on the left and inhomogeneous layers on the right. Produced by the author.

Homogeneous layers

First, the value of R was found for all materials of the wall. The R, also called the thermal resistance, indicates how well a material prevents heat flow and is calculated by using the material's dimensional thermal conductivity, λ_d and the thickness of the material, d. The R-value of a homogeneous layer is given by the formula:

$$R = \frac{d}{\lambda_d} \; (m^2K/W)$$

Then the total thermal resistance was calculated. The total thermal resistance for a construction part of homogeneous layers is equal to the sum of the thermal resistance for each of the material layers, in addition to the heat resistance of internal surface resistance R_{si} and external surface resistance R_{se} of the selected building part. Thus, total heat resistance was calculated according to the following equation:

$$R_{tot} = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \quad (m^2K/W)$$

The u-value was thereby found by dividing one by the total thermal resistance and adding u-value correction. This is given by the equation:

$$U = \frac{1}{R_{tot}} + \Delta U \quad (W/m^2K)$$

ΔU is a correction supplement that considers three factors:

- ΔU_g Unintentional air gaps penetrating the insulating layer
- ΔU_r Precipitation on inverted roofs
- ΔU_f Mechanical fasteners puncturing the insulation

Inhomogeneous layers

First, the upper and lower limit value was calculated. The upper and lower limit values are theoretical values of the thermal resistance, and the real thermal resistance must be between those values.

Firstly, the inhomogeneous composite was divided into fractions, so that each fraction consisted of planar, homogeneous layers. The upper limit value, $R_{tot,\ upper}$, was calculated as an area average of the thermal resistance of all the fractions of the building part, area shares for each fraction, f_a, f_b, ..., f_q, and total thermal resistance for each fraction type, including internal and external surface resistance, $R_{tot,\ a}$, $R_{tot,\ b}$, ..., $R_{tot,\ q}$.

The following formula was used for the calculation of the upper limit value:

$$R_{tot,upper} = \frac{1}{\frac{f_a}{R_{tot,a}} + \frac{f_b}{R_{tot,b}} + \ldots + \frac{f_q}{R_{tot,q}}} \quad (m^2K/W)$$

To find the area share, f_q, the total area of all layers in one fraction q, ΣA_q, and total area for the building part, A_T, was used. Area share was calculated from the following equation:

$$f_q = \frac{\Sigma A_q}{A_T}$$

The lower limit value, $R_{tot, lower}$, was found by first calculating equivalent thermal resistance, R_j, for each of the composite layers of the building part. To do this, area share for each fraction type, f_a, f_b, ..., f_q, and the thermal resistance of each of the materials in every layer of a fraction, R_{aj}, R_{bj}, ..., R_{qj} was needed. Equivalent thermal resistance was calculated by the following equation:

$$R_j = \frac{1}{\frac{f_a}{R_{aj}} + \frac{f_b}{R_{bj}} + \ldots + \frac{f_q}{R_{qj}}} \quad (m^2K/W)$$

Furthermore, the lower limit value was found in the same way as for building parts of homogeneous layers, using the same equation:

$$R_{tot,lower} = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \quad (m^2K/W)$$

Then, the average of the upper and lower limit values was calculated. This is the most real-life R-value, and it was found by using the following equation:

$$R_{tot} = \frac{R_{ttot,upper} + R_{tot,lower}}{2} \quad (\frac{m^2K}{W})$$

Lastly, the u-value was found by the same equation as for homogenous layers, where the correction supplement is the same for building parts with inhomogeneous layers as for homogeneous layers:

$$U = \frac{1}{R_{tot}} + \Delta U \quad (W/m^2K)$$

See Appendix B: Example of U-value Calculation Conducted in Microsoft Excel for Excel sheets of u-value calculations for examples of buildings parts with both homogeneous and inhomogeneous layers.

4.3. Energy Simulation in SIMIEN

SIMIEN is an energy simulation tool that has various features, including energy labeling, calculation of energy consumption, mapping of indoor climate, and evaluation against building regulations

(ProgramByggerne, n.d.). In this thesis, SIMIEN has been used to simulate energy consumption for the concepts. A total of 16 simulations have been carried out in SIMIEN, one for each concept, in addition to the TEK17 concept.

SIMIEN is a program used across the building sector, because of its user-friendliness, as well as its complex simulations. Here, the use of u-values and other central data which are relevant to the selected case is used to describe the case in detail.

The information entered in the program has been as accurate as possible, but in some places, it has been necessary to make assumptions or estimates. This applies, for example, to u-values and material properties for existing building parts.

4.3.1. Implementation of Energy Simulation in SIMIEN

First, the location and belonging climate zone for the building in question was chosen. The whole building was defined as one construction zone, defined by the outer walls. Relevant information was entered for all walls. This included information such as size, number of windows and doors, and their respective u-value. Furthermore, calculated u-values for the specific building parts were entered, as well as values for the relevant energy supply system and ventilation system. Default values were used for internal loads and heating, these were taken from the standard SN-NSPEK 3031:2020 (Standard Norge, 2020). Finally, an evaluation against TEK17 was performed for each concept. Only the relevant results for the problem were selected, and these laid the foundation for the balancing. See the simulation for the TEK17 concept in Appendix C: Energy Simulation in SIMIEN.

4.4. Life Cycle Assessment

There are several different tools that can be used to complete a life cycle assessment. In this thesis, it was chosen to use One Click LCA on the recommendation of the external supervisor. This is the descendant of klimagassregnskap.no, a well-established tool used in many construction projects in the industry. It has also been ranked the highest rated life cycle assessment software for BREEAM (One Click LCA, n.d.-b). It is also used by Statsbygg, which is the government's developer, property manager and construction consultant (One Click LCA, n.d.-a). Read more about how a life cycle assessment is carried out in 3.2.1.

One Click LCA is a tool used to calculate the climate impacts of buildings during its life cycle. It provides values for greenhouse gas emissions, acidification, eutrophication, ozone depletion potential and more. In the thesis, the values for greenhouse gas emissions for each concept will be used. This includes emissions from materials, transportation, maintenance and replacement and disposal at end of life. See examples in Appendix D: CO_2 Estimates Conducted in One Click LCA for the Slab on Ground Concepts.

4.4.1. Implementation of Life Cycle Assessment

First, the estimated lifetime of the building, set to 50 years, was entered into One Click LCA (SINTEF Byggforsk, 2004). Then the materials were entered for each individual concept. Here, the materials were categorized into groups according to concept, so that both the emissions from each material, as well as an overall value for the entire concept, were shown. The program allows you to choose from specific materials from manufacturers or One Click LCA's own values for more general materials, such as wood and concrete. Thus, some results may be lower if e.g., locally produced wood is used.

The total greenhouse gas emissions from each composite concept was then used in the balancing. These values do not consider energy consumption during the life cycle with each individual concept, they only include the values for the concepts separated from the rest of the building. Values for energy consumption with the various concept was, however, used in the balancing, read more about this in 4.6.

4.5. Cost Estimates

The cost estimates in this thesis are primarily conducted by using Holte SmartKalk. Where costs were not found, prices have been collected directly from manufacturers. SmartKalk is a calculation system used to calculate the price of construction projects (Holte, n.d.). The program has great flexibility as it is very detailed, and it is possible to replace even smallest part of the calculation, for example screws and nails. This provides great control over what is included in the calculation. In addition, SmartKalk considers increased productivity for larger areas. For example, the costs will be lower per m^2 if several walls are re-insulated compared to one. This gives more real-life like values. The cost estimates include materials, construction, and machine rental, and are primarily intended for comparison of the concepts. However, they will provide a rough estimate of the actual cost of choosing these remodeling solutions.

4.5.1. Implementation of Cost Estimate

In the program, one can either choose to build a building part from scratch or choose a finished composite and then replace the desired elements. In the thesis, it was chosen to select finished composites and replace the elements that did not fit with the concepts. This was done to ensure that all costs were included. For the reuse concepts for doors and windows, the cost of the window itself was replaced with the cost of the renovation job.

4.6. Balancing

Finding the balance between energy consumption, CO_2 estimates, and the cost is difficult. This depends on which of the three factors is prioritized for each project. For this project, an attempt was made to weigh all three equally. A comparison was made of the concepts for each building part in the form of a selection. First, the concepts were compared to see if one of the concepts has the worst results for all three factors. This concept was then opted out. Then, the saved cost from saved energy through the life cycle was subtracted from the investment cost. This value is called the total cost. This made it possible to find out how much the concepts would cost in the long run by including both investment cost and saved cost over time. The cost is presented in 2021 NOK. The same process was completed for emissions, where saved emissions from saved energy were subtracted from the emissions of the concept, resulting in what is called total emissions. This showed the amount of emissions that the concept will generate in the long run, thus making it easier to compare the concepts. The concepts were then be compared based on total cost and total emissions, and the most balanced concept was chosen. A fictional example will be explained to make this balancing process easier to understand:

Table 3: Fictional example.

	Saved energy per year	Cost	Emissions
	kWh	NOK	tonnes CO_2 eq
Concept 1	0	2,000,000	15
Concept 2	2650	800,000	4
Concept 3	2500	600,000	9

Table 3 shows all the results of three fictional concepts. First, concept one will be opted out because it has the worst results for all three factors. Then the selection takes place between concept two and concept three. They both save almost the same amount of energy each year. Concept two is more expensive but emits less greenhouse gases, and concept three is the opposite. To compare the two remaining concepts, the total cost and total emissions are calculated, see the results in Table 4.

Table 4: Total cost and total emissions of the fictional example.

	Total cost	Total emissions
	NOK	tonnes CO_2 eq
Concept 1	2,000,000	15
Concept 2	798,870	3.96
Concept 3	598,934	8.96

Concept two has a 33% higher cost than concept three, but the emissions of concept three is 126 % higher than the emissions of concept two. Concept two is therefore chosen, because it is overall a more balanced concept.

The value for greenhouse gas emissions from energy is taken from The Norwegian Water Resources and Energy Directorates "Klimadeklarasjon for fysisk levert strøm i 2019" (translated: "Climate declaration for physically supplied electricity in 2019"). The calculations that were carried out show that the electricity in Norway is mainly from renewable sources, and that electricity emitted 17 g CO_2e/kWh in 2019 (Norwegian Water Resources and Energy Directorate, 2020a). This value will be used in calculations of saved cost from saved energy. One Click LCA has a feature that shows emissions from energy consumption, but they use a much higher factor because they use older numbers than The Norwegian Water Resources and Energy Directorate does.

For saved costs from saved energy, The Norwegian Water Resources and Energy Directorates "Langsiktig kraftmarkedsanalyse 2020-2040" (translated:" Long-term power market analysis 2020-2040") has been used (Norwegian Water Resources and Energy Directorate, 2020b). It is assumed that the price will rise steadily from the year 2030, and based on this, an average value has been calculated for the period 2022-2071, with the resulting cost being 0.4264 NOK/kWh. See Appendix F: Calculation of Energy Cost for the calculation.

This price does not include grid rent. This is a cost that must be included regardless of which concept is chosen. The grid rent is set together for the entire building, not for each part of the building, and it would therefore not be appropriate to include grid rent for each concept. Although the price for grid rent depends somewhat on how much electricity is used, the differences are not so substantial that it would lead to a different conclusion than what is presented here. The price including grid rent will result in the actual savings being much larger than what emerges from this thesis, but the relative difference between the concepts will not be much affected.

4.7. Weaknesses

There are several weaknesses to the chosen methods; however, assessments have been made to try to minimize these weaknesses. U-value calculations do not consider destroyed or worn construction parts or human error during mounting. Because of this, the result of the calculation is seen as an ideal case, which is not the reality. However, the method provides an estimate that can be used in comparison and for energy simulations. In addition, the method is widely used and accepted in the construction industry.

Furthermore, it is important to point out that SIMIEN does not give results that correspond entirely with reality. This is because many of the values are calculated and not measured. Thus, the input data does not consider leakages and skews. Air leakages and heat loss are examples of such. In addition, it is important to consider that human errors can affect the simulation results, as one wrong keystroke can have a significant impact. To avoid this, all models have been verified twice. Nevertheless, an energy simulation in SIMIEN can provide a realistic picture of the building's energy consumption and it is sufficient for the purpose of comparing the concepts.

In the life cycle analyses and cost estimates, all the choices that have been made have influenced the outcomes. Every keystroke has an impact, which means that if someone else were to carry out the analyses and estimates, it could have resulted in different outcomes. Furthermore, it could have been helpful to use life cycle cost to get a better picture of what each concept would cost from cradle-to-grave, as life cycle cost also includes operational and demolition phase. In the cost estimates, replacement or waste management are not included. The cost estimates will still give a good picture as investment cost is the most significant part of the total cost.

Nevertheless, there are primarily weaknesses associated with the balancing. The balancing is based on all the methods, and thus any mistakes made in the methods will continue to follow into the balancing. To avoid this, the methods have been carefully implemented, and all input values have been double-checked. The greatest uncertainties are related to the emissions from and the price of electricity. Emissions may be lower in the future, upon transition to more renewable sources. Changes in demand and price developments in the market could lead to changed costs. Furthermore, the service life of the building is set at 50 years. This is used as a basis for calculating saved costs and saved emissions from saved energy, in addition to the life cycle assessment. However, this does not mean that the building will not last longer than 50 years, and this may affect the results where life cycle has been used. If the results had been used to determine whether the concept is worth the investment or not, all these weaknesses could have had major consequences for the conclusion. Nevertheless, the main goal of these results is to use them to compare the concepts. Thus, the percentage change due to change in one of the three uncertainties; electricity price, emissions from electricity and service life, would still be the same. It is thus considered that these methods are well suited for the balancing process.

5. Building Concepts

This chapter describes the all the concepts in detail. There will be three different concepts for each building part, and the building parts considered are roof, wall, windows, doors, and slab on ground. For the roof, wall, and slab on ground, the variation in concept mainly consists of different dimensions and types of insulation. One concept for each building part is made to replicate a standard solution for that specific building part. This means that the materials chosen is often used for its purpose, and the u-value meets the minimum requirements of TEK17, thus not being a particularly energy-efficient solution. U-values have been used when carrying out the choice of concept, however, they will be presented in their entirety in the results chapter.

5.1. Roof Concepts

All three roof concepts consist of plasterboard ceiling, vapor barrier, insulation and rafters, wind barrier, ventilation 48x48 mm, suspended ceiling, roofing. Stone wool, aerogel, and wood fiber are the three insulation types chosen for the roof, see Figure 11.

Figure 11: The insulation types of the roof concepts. Stone wool to the left; Source: (Rockwool, n.d.), Aerogel in the middle; Source: (Glava, n.d.-a) and wood fiber to the right; Source: (Hunton Fiber, n.d.-a).

The first roof concept is the standard solution, which consists of 200 mm stone wool panels from Rockwool, which has a thermal conductivity of 0.037 W/mK (Rockwool, n.d.). The anorthosite used to make the Rockwool insulation is extracted in Nærøydalen, inside the World Heritage Site (Korneliussen et al., 2020). This will not provide direct guidance for the choice of solution, but it is an interesting fact that the stone taken out of the World Heritage Site, it returned and used inside the World Heritage Site. Nærøydalen is one of the largest anorthosite fields in the world, and extraction has been practiced here since the 1960s (Korneliussen et al., 2020). The stone is transported to Rockwool's factories in Trondheim and Moss. The factory in Moss is being electrified, which will lead to reduced emissions by up to 80% (Rockwool, n.d.). As this factory is not currently operational, this electrification will not be included in the calculation. The amounts of emissions used in the thesis will therefore be current values, and not the values that will exist when the building is to be built.

The second concept consists of 150 mm Spaceloft Aerogel (hereby called Aerogel) from Aspen Aerogel. Aerogel has a thermal conductivity of 0.015 W/mK, making it one of the most energy-efficient insulation materials in the world (Glava, n.d.-a). The material is particularly suited to use in areas that are difficult to insulate, such as arches, and building parts where you want to reduce the amount of insulation to maintain the facade expression. Aerogel is produced by first creating a gel made by combining silica with a solvent. The liquid is then extracted from the gel through a process called supercritical drying. This process causes the liquid component to be removed and replaced by air, while the gel structure is maintained. This results in a solid material with an extremely low density and thermal conductivity (Woods, 2017). This material is still very new on the market, and this is reflected on its high price.

The third concept consists of 400 mm wood fiber insulation panels from Hunton, which has a thermal conductivity of 0.038 W/mK (Hunton Fiber, n.d.-a). This insulation material is produced by waste from pine and spruce. The trees absorb and store CO_2, but some of this is emitted during production. Nevertheless, wood fiber insulation stores significantly more than what is emitted during production, and the total emission is negative (Hunton Fiber, n.d.-b).

5.2. Wall Concepts

The existing wall consists of concrete hole blocks and approx. 13 mm external plaster. From inside to outside, the concepts consist of gypsum board, internal application with electricity and piping, vapor barrier, existing plaster, existing lightweight clinker blocks, existing exterior plaster, adhesive mortar, insulation with fixing plugs, primer, reinforced rough plaster, and final plaster. It will be upgraded by adding insulation on the outside, to prevent moisture in the construction. Since a new roof is to be laid, the exterior insulation will not lead to problems regarding the roof extension.

The project manager wants the façade of the building to be as similar as possible to the existing building (G. Johansen, personal communication, January 26, 2021). It has therefore been chosen to have plaster on the outside. As this is not possible to do on all types of insulation, this have provided guidelines for the choice of insulation. The wall concepts consist of the three insulation types, stone wool, EPS, and glass wool, see Figure 12.

Figure 12: The insulation types of the wall concepts. Stone wool to the left; Source: (Rockwool, n.d.), EPS in the middle; Source: (Glava, n.d.-d) and glass wool to the right; Source: (Glava, n.d.-c).

The first concept consists of 300 mm stone wool panels from Rockwool. The information about the insulation in 3.1.1. also applies to this solution, as it is the same insulation choice. Thus, it has a thermal conductivity of 0.037 W/mK.

The second concept consists of 200 mm expanded polystyrene (EPS) panels from Glava, which has a thermal conductivity of 0.038 W/mK (Glava, n.d.-d). EPS is an insulation material that consists of 91-91% polystyrene and 4-7% pentane. It is produced by adding small beads of polystyrene to pentane, which acts as a leavening agent, and then exposing it to heat. The polyester beads will then be expanded into balls consisting of about 98% air. Furthermore, these balls are fused to make EPS panels (Berge, 2020).

The third concept consists of 300 mm glass wool panels from Glava, with a thermal conductivity of 0.035 W/mK (Glava, n.d.-c). Glass wool is produced by quartz sand, dolomite, and recycled glass. This glass can, for example, come from broken car and house windows, and glass wool insulation can contain as much as 70% recycled glass (Glava, n.d.-b).

5.3. Window and Door Concepts

Recommendations from the technical building assessment, advice that windows and doors are be replaced and upgraded to better insulated ones (G. Johansen, personal communication, October 10, 2020). This is because reusing existing windows and doors will be costly and technically weaker than new ones. Despite this, the concepts will include the reuse of existing windows and doors. This is done because it is a wish of the project manager, and it is also beneficial to see how the reuse concepts affects the various factors compared to new solutions (G. Johansen, personal communication, January 26, 2021).

Since the u-value for windows and doors are not calculated, thus not being results, these values will be presented in the following subchapters.

For the first window concept, the windows will be renovated and reused. First, the window frame is scraped down to bare wood, the glass is dismantled, and rotten wood is replaced. The window frame is then primed, and the glass is reassembled. Damaged glass will be replaced with new. Finally, everything is painted with two coats of paint. Some of the windows have an interior product window. For this concept, a product window will be installed on those who lack it. This will give an estimated u-value equal to 2.6 W/(m²K) (Riksantikvaren, 2020).

In the second window concept, the frames will be renovated in the same way as the first concept. The outer glass will be retained; however, the product window will be replaced by energy glass. Energy glass has a thin coating of metal or metal oxide on the side that faces the space between the two glasses. This causes the heat to reflect into the room (Thue, 2021). This concept will give an estimated u-value of 1.6 W/(m²K) (Riksantikvaren, 2020).

The third window concept is to replace all the windows with triple pane windows with gas filling. This will give a u-value of 0.8 W/(m²K), which meets the passive house requirement.

For the first door concept, the doors will be renovated and reused. The renovation of the doors will happen in the same way as the renovation of the windows. This will give the doors an estimated u-value of 2.6 W/(m²K).

The second and third door concepts consist of new doors with a u-value of 1.2 W/(m²K) and 0.8 W/(m²K). A u-value of 1.2 W/(m²K) is the minimum requirement for doors, so the second concept is considered a standard solution. Doors with a u-value of 0.8 W/(m²K) are an energy-efficient solution that meets the passive house requirement.

5.4. Slab on Ground Concepts

XPS, EPS, and Glasopor are the three insulation types chosen for the slab on ground concepts, see Figure 13. For the XPS and EPS concepts, the construction consists of draining masses with drainage pipes, radon barrier, insulation, moisture barrier, and screed. For the last concept, this will be somewhat different, because Glasopor Foam Glass (hereby called Glasopor) acts as combined insulation and draining masses.

Figure 13: The insulation types of the slab on ground concepts. XPS to the left; Source: (Isodren, n.d.), EPS in the middle; Source: (Glava, n.d.-d) and Glasopor to the right; Source: (Glasopor, n.d.-a).

The first concept consists of 150 mm extruded polystyrene (XPS). XPS is an insulation material made from polystyrene using an extrusion process (Isodren, n.d.). Extrusion is a process where a material is deformed by the application of force (Maier & Calafut, 1998). XPS is an insulation material that can be used in ceilings, walls, floors, and the ground.

Concept number two consists of 350 mm EPS, which has a thermal conductivity of 0.038 W/mK. This is the same type of insulation used for the EPS wall concept.

The last slab on ground concept consists of 800 mm Glasopor, a material that has a thermal conductivity of 0.97 W/mK (Glasopor, n.d.-b). The reason why the Glasopor layer is so thick is because Glasopor is a granular material with good draining properties, so, as mentioned above, it will act as a draining mass in addition to insulation. The Glasopor concept will therefore not have a layer of draining masses. Glasopor is produced from 100% recycled glass packaging from households in Norway. The glass is crushed to fine powder, then an activator is added, and this is baked at a high temperature. The activator ensures that air bubbles are formed during baking. Therefore, Glasopor consists of 20% glass and 80% air. This makes it a very light material, which means that much larger quantities of Glasopor can be transported to the building site in one truck, compared to traditional rock masses (Glasopor, n.d.-a).

6. Results

In this chapter, results are presented. The presentation of results is comprehensive and repetitive, seeing that four methods have been performed on 15 concepts, which leads to large amounts of results. To clearify, the results are presented in tables and diagrams, and explained in text.

6.1. Result of u-value calculations

The results for the u-value calculations are shown in Table 5. It is important to emphasize that the u-value is not only affected by the insulation, but also by all the other components of the building part. However, it is the insulation that differentiates the concept variations, which is why the insulation thickness, and the thermal conductivity of the insulation material is presented.

Table 5: Results of the u-value calculations.

	Insulation thickness	Thermal conductivity	U-value construction
Roof	mm	W/mK	$W/(m^2K)$
Stone wool	200	0.037	0.18
Aerogel	150	0.015	0.10
Wood fiber	400	0.038	0.11
Concrete wall			
Stone wool	300	0.036	0.11
EPS	200	0.038	0.17
Glass wool	300	0.035	0.11
Slab on ground			
XPS	150	0.034	0.18
EPS	350	0.031	0.08
Glasopor	800	0.097	0.12

The results show that the thermal conductivity of the insulation material has a great impact on the u-value. Although the Aerogel roof concept has the thinnest insulation, its low thermal conductivity results in a u-value of 0.10 $W/(m^2K)$. This is the lowest value out of the three roof concepts. The 200 mm stone wool concept, with a thermal conductivity of 0.37 W/mK, has a u-value of 0.18 $W/(m^2K)$, which is the minimum requirement for TEK17. The wood fiber concept is twice as thick as the stone wool concept. With a thermal conductivity of 0.038 W/mK, this corresponds to a u-value of 0.11 W/mK. Both the Aerogel and the wood fiber concept are solutions suitable for low-energy buildings.

For the wall concepts, two of the solutions, stone wool, and glass wool, have a u-value of 0.11 W/(m^{2}K). They have an equal thickness of 300 mm and thermal conductivity of 0.036 W/mK and 0.035 W/mK, which shows that a difference of 0.001 W/mK does not substantially influence the u-value. Both concepts are suitable for a passive building. The EPS concept has a u-value of 0.17 W/(m^{2}K) with a thickness of 200 mm and a thermal conductivity of 0.038 W/mK. This is a slightly more energy-efficient concept than the minimum requirement for TEK17, which is 0.22 W/(m^{2}K).

Among the slab on ground concepts, there are large differences in thickness and u-value. The XPS concept has a thickness of 150 mm, and a thermal conductivity of 0.034 W/mK, which corresponds to a u-value of 0.18 W/(m^{2}K), the minimum requirement of TEK17. The350 mm EPS concept has a thermal conductivity of 0.031 W/mK, which corresponds to a u-value of 0.08 W/(m^{2}K), suitable for a passive building. The last concept, Glasopor, has a thickness of 800 mm. With a thermal conductivity of 0.097 W/mK, this corresponds to a u-value of 0.12 W/(m^{2}K), appropriate for a low-energy building.

No u-value calculations have been carried out for windows and doors, as these are values obtained from manufacturers. Table 6 shows the u-values of the various window and door concepts.

Table 6: U-values for windows and doors.

	U-value construction
Window	
Reuse	2.6
Reuse, change to energy glass	1.6
Triple pane window with gas filling	0.8
Door	
Reuse	2.6
New 1.2	1.2
New 0.8	0.8

6.2. Result of Energy Simulation in SIMIEN

The energy simulation in SIMIEN results in a lot of information. Since the only results that are relevant are energy consumption, the rest of the results are excluded. Figure 14 shows saved energy. This is based on the energy consumption of a solution that meets the minimum u-value requirements for TEK17 compared to the various concepts. That is, how much energy one saves by choosing a certain concept compared to the TEK17 concept, i.e., TEK17 defines the zero value. A table with all values can be found in Appendix G: Results of the Energy Simulation Conducted in SIMIEN.

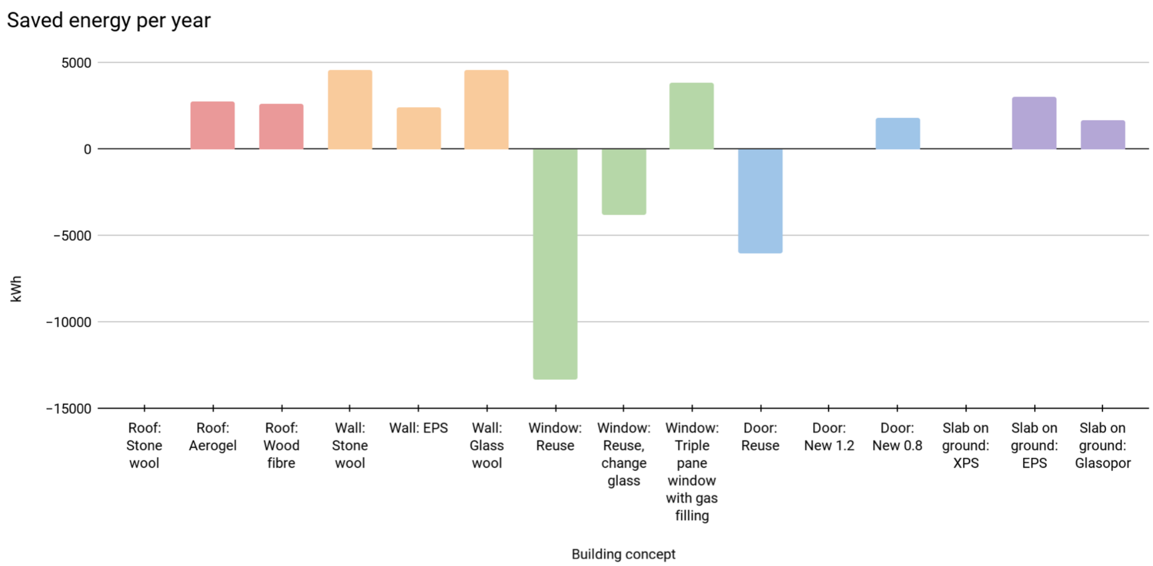

Figure 14: Results of the SIMIEN simulations. The diagram shows saved energy compared to the TEK17 for each concept.

The roof concepts are shown in red in Figure 14. For a stone wool concept with a u-value of 0.18 W/(m²K), 0 kWh is saved, as this concept has the same u-value as the TEK17 concept. An Aerogel concept with a u-value of 0.10 W/ (m²K) and a glass wool concept with a u-value of 0.11 W/(m²K) will result in almost the same amount save of saved energy, 2731 kWh and 2580 kWh per year.

For the wall concepts, shown in orange, the stone wool and glass wool concepts save the same amount of energy. They have a u-value of 0.11 W/(m²K), which results in saving 4552 kWh per year. The EPS concept has a u-value of 0.17 W/(m²K) and saves more than half of what the other two concepts do, with 2428 kWh per year.

For the window concepts, shown in green, there is a large spread in results. New triple pane windows with gas filling with a u-value of 0.8 W/(m²K), resulting in 1366 kWh saved energy per year compared to the TEK17 concept. However, for the reuse concepts, nothing is saved. Instead, these concepts require more energy than the TEK17 solution. This is because the u-values are higher than the minimum TEK17 requirement for windows, which is 1.2 W/(m²K). The reuse concept, where the windows are only repaired, has a u-value of 2.6 W/(m²K) and thus requires 4856 kWh more energy compared to the TEK17 concept. Lastly, the reuse concept, where the product windows are replaced with energy glass, has a u-value of 1.6, thus requires 1366 kWh more energy each year. This shows how substantial difference it makes to replace the windows compared to reusing old ones, seen from an energy efficiency perspective.

Regarding the door concepts, shown in blue, the same applies to the recycling concept. The recycling concept has a u-value of 2.6 W/(m²K) and requires as much as 6069 kWh more energy each year compared to the TEK17 concept. The new doors with a u-value of 1.2 W/(m²K) save no energy, as they have the same u-value as the minimum requirement for TEK17. Lastly, the concept including new energy-efficient doors, having a u-value of 0.8 W/(m²K), saves 1821 kWh energy every year.

For the slab on ground concepts, shown in purple, most energy can be saved by using the EPS concept. With a u-value of 0.08 W/(m²K), choosing this concept will save the building 3035 kWh energy every year compared to the TEK17 concept. The Glasopor concept has a u-value of 0.12 W/(m²K), which results in 1669 kWh saved energy per year. An XPS will not result in any saved energy, as it has the same u-value as a TEK17 concept, with a u-value of 0.12 W/(m²K).

6.3. Results of Life Cycle Assessment

The results from the life cycle assessment carried out in One Click LCA are presented in Figure 15. A table with all the values can be found in Appendix H: Results of the CO_2 Estimates Conducted in One Click LCA.

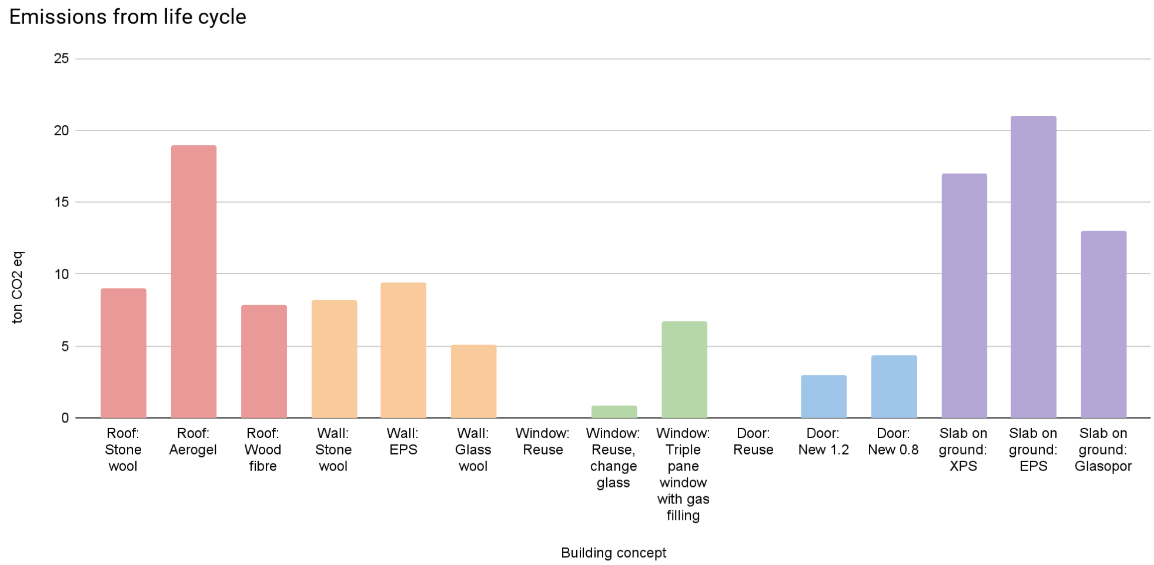

Figure 15: Results of the life cycle assessments.

There are large differences between the emissions from the various concepts. For the roof and wall concepts, these differences are based on the choice of insulation material, as the rest of the construction is the same. The roof concepts are shown in red. A stone wool roof concept will through its life cycle result in 9 tonnes of CO_2 eq of emissions. An Aerogel concept has much higher emissions with 19 tonnes of CO_2 eq. Furthermore, by choosing a wood fiber concept, this will lead to the lowest emissions, with 7.9 tonnes of CO_2 eq. In other words, the emissions for stone wool and wood fiber are quite similar, while Aerogel emits more than twice as much as the other two concepts.

Among the wall concepts, shown in orange, the EPS concept emits the most, with 9.4 tonnes of CO_2 eq during its life cycle. The stone wool concept emits a little less, with 8.2 tonnes of CO_2 eq. Lastly, the glass wool concept emits just over half of the EPS concept, with a value of 5.1 tonnes of CO_2 eq.

When it comes to window concepts, shown in green, there have been difficulties in collecting values. A concept with brand new triple pane windows emits 6.7 tonnes of CO_2 eq. For the reuse concepts, it is difficult to find greenhouse gas emission values, as this depends on what renovation work must be done. The companies doing this renovation job do not conduct life cycle assessments of the renovation process, hence, the value is set to zero. The is not the reality, nonetheless, one can assume that the reuse concepts will have lower emissions than new windows because it reuses parts of or the entire window. Further, the value for the reuse concept when switching to energy glass is a result of the life cycle assessment of the new energy glasses that will replace the product windows. The value will thus be slightly higher than the result shown here because it does not consider the waste renovation process and further emissions through material use, power consumption, etc. during the renovation process. However, the largest emission component, the glass, is included.

The door concepts are shown in blue. For a concept with new doors of a u-value of 1.2 W/(m^{2}K), this will lead to an emission of 3 tonnes of CO_2 eq through the life cycle. For a concept with new doors with a u-value of 0.8 W/(m^{2}K), this value will result in a somewhat higher value, with 4.4 tonnes of CO_2 eq. For the reuse concept for doors, the same difficulties for arose as for the reuse concepts for windows. Therefore, the value is set to zero.

Slab on ground is the part of the building with the highest emissions. These concepts are shown in purple. An EPS concept results in the most emissions, with a value of 21 tonnes of CO_2 eq. Furthermore, XPS and Glasopor have result in, respectively, 17 and 13 tonnes of CO_2 eq.

6.4. Results of Cost Estimates

The results of the cost estimates conducted in Holte SmartKalk are presented in Figure 16. A table of all values can be found in Appendix I: Results of the Cost Estimates Conducted in Holte SmartKalk.

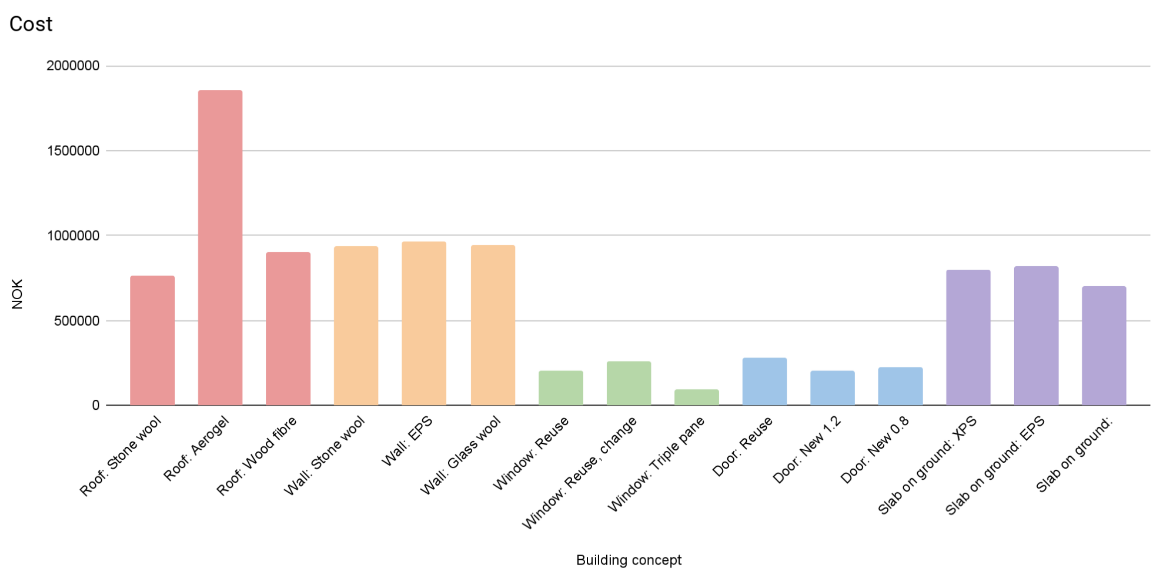

Figure 16: Results of the cost estimations.

As for the difference in emissions, the difference in cost the roof and wall concepts are affected by the choice of insulation. This is because the rest of the construction is the same. For the slab on ground concepts, the insulation material has the greatest impact on the difference in cost.

The diagram shows that the largest cost differences are found among the roof concepts, shown in red. Aerogel is a relatively new material, and it is currently very expensive. For this project, an Aerogel roof concept will cost as much as NOK 1,857,815. This is more than twice as much as the other two concepts. A stone wool concept will cost NOK 761,477 and a wood fiber concept NOK 901,298.

For the wall concepts, shown in orange, the variation is much smaller, and there is very little that separates the cost of the three concepts. A stone wool concept costs NOK 938,299, an EPS concept costs NOK 963,919, and a glass wool concept costs NOK 940,903.

Among the window concepts, shown in green, the reuse concepts are more than twice as expensive as new windows. The prices are retrieved from a renovation company, Walløe & Nilsen, and include the renovation job, materials, and the work with installation (S. Tellevik, personal communication, 18. May 2021). However, the transport from and to the construction site is not included. In other words, these two concepts will be even more expensive than presented here. The recycling concept where the windows are repaired costs NOK 202,395. Furthermore, the recycling concept where the product windows are replaced with energy glass costs NOK 262,395. Lastly, a concept with brand new triple pane windows costs NOK 97,722.

For the door concepts, shown in blue, the renovation job does not make as much of a difference as for the window concepts. Nevertheless, the diagram shows that the recycling concept is the most expensive alternative, with a cost of NOK 277,530. The concepts with new doors with a u-value of 1.2 $W/(m^2K)$ costs NOK 206,060, and new doors with a u-value of 0.8 $W/(m^2K)$ costs NOK 222,530.

For the slab on ground concepts, shown in purple, the EPS concept is the most expensive, with a cost of NOK 822,402. Furthermore, an XPS concept costs NOK 796,984 and a Glasopor concept costs NOK 705,128.

7. Discussion

In this chapter, the concepts are compared, and an attempt is made to find a balance between energy efficiency, CO_2 emissions, and cost. The chosen combination of concepts will be compared with the combination of concepts that is most energy-efficient, the one with the least emissions and the most cost-effective. The recommended concepts will also be compared with the TEK17 concept to see how much energy, emissions and costs are saved in comparison. Furthermore, the balancing process is discussed, including how it affects the outcome and whether such a balancing is appropriate. Then, the sustainability of the recommendations and the project itself is evaluated. Finally, it is determined how these concepts can be implemented in other building projects.

7.1. Balancing

For remodeling, it is easy to determine the difference between saved energy, emissions, and cost of the various concepts, however, it is more difficult to assess which concept is most suited. This depends on the goal of the remodeling. The goal can be a building with the lowest possible energy consumption, the lowest emissions, the most economically efficient, or a combination of all three. For this thesis, the goal is to balance the three factors. Saved money from saved energy and saved emissions from saved energy will also be used in the comparison. Appendix J: Total Costs and Total Emissions shows an overview of all the values used in the comparison.

7.1.1. Roof

The Aerogel concept is the most expensive roof concept. Although it results in the most saved energy, this only makes up NOK 58,230 over 50 years. That is much lower than the difference between the cost of the Aerogel concept and the other two, meaning it will still be the most expensive solution in the long run, even if it is the most energy-efficient. In addition, Aerogel is the concept that emits the most greenhouse gases. Saved energy will lead to 2.32 tonnes of CO_2 eq saved energy over 50 years. This value is also much smaller than the difference between emission from the Aerogel and the other concepts. In other words, Aerogel is the least sufficient concept.

The stone wool and wood fiber concepts are compared through total cost, i.e., cost minus saved cost from saved energy and total emissions, i.e., emissions minus saved emissions from saved energy. Stone wool has a total cost of NOK 761,477 and total emissions of 9 tonnes of CO_2 eq through the life cycle and wood fiber has a total cost of NOK 846,303 and total emissions of 5.71 tonnes of CO_2 eq during the life cycle, see Figure 17.

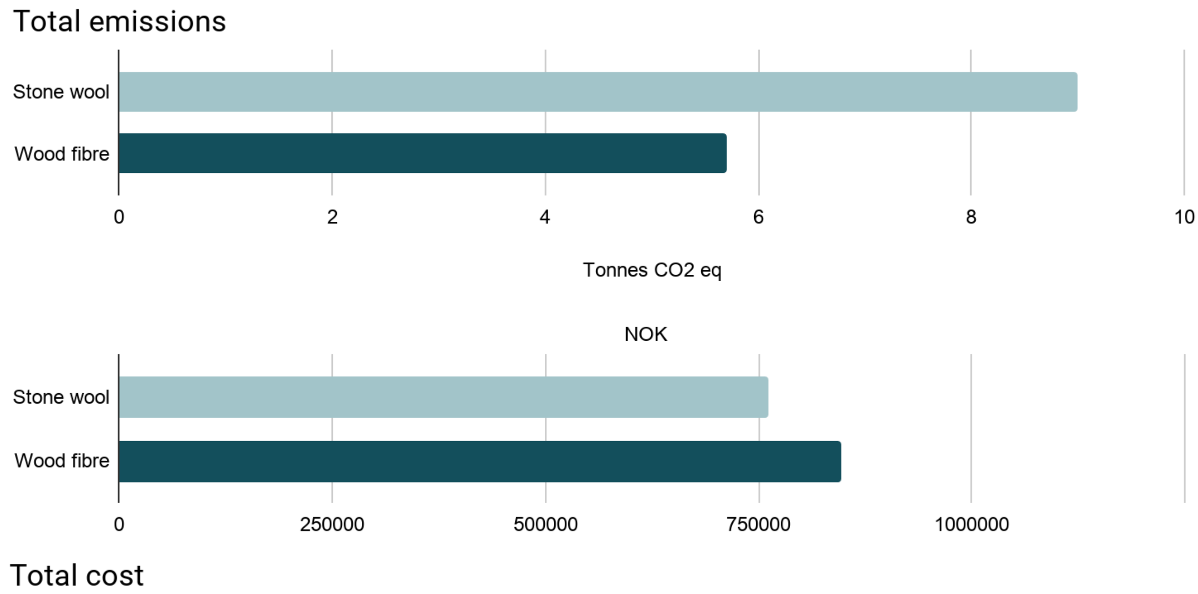

Figure 17: The total cost and total emissions of the stone wool (shown in light blue) and wood fiber (shown in dark blue) concepts.

Fiber is a more energy-efficient concept, which means that the total cost and emissions are lower than the initial values. Since the stone wool concept does not save any energy compared to the TEK17 concept, the total cost and emissions will be the same as initial cost and emissions. The stone wool concept emits 58% more greenhouse gases than the wood fiber concept. Furthermore, although stone wool is somewhat cheaper than wood fiber, the cost of the wood fiber concept is only 11% higher than the cost of the stone wool concept. These differences are illustrated in Figure 17. The difference between emissions is much greater than the difference between cost, thus, it is argued that wood fiber concept is overall the most balanced among the roof concepts.

7.1.2. Wall

The EPS wall concept is the option that saves the least energy, costs the most, and has the highest emissions. It is thus easy to exclude the EPS concept and choose one of the remaining. The stone wool concept and the glass wool concept save the same amount of energy, as they have the same u-value. In total, the stone wool concept costs NOK 841,249 and has total emissions of 4.33 tonnes of CO_2 eq. This includes saved costs and emissions from saved energy. In comparison, the glass wool concept costs a total of NOK 843,853 and emits a total of 1.23 tonnes of CO_2 eq. The glass wool concept emits much less emissions but is in return a bit more expensive than the stone wool concept. The glass wool concept is, however, only 0.3% higher, which makes up very little of the total cost. Thus, the glass wool concept is the most balanced, and best suited for the project.

7.1.3. Window

Among the window concepts, the two reuse concepts have the poorest results for both saved energy and cost. Because they perform so poorly, these concepts require more energy than the TEK17 concept. This affects the total emissions so much, that even though the windows are reused, the total emissions will be higher than for the new window concept. For the reuse concept which only includes repairing the windows, the total cost will be NOK 487,075 and the total emissions will be 11.35 tonnes of CO_2 eq, even though the concept has no initial emissions. Read the justification for why this concept have no emissions in 6.3. In other words, all the emissions come from the extra energy that the building requires by choosing this solution. The emissions that are a result of the required energy during the operational phase is shown in light blue in Figure 18. The additional cost from the operational phase is shown in light blue in Figure 19.

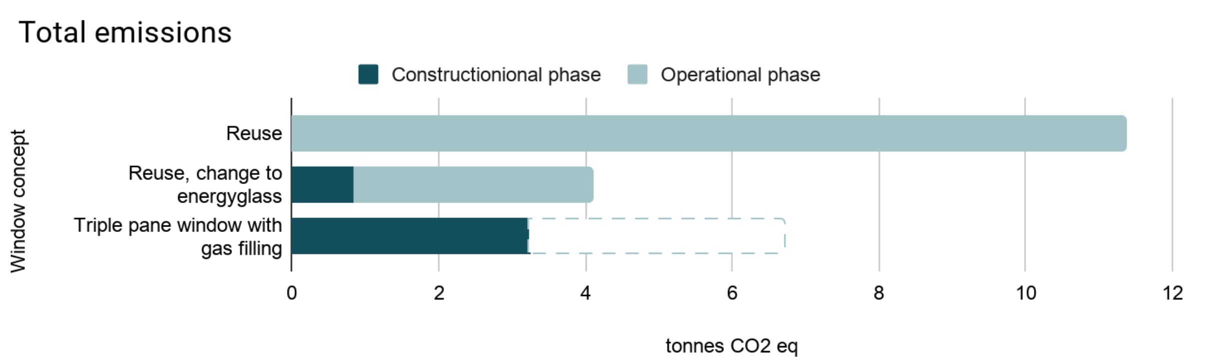

Figure 18: Total emissions of the window concepts. Dark blue represents the cost during constructional phase and light blue the cost during operational phase. The dashed line is saved emissions.

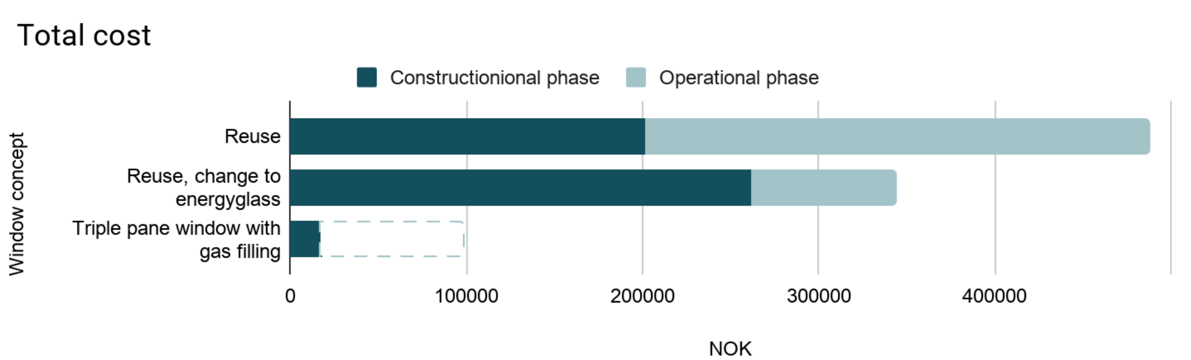

Figure 19: Total cost of the window concepts. Dark blue represents the cost during constructional phase and light blue cost during the operational phase. The dashed line is saved cost.

For the reuse concept with changing to energy glass, the total cost is NOK 343,279 and the total emissions are 4.08 tonnes of CO_2 eq. The cost is high for both reuse concepts, as the renovation work cost more than new windows, and the required energy will result in an additional cost. A concept with new windows, has a total cost of NOK 16,847, and total emissions of 3.48 CO_2 eq. These values are lower than initial cost and emissions because this concept causes the building to save energy. The saved cost and emissions are shown with a dashed line in Figure 18 and Figure 19.

The concept with new windows has the lowest total cost and total emissions. Even though reusing the windows is preferred by the project manager, it is still recommended to choose the concept with new windows, as this is the most energy-efficient and cost-effective concept, in addition to emitting the least emissions in the long run.

7.1.4. Door

For the door concepts, the biggest difference among the factors is found in saved energy. The reuse concept will need 6069 kWh extra energy every year, which leads to a total cost of NOK 406,930 and total emissions of 5.16 tonnes of CO_2 eq. Compared to the concepts with new doors, the concept with doors of u-value 1.2 W/(m^{2}K) will result in a total cost of NOK 206,060 and an emission of 3.00 tonnes of CO_2 eq, and the concept with doors of u-value 0.8 W/(m^{2}K) will results in a total cost of NOK 183,710 and total emissions of 2.85 tonnes of CO_2 eq. This means that the reuse concept has the worst result for all three factors, because it needs so much more energy compared to a TEK17 concept. When comparing the two concepts with new windows, the concept with new doors with a u-value of 0.8 W/(m^{2}K) has the best results when looking at the total values, despite it initially being more expensive and emitting more than the other concept with new windows. Since it saves so much energy, it will still be more sufficient to choose this concept. It is therefore recommended to choose the concept with new doors with a u-value of 0.8 W/(m^{2}K) for this project.

7.1.5. Slab on Ground

For the slab on ground concepts, it is necessary to compare the total cost and the total emissions for all three concepts. This is because none of the solutions has the best or worst results for all three factors only by looking at initial values. The XPS concept will lead to a total cost of NOK 796,984 and total emissions of 17.00 tonnes of CO_2 eq. Furthermore, the EPS concept will lead to a total cost of NOK 757,702 and total emissions of 18.42 tonnes of CO_2 eq. Finally, the Glasopor concept will lead to a total cost of NOK 669,543 and total emissions of 11.58 tonnes of CO_2 eq. By looking at these values, it is easy to see that Glasopor is the concept that will be the most balanced concept in the long run, as it has the lowest values for both total cost and total emissions. It is therefore recommended to choose the Glasopor concept.

7.2. Comparing the Chosen Combination of Concepts with Extreme Combinations

To better assess whether the chosen combination of concepts is really balanced or not, three extreme combinations have been made. These are combinations of concepts, where only one factor has been emphasized. That is, for the combination emphasizing cost, all the concepts with the lowest cost have been included. The same goes for the combinations emphasizing the other two factors. Table 7 shows a presentation of the values for the extremes of the concept combinations.

Table 7: The chosen concepts in comparison with extreme combinations. The left column shows the emphasized factor and what concepts are included in the combination. The underlined concepts are also a part of the chosen combination. The value of the factor that has been emphasized is marked in bold writing and with a blue background.

	Saved energy per year	Cost	Emissions
The emphasized factor and concepts included in the combination	kWh	NOK	tonnes CO_2 eq
Saved energy per year Roof: Aerogel Wall: Glass wool Window: New triple pane Door: New 0.8 Slab on ground: EPS	**15932**	3 941 372	56.2
Cost Roof: Stone wool Wall: Stone wool Window: New triple pane Door: New 1.2 Slab on ground: Glasopor	7587	**2 708 686**	39.9
Emissions Roof: Wood fiber Wall: Glass wool Window: Reuse Door: Reuse Slab on ground: Glasopor	-2124	3 027 254	**26.0**
The chosen combination of concepts Roof: Wood fiber Wall: Glass wool Window: New triple pane Door: New 0.8 Slab on ground: Glasopor	11988	2 867 582	37.1

The underlined concepts are a part of the recommended concepts. The values of the table show that the chosen combination of concepts has the second-best values for all three factors compared to the extreme combinations. For saved energy per year and cost, the selected combination of concepts is not far from the values of the extreme combinations. The factor that has the most significant difference between the extreme combination and the chosen combination is emissions. For this extreme combination, the reuse concepts have been included for both window and door. These concepts have no value for emissions and are therefore set to zero. Nevertheless, these concepts will result in greenhouse gas emissions, so the value for emissions will be higher than zero. Thus, the value of emissions for the recommended concepts would be closer to the combination emphasizing emissions in real life.

For the combination where saved energy per year is emphasized, three of five of the concepts from the recommended combination have been used, for the combination where cost is emphasized, two of five of the concepts have been used, and for the combination where emissions are emphasized, three of five of the concepts have been used. In total, all the selected concepts have been used in at least one of the extreme combinations. This indicates that the chosen combination represents a good balance between the three factors.

7.3. The Balancing Process

The balancing process carried out in this thesis is not entirely uncontroversial. The balancing is conducted based on the three concepts that have been chosen for each building part. Although several concepts have been investigated as part of the preparatory work of the thesis, there are many more suitable concepts which have not been explored. In other words, the choice of the three concepts lays the foundation for the entire balancing process.

Referring to the research question, on how the balancing of energy efficiency, CO_2 emissions, and costs will impact the remodeling choices made for the building structure of the UNESCO World Heritage Centre in Aurlandsvangen, there are several ways that the balancing may affect the outcome. For this thesis, choices have been made to weight the factors equally, in order to find concepts that are balanced between the three factors. When carrying out the balancing, one can end up with a concept that has mediocre results for all three factors. For this thesis such a concept will be preferred rather than a concept that has good results for one of the factors and bad for the remaining two. In such a case, it is relevant to debate whether a concept with good results for one of the factors and bad for the others, or a concept that has mediocre results for all the factors, is the better solution.

What choice would be better depends on what the project wants to achieve. Energy efficiency and low emissions are attributes that should be an ambition for every project, thus these are two important factors. The cost of a project does not matter to the rest of the world in the same way as high energy consumption and high emissions do, through global warming. For some projects, finances may not be a problem as they have more capital, and they are thus able to spend more money to get more energy-efficient and low-emission solutions. In these cases, it is relevant to weight cost lower than the other two factors. For some projects, finances will be scarce, and, in such cases, a completely balanced concept will be more appropriate than a concept that prefers only low cost. This is because that would result in a cost-effective building that has high energy consumption and large emissions. This is by no means desirable, and it is thus better to utilize concepts that are equally balanced.

A low cost is prioritized over environmentally friendly solutions in many scenarios (Hayles & Kooloos, 2008). This thesis attempts to help solve this issue, by finding a balance between the three factors. In this thesis, cost is still central, but in addition to the investment cost, the focus is put on the long-term cost. Energy-efficient solutions are often neglected because such solutions have high investment costs (Hayles & Kooloos, 2008). Nevertheless, several examples show that in the long run, it is economically feasible to choose energy-efficient solutions (UngEnergi, 2017). It is therefore argued that this assessment of cost is appropriate when selecting concepts. It is also possible to acquire economic funding from various organizations in Norway, such as Enova, by selecting energy-efficient solutions (Enova, n.d.). This can make the building even more cost-effective. Such compensations are not included in the assessments, but it is still worth mentioning.

For many projects, it is appropriate to prioritize energy efficiency. This is because; if the building is energy-efficient, it will lead to lower costs and emissions in the long run. This has been implemented through total emissions and total cost. In addition, energy requirements will be reduced in the future, thus, it is future-oriented to focus on energy efficiency in construction projects. For precisely that reason it could have been convenient to favor energy efficiency in this thesis. Nevertheless, choices are made to find a balance, specifically to understand how such a balance affects the concept choices.

To prevent scenarios where the outcome of the balancing having mediocre results, it is, nevertheless, the choices made in advance of the balancing that are the most impactful. It is therefore essential to make careful choices when selecting concepts for each building part prior to the balancing. The comparison shows that several of the concepts that have been chosen for the recommended combination of concepts are also included in the extreme combinations. This indicates that the choices made before the balancing have been appropriate, and that the chosen concepts have satisfactory results for all factors.

7.4. Sustainability

The balancing has been an attempt to meet the Sustainable Development Goals and thus create sustainable remodeling solutions. When assessing whether the balancing results in sustainable concepts, it is useful to utilize the relevant SDGs. Nevertheless, the SDGs are very general, and it is more appropriate to look at goals specifically developed for construction projects. The quality principles from Bygg21 have been prepared with the intention of fulfilling the SDGs and are thus a good indicator of whether sustainability has taken place or not (Bygg21, 2018a). The same applies to the green building certification system BREEAM, which aims to promote more sustainable buildings (Norwegian Green Building Council, 2016). Therefore, these will primarily be used as justification for whether the concept choices and the balancing process is sustainable or not. Relevant SDGs will also be mentioned where it is appropriate.

Quality principle 8 from Bygg21 recommends reducing the total need to buy energy. They recommend doing this by first reducing energy needs, and then choosing solutions that produce energy locally (Bygg21, 2018a). This has been incorporated with the energy efficiency factor, where the goal is to find concepts leading to reduced energy need. Furthermore, this is in line with SDG 9, which promotes for buildings to utilize energy in a cautious way, as it leads to a more sustainable infrastructure (Department of Economic and Social Affairs, n.d.-e).

Both quality principle 8 and 10 focus on lifetime costs and seeing costs as something more than an investment. They recommend doing this to avoid choosing inadequate energy solutions. Both resources and costs related to day-to-day operations and the long term perspective are equally important and a combination will lead to the highest possible economic value for all parties involved (Bygg21, 2018a). This is also important for BREEAM, which focuses on informing about the benefits of seeing sustainability in a life cycle perspective and recommends comparing cost through the building's life with the investment cost (Norwegian Green Building Council, 2016). This has been implemented by using saved energy, to determine how much cost the building will save over 50 years in electricity expenses. This gives a better assessment of the profitability of a concept and provides a more realistic picture of the actual costs of choosing a concept. Furthermore, this promotes working towards SDG 9, 11 and 12, as seeing the building in a life perspective will lead to the choice of more sustainable solutions which in turn leads to a more sustainable buildings (Department of Economic and Social Affairs, n.d.-e, n.d.-f, n.d.-g).

Quality principle 9 recommends choosing building products with low greenhouse gas emissions, something that also goes hand in hand with SDG 12, which promotes reducing material footprint, for a more sustainable use of resources (Bygg21, 2018a; Department of Economic and Social Affairs, n.d.-g). In BREEAM, the climate impact is central, where emissions from greenhouse gases are a focal point. BREEAM is committed to promoting the benefits of choosing solutions that have a low climate impact through the life cycle (Norwegian Green Building Council, 2016). It is therefore essential to find a solution with low initial emissions that also leads to low emissions during its life cycle. In the balancing part, initial emissions and saved emissions from saved energy have been merged, to easier evaluate the total impact from each individual concept. This has been done to ensure the most sustainable balancing possible. Even though initial costs have been used instead of life cycle cost, the focus on saved costs and saved emissions from saved energy means that the balancing looks beyond just investment costs.

Two of the chosen concepts, wood fiber roof and Glasopor slab on ground, are suitable for a low-energy building, and three of the chosen concepts, glass wool walls, new triple pane windows and doors with a u-value of 0.8 W/(m^2/K), are suitable for a passive building. Such energy-efficient buildings are seen as more sustainable compared to buildings meeting the minimum TEK17 requirements (Norwegian Ministry of Local Government and Regional Development, 2010). Concerning BREEAM-NOR certification, it is difficult to confirm whether this is achievable for the case building, as it is strongly dependent on the energy supply and energy system (Norwegian Green Building Council, 2016). This is not considered in this thesis; however, the two accompanying master's theses have chosen solutions for these systems. Nevertheless, the results show that with the selected results, the building saves 6% energy compared to the minimum requirement of TEK17. This gives one point in BREEAM-NOR (Norwegian Green Building Council, 2016). When the energy system is included in the assessment, saved energy will probably be even higher, resulting in more points. Furthermore, BREEAM-NOR gives points based on the sustainability of the materials (Norwegian Green Building Council, 2016). Since the focus is on choosing materials with low greenhouse gas emissions, there are also points to gain in this category. Whether a BREEAM-NOR certification is achievable must be assessed in a further investigation.

The most decisive factor for whether this will be a sustainable building or not, is not whether the concepts that have been chosen in this thesis are sustainable, but whether the project is sustainable in itself. The choices have been made based on the preliminary project, which has set clear guidelines for the initial concept selection. Since the design is already determined, the choices are made to fit this design. In the preliminary project, focus has been placed on 9 of the Sustainable Development Goals, and the goals are to be used as a basis for the development of the building (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020). As a whole, the project promotes working towards several of these SDGs. For instance, the center will cause locals and tourists to meet. In this way, they can exchange knowledge and socialize. In addition, the center will lead to increased knowledge for those who visit it. This helps working towards SDG 3 and 4 (Department of Economic and Social Affairs, n.d.-b, n.d.-c). Furthermore, the center has great ambitions to use innovative energy solutions that are renewable, helping the work towards SDG 7 (Department of Economic and Social Affairs, n.d.-d). Nevertheless, there is little information on how these goals are to be achieved in concrete terms. It is listed as a proposal for further work to specify how the center will work with SDGs. This is an important part of the work towards a sustainable project, not only because it will show what the center plan on doing. But also, because it will result in the project group being more informed on what it takes to meet the indicators, and work towards the Sustainable Development Goals. By increased knowledge, they will better be able to create a holistic sustainable project.

For this thesis, it is nevertheless the building that is in center, and it is therefore natural to assess the sustainability of the building itself. In the preliminary project, Sustainable Development Goal 12 is brought forward, because of the focus being on using the existing buildings rather than demolishing and building new (Nærøyfjorden Verdensarvpark & Aurland Kjøle- og Fruktlager SA, 2020). Even if the building is to be reused, a glass facade will be built, that covers more than half of the building. A UNESCO World Heritage Centre is a building that stands out in the international community and should therefore be future oriented when it comes to technical building solutions. The glass facade will lead to the building being modernized, and for the existing building will be clearly visible in the landscape, even if large parts of the original building are covered. It is thus a satisfying solution when as regards to visuality and attracting tourists. Nevertheless, glass has a high climate impact, and it is not energy-efficient, as the solution will generate high costs for the project. It can therefore be questioned whether the building design really is sustainable when such solution is part of the design. For this discussion, it is relevant to determine what is most important for the project; the sustainability perspective or to attract tourists. The best solution would be a building design that manages to combine these two aspects. As of now, this is not the case, therefore, more work should be done to create a holistic design that meets all criteria.

7.5. Transferability to Other Projects

The existing building in Aurlandsvangen currently has few rooms that are heated daily. The building is leaking, and there is air circulation through the building, especially on the third floor and in the attic. This means that the building requires a comprehensive rehabilitation if the building is to be used all year round for the desired function. Furthermore, the goal of this remodeling is ambitious, as it concerns a very special building project. This must be considered if any of the solutions are to be implemented in other projects. It can thus be difficult to implement the chosen concepts directly to other buildings. Nevertheless, the thesis provides good insight into emissions, cost, and energy efficiency of the various materials, which can be sufficient for other projects. In addition, the thesis not only presents the selected concepts, but also the concepts that were opted out. This provides several possible options for other project, as the opted out concepts may be better suited for other projects than the concepts that have been chosen for the case building.

8. Recommendation and Conclusion

Reducing greenhouse gas emissions from the construction industry, by increasing energy efficiency and utilizing low-emission materials, is essential to achieve national and international climate goals. As cost is the decisive factor for many projects, cost cannot be neglected when selecting building solutions. In this thesis, the aim is to find a balance between energy consumption, CO_2 emissions and cost, and determine how this balancing affects the choice of concepts. Furthermore, there is great potential for improving the existing building stock regarding environmental considerations, and the thesis therefore concerns the remodeling of an old concrete building into a UNESCO World Heritage Centre.

The energy calculations show a great potential for increasing the energy efficiency of the case building beyond TEK17. The results show that in the long run, energy-efficient remodeling is profitable, and it is therefore recommended to choose solutions that have an energy need significantly lower than the energy requirements of TEK17.

Based on the balancing process, it is recommended to choose the wood fiber concept for the roof, the glass wool concept for the wall, new windows, new doors with a u-value of 0.8 $W/(m^2K)$ and the Glasopor concept for slab on ground. This will result in 11988 kWh saved energy each year compared to the TEK17 concept, an emission of 37.1 tonnes of CO_2 eq and a cost of NOK 2,867,581. If saved energy is considered, the total cost will be 2,560,256 and the total emissions will be 24.85 tonnes of CO_2 eq. These values are likely to be even lower in reality, as the building is expected to exist longer than the chosen time period, which is set to 50 years, and because the grid rent is not included.

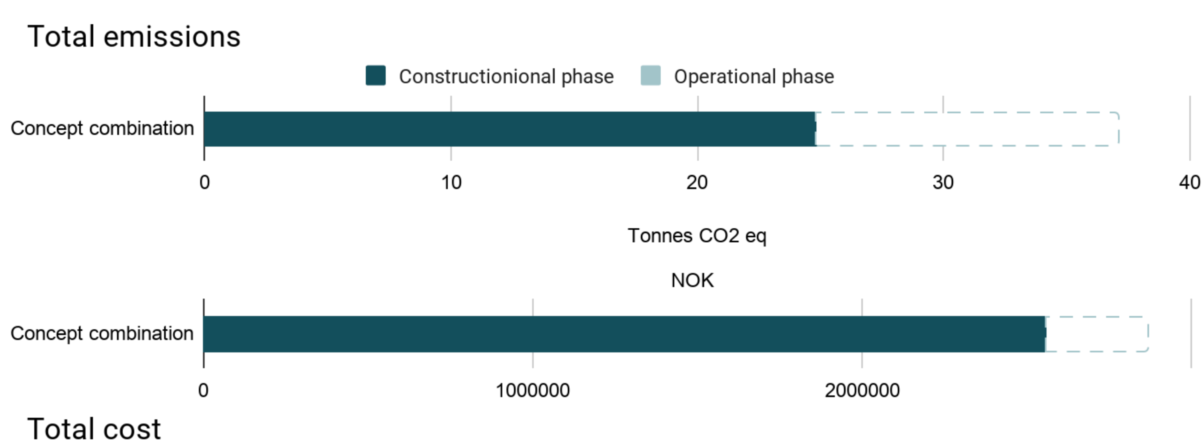

Figure 20: Total emissions and cost of the recommended combination of concepts. Dark blue represents the emissions/cost during constructional phase and the light blue dashed line is saved emissions/cost during the operational phase.

In this thesis, it has been chosen to weight all the factors equally. It could be relevant to prioritize energy efficiency above the other factors, because energy-efficient buildings lead to lower emissions and lower costs over a longer period of time. Nevertheless, choices have been made to weight the factors equally, to try to find a balanced concept and investigate how the balancing will affect the choices. For some projects, cost will not be so important, because they have the funds to build without thinking about finances. For projects where finances are important, it is essential that costs are not favored above energy efficiency and CO_2 emissions. In such cases, a perfectly balanced concept will be the most sustainable, to avoid buildings with high climate impact.

Nevertheless, the outcome of the balancing process is most affected by the choices that were made prior to the balancing. Such balancing does not necessarily lead to concepts that are well balanced if the foregoing decisions are not well thought through. All the selected concepts are used in at least one of the extreme concept combinations, which indicates that the chosen combination represents a thorough balancing of energy efficiency, CO_2 emissions and cost.

By incorporating saved cost and saved emissions from saved energy, it is possible to see the concepts as more long term than just looking at investment cost and initial emissions. This goes hand in hand with the quality principles from Bygg21 and BREEAM's recommendations. Nevertheless, such an assessment is not entirely complete, as end-of-life is not included in the results. However, the results sufficient for its purpose, as they are primarily intended for comparison of the concepts.

Furthermore, it is highly relevant to discuss whether the project is sustainable in itself. The project, as a whole, meets several aspects of the Sustainable Development Goals, however effort should be done to develop a more sustainable building design. In particular, the glass façade is a hinderance for the building's sustainability. It will generate high emissions, it is not energy-efficient, and it will lead to high costs for the project. For the detailed engineering, measures should be taken to a find more future-oriented and environmentally sustainable building design, that also will manage to attract tourists. Nevertheless, the project is still in the early stages, and there is still room for change, to ensure the inclusion of more sustainable solutions to meet all the criteria.

9. The Full Concept Recommendation

This thesis has been conducted in connection to a larger project, which includes three master's theses. In this chapter, the conclusions from the three theses are presented, in desire to create a complete concept recommendation. Advice for implementation into the project will also be discussed. This chapter has been written in collaboration with Halldór Þrastarson and Sylvi Brækken.

9.1. Study Conducted by Berit

UNESCO World Heritage Centre in Aurlandsvangen: Balancing Energy Efficiency, CO_2 Emissions and Costs when Remodeling the Building Structure

For the building structure, it is recommended to choose the 400 mm wood fiber concept for the roof, the 300 mm glass wool concept for the wall, new triple pane windows with gas filling, new doors with a u-value of 0.8 W/(m2K) and the 800 mm Glasopor concept for slab on ground. This will result in 11988 kWh saved energy each year compared to the TEK17 concept, an emission of 37.1 tonnes of CO2 eq and a cost of NOK 2,867,581. When considering saved emissions and saved cost from saved energy, this combination of concepts will result in a total cost of 2,560,256 and total emissions of 24.85 tonnes of CO2 eq. These concepts were chosen as a result of the balancing process that was carried out, in an attempt to balance energy efficiency, CO2 emissions and cost.

9.2. Study Conducted by Halldór

Keeping Old Buildings Green with Relevant Technology - A Case Study of UNESCO World Heritage Center, Nærøyfjordområdet

The recommended Building Management system (BMS) for the building is Model Predictive Control (MPC). This control method uses a model to predict future states of the building and can therefore reduce energy use by 15-20%. MPC has great potential to act on external disturbances and includes for example weather forecasts in the model and can therefore adapt to future climate change. This method is complicated and expensive, but it is believed that this will pay off in the long run.

The Water-Thermal Energy Production System (WEPS) was chosen as an energy source for the Heating Ventilation and Air Conditioning (HVAC) system. This system uses the least amount of energy, has the lowest CO2 emissions of the systems that were researched. However, WEPS costs significantly more than the other systems. The practical pros and cons as well as the low energy use and CO2 emissions out value the other systems and therefore this system was chosen.

9.3. Study Conducted by Sylvi

The recommended combination of energy technologies is a combination with a water-to-water heat pump, flat plate collectors and standard solar panels. This combination gave energy savings of 99 MWh/year, emissions of 254.8 tonnes of CO2 eq, an initial cost of NOK 1,178,383 and a net present value of NOK -295,339.

9.4. Implementation Into the Project

When implementing these recommendations to the project, it is important to be aware that the recommended WEPS system and the recommended combination of energy technologies does not correlate perfectly. The WEPS system in Halldór's thesis is covering 90% of the energy need, while the water-to-water heat pump in Sylvi's thesis is covering 60%, while the solar thermal collector system is covering 30%. It is therefore not possible to implement all the recommended solutions. Nevertheless, both these recommendations include a water-to-water heat pump, which indicates that these recommendations should be considered. With proper control methods for these systems, such as the MPC, the efficiency of the system output can be increased by 15-20%.

All the concepts must be seen in relation to each other, as the energy consumption of the various concepts will impact each other. It is all a part of a bigger system that comprises the whole building, where many factors are working simultaneously. That is, if one recommendation is fully implemented, then that affects the energy consumption of the other recommendations. Thus, when implementing the recommendations, it is possible to opt out parts of the recommendations, and still end up with a highly efficient building. Furthermore, more concepts were considered and assessed than what is presented in this recommendation. These are also concepts that are relevant for the building. More information can be found in the respective master theses:

Halldór Þrastarson. (2021). *Keeping Old Buildings Green with Relevant Technology - A Case Study of UNESCO World Heritage Center, Nærøyfjordområdet*

Sylvi Brækken. (2021). *Weighing the Importance of Energy Savings, CO_2 Emissions and Costs When Implementing Renewable Energy Technologies. Case: Nærøyfjorden UNESCO World Heritage Centre.*

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Appendix A: Illustrations of the Concept Building


sakte

Appendix B: Example of u-value Calculation Conducted in Microsoft Excel

U-value calculation for a construction with inhomogeneous layers: Wood fiber wall concept.

Upper limit value

Layer	Thickness d [m]	Thermal conductivity λ [W/mK]	Thermal resistance R=d/λ [m2K/W]	R (Fraction A)	R (Fraction B)
Internal surface resistance Rsi			0,10	0,10	0,10
Ceiling (plasterboard)	0,0125	0,06	0,21	0,21	0,21
Vapor barrier	0,00015	0,03	0,01	0,01	0,01
Insulation: wood fibre	0,4	0,038	10,53	10,53	
Rafters	0,396	0,13	3,05		3,05
Wind barrier	0,001	0,03	0,03	0,03	0,03
Ventilation 48x48					
Suspended ceiling					
Roofing					
External surface resistance Rse			0,10	0,10	0,10
SUM	0,41			10,97	3,49

Area share

	Thickness d [m]	Length along the wall [m]	Area [m2]	Area share
Fraction A	0,41	0,55	0,23	0,92
Fraction B	0,41	0,05	0,02	0,08
SUM			0,25	1,00

R_{upper}	9,37

Varmemotstand for legeringsmateriale 1

Material	Thermal conductivity λ [m2K/W]
Insulation: wood fibre	10,53
Rafters	3,05
R_{alloy}	8,80

Lower limit value

Layer	Thickness d [m]	Thermal conductivity λ [W/mK]	Thermal resistance R=d/λ [m2K/W]
Internal surface resistance Rsi			0,10
Ceiling (plasterboard)	0,0125	0,06	0,21
Vapor barrier	0,00015	0,03	0,01
Alloying material			8,80
Wind barrier	0,001	0,03	0,03
External surface resistance Rse			0,1
R_{lower}			9,24

Correction supplement

ΔU_g (Unintentional air gaps penetrating the insulating layer)	
ΔU_r (Precipitation on inverted roofs)	
ΔU_f (Mechanical fasteners puncturing the insulation)	
ΔU_{total}	0

U-value	0,107

U-value calculation for a construction with homogeneous layers: XPS slab on ground concept.

Total thermal resistance

Layer	Thickness d [m]	Thermal conductivity λ [W/mK]	Thermal resistance R=d/λ [m2K/W]
Internal surface resistance R_{si}			0,17
Draining masses	0,2	0,21	0,95
Radon barrier	0,0004	0,03	0,01
Insulation: XPS	0,15	0,034	4,41
Moisture barrier	0,0002	0,03	0,01
Screed	0,05	2	0,03
External surface resistance R_{se}			0,04
R_{total}	0,401		5,62

Correction supplement

ΔU_g (Unintentional air gaps penetrating the insulating layer)	
ΔU_r (Precipitation on inverted roofs)	
ΔU_f (Mechanical fasteners puncturing the insulation)	
ΔU_{total}	0

U-value	0,18

Appendix C: Energy Simulation in SIMIEN

This energy simulation shows an evaluation against TEK17 for the TEK17 concept. In SIMIEN, the u-value of the glass façade is included as part of the u-value of the wall. This means that the wall in SIMIEN has a much lower u-value than the concrete wall has by itself. Thus, the results from the SIMIEN simulation show that the walls do not meet the u-value requirements of TEK17. The U-value requirements for glass facades are not defined in TEK17, and there are varying practices for how this is solved in the industry. In this thesis it is assumed that the u-value requirements of the glass façade are set in the same way as the u-value requirements for windows, with a maximum value of 1.2 W/(m^2K) (Bjørnulf & Bryn, 2017; Enova, 2007). With a u-value of 0.7 W/(m^2K), the glass façade will thus meet the u-value requirement for windows.

SIMIEN

Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 11:10 8/6-2021
Programversjon: 6.016
Simuleringsansvarlig: Berit, Halldor & Sylvi
Firma: Undervisningslisens
Inndatafil: C:\Users\583256\OneDrive - Høgskulen på Vestlandet\Desktop\Concept.smi
Prosjekt: UNESCO World heritage center in Aurland
Sone: Concept building;

Resultater av evalueringen	
Evaluering av	Beskrivelse
Energiramme	Bygningen tilfredsstiller energirammen ihht. §14-2 (1)
Minstekrav	Bygningen tilfredsstiller ikke minstekravene i §14-3
Luftmengder ventilasjon	Luftmengdene tilfredsstiller minstekrav gitt i NS3031:2014 (tabell A.6)
Energiforsyning	Fossilt brensel benyttes ikke i oppvarmingsanlegget (§14-4)
Samlet evaluering	Bygningen tilfredsstiller ikke byggeforskriftenes energikrav

Energiramme (§14-2 (1), samlet netto energibehov)	
Beskrivelse	Verdi
1a Beregnet energibehov romoppvarming	56,6 kWh/m²
1b Beregnet energibehov ventilasjonsvarme (varmebatterier)	14,0 kWh/m²
2 Beregnet energibehov varmtvann (tappevann)	10,0 kWh/m²
3a Beregnet energibehov vifter	15,7 kWh/m²
3b Beregnet energibehov pumper	1,1 kWh/m²
4 Beregnet energibehov belysning	23,0 kWh/m²
5 Beregnet energibehov teknisk utstyr	2,9 kWh/m²
6a Beregnet energibehov romkjøling	0,0 kWh/m²
6b Beregnet energibehov ventilasjonskjøling (kjølebatterier)	6,6 kWh/m²
Totalt beregnet energibehov	130,0 kWh/m²
Forskriftskrav netto energibehov	130,0 kWh/m²

Minstekrav (§14-3)		
Beskrivelse	Verdi	Krav
U-verdi yttervegger [W/m²K]	0,49	0,22
U-verdi tak [W/m²K]	0,34	0,18
U-verdi gulv mot grunn og mot det fri [W/m²K]	0,12	0,18
U-verdi glass/vinduer/dører [W/m²K]	1,2	1,2
Lekkasjetall (lufttetthet ved 50 Pa trykkforskjell) [luftvekslinger pr time]	0,8	1,5

SIMIEN

Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 11:10 8/6-2021
Programversjon: 6.016
Simuleringsansvarlig: Berit, Halldor & Sylvi
Firma: Undervisningslisens
Inndatafil: C:\Users\583256\OneDrive - Høgskulen på Vestlandet\Desktop\Concept.smi
Prosjekt: UNESCO World heritage center in Aurland
Sone: Concept building;

Energiforsyning (§14-4 (1))	
Beskrivelse	Verdi
Bruker fossilt brensel til oppvarming	Nei

Krav til formålsdelte energimålere (§14-2 (6))
Yrkesbygninger skal ha formålsdelte energimålere for oppvarming og tappevann.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

Krav til isolering av rør, utstyr og kanaler (§14-3 (2))
Rør, utstyr og kanaler som er knyttet til bygningens varmesystem skal isoleres. Isolasjonstykkelsen skal være økonomisk optimal beregnet etter norsk standard eller en likeverdig europeisk standard.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

Krav til energifleksible varmeløsninger (§14-4 (2))
Bygning over 1000 m2 oppvarmet bruksareal skal ha energifleksible varmesystemer og tilrettelegges for bruk av lavtemperatur varmeløsninger.
Dette er ikke en del av evaluering i SIMIEN og må derfor dokumenteres på annen måte.

SIMIEN

Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 11:10 8/6-2021
Programversjon: 6.016
Simuleringsansvarlig: Berit, Halldor & Sylvi
Firma: Undervisningslisens
Inndatafil: C:\Users\583256\OneDrive - Høgskulen på Vestlandet\Desktop\Concept.smi
Prosjekt: UNESCO World heritage center in Aurland
Sone: Concept building;

Energibudsjett reelle verdier (§14-2 (5))		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	66836 kWh	44,1 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	23780 kWh	15,7 kWh/m²
2 Varmtvann (tappevann)	25509 kWh	16,8 kWh/m²
3a Vifter	28100 kWh	18,5 kWh/m²
3b Pumper	640 kWh	0,4 kWh/m²
4 Belysning	27248 kWh	18,0 kWh/m²
5 Teknisk utstyr	41925 kWh	27,6 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	2073 kWh	1,4 kWh/m²
Totalt netto energibehov, sum 1-6	216111 kWh	142,5 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	124991 kWh	82,4 kWh/m²
1b El. til varmepumpesystem	28096 kWh	18,5 kWh/m²
1c El. til solfangersystem	817 kWh	0,5 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
6. Annen energikilde	0 kWh	0,0 kWh/m²
7. Solstrøm til egenbruk	-0 kWh	-0,0 kWh/m²
Totalt levert energi, sum 1-7	153904 kWh	101,5 kWh/m²
Solstrøm til eksport	-0 kWh	-0,0 kWh/m²
Netto levert energi	153904 kWh	101,5 kWh/m²

SIMIEN

Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 11:10 8/6-2021
Programversjon: 6.016
Simuleringsansvarlig: Berit, Halldor & Sylvi
Firma: Undervisningslisens
Inndatafil: C:\Users\583256\OneDrive - Høgskulen på Vestlandet\Desktop\Concept.smi
Prosjekt: UNESCO World heritage center in Aurland
Sone: Concept building;

Dokumentasjon av sentrale inndata (1)

Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	869	
Areal tak [m²]:	473	
Areal gulv [m²]:	497	
Areal vinduer og ytterdører [m²]:	120	
Oppvarmet bruksareal (BRA) [m²]:	1517	
Oppvarmet luftvolum [m³]:	5547	
U-verdi yttervegger [W/m²K]	0,49	
U-verdi tak [W/m²K]	0,34	
U-verdi gulv [W/m²K]	0,12	
U-verdi vinduer og ytterdører [W/m²K]	1,20	
Areal vinduer og dører delt på bruksareal [%]	7,9	
Normalisert kuldebroverdi [W/m²K]:	0,09	
Normalisert varmekapasitet [Wh/m²K]	70	
Lekkasjetall (n50) [1/h]:	0,80	
Temperaturvirkningsgr. varmegjenvinner [%]:	82	

Dokumentasjon av sentrale inndata (2)

Beskrivelse	Verdi	Dokumentasjon
Estimert virkningsgrad gjenvinner justert for frostsikring [%]:	81,9	
Spesifikk vifteeffekt (SFP) [kW/m³/s]:	1,50	
Luftmengde i driftstiden [m³/hm²]	8,12	
Luftmengde utenfor driftstiden [m³/hm²]	2,00	
Systemvirkningsgrad oppvarmingsanlegg:	2,08	
Installert effekt romoppv. og varmebatt. [W/m²]:	80	
Settpunkttemperatur for romoppvarming [°C]	19,9	
Systemeffektfaktor kjøling:	2,50	
Settpunkttemperatur for romkjøling [°C]	22,0	
Installert effekt romkjøling og kjølebatt. [W/m²]:	30	
Spesifikk pumpeeffekt romoppvarming [kW/(l/s)]:	0,00	
Spesifikk pumpeeffekt romkjøling [kW/(l/s)]:	0,00	
Spesifikk pumpeeffekt varmebatteri [kW/(l/s)]:	0,50	
Spesifikk pumpeeffekt kjølebatteri [kW/(l/s)]:	0,60	
Driftstid oppvarming (timer)	11,0	

SIMIEN

Evaluering Energiregler 2016

Simuleringsnavn: Evaluering
Tid/dato simulering: 11:10 8/6-2021
Programversjon: 6.016
Simuleringsansvarlig: Berit, Halldor & Sylvi
Firma: Undervisningslisens
Inndatafil: C:\Users\583256\OneDrive - Høgskulen på Vestlandet\Desktop\Concept.smi
Prosjekt: UNESCO World heritage center in Aurland
Sone: Concept building;

Dokumentasjon av sentrale inndata (3)		
Beskrivelse	Verdi	Dokumentasjon
Driftstid kjøling (timer)	24,0	
Driftstid ventilasjon (timer)	11,0	
Driftstid belysning (timer)	11,0	
Driftstid utstyr (timer)	11,0	
Oppholdstid personer (timer)	11,0	
Effektbehov belysning i driftstiden [W/m²]	8,00	
Varmetilskudd belysning i driftstiden [W/m²]	8,00	
Effektbehov utstyr i driftstiden [W/m²]	1,00	
Varmetilskudd utstyr i driftstiden [W/m²]	1,00	
Effektbehov varmtvann på driftsdager [W/m²]	1,60	
Varmetilskudd varmtvann i driftstiden [W/m²]	0,00	
Varmetilskudd personer i oppholdstiden [W/m²]	3,20	
Total solfaktor for vindu og solskjerming:	0,38	
Gjennomsnittlig karmfaktor vinduer:	0,09	
Solskjermingsfaktor horisont/utspring (N/Ø/S/V):	1,00/1,00/1,00/1,00	

Inndata bygning	
Beskrivelse	Verdi
Bygningskategori	Kulturbygg
Simuleringsansvarlig	Berit, Halldor _Sylvi
Kommentar	

Appendix D: CO_2 Estimates Conducted in One Click LCA for the Slab on Ground Concepts

Ressurs	Mengde				CO_2e	Transport, kilometer		Transport, leg2, kilometer		Levetid	Lokalisering
Gulv på grunn - Glasopor	0.54	m			13t - 9%	Data etter komponent		0		Data etter komponent	Data etter komponent
Radon- og fuktmembran for byggep	498	m^2 x	1,2	mm	1,4t - 0,97%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Dampsperre i plast, 0.2 mm (Tomm	498	m^2 x	0.2	mm	0,22t - 0,2%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Ferdigbetong, normal styrke, generi	498	m^2 x	50	mm	6,4t - 5%	70	Betongbil, omtrent 8m3	0	Betongbil, omtrent 8m3	Fast	Norge IEA2018
Cellulært glassaggregat, 10-60 mm,	498	m^2 x	800	mm	3,1t - 2%	70	Dumper, 19 tonns	0	Dumper, 19 tonns	Fast	Lokal, intet behov
Avrettingsmasse, C25, 10-60 mm, 1.7	498	m^2 x	10	mm	1,5t - 1%	70	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Gulv på grunn - EPS	0.6	m			21t - 15%	Data etter komponent		0		Data etter komponent	Data etter komponent
Pukk, 0. sprengstein, 3000 kg/m3 (F	100	m^3			0,74t - 0,5%	20	Dumper, 19 tonns	0	Dumper, 19 tonns	Fast	Lokal, intet behov
Radon- og fuktmembran for byggep	498	m^2 x	1,2	mm	1,4t - 0,97%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Dampsperre i plast, 0.2 mm (Tomm	498	m^2 x	0.2	mm	0,22t - 0,2%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Ferdigbetong, normal styrke, generi	498	m^2 x	50	mm	6,4t - 5%	70	Betongbil, omtrent 8m3	0	Betongbil, omtrent 8m3	Fast	Norge IEA2018
EPS-isolasjon, T: 10-2400 mm, 600 x	498	m^2 x	350	mm	12t - 9%	180	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Gulv på grunn - XPS	0.4	m			17t - 12%	Data etter komponent		0		Data etter komponent	Data etter komponent
Pukk, 0. sprengstein, 3000 kg/m3 (F	100	m^3			0,74t - 0,5%	20	Dumper, 19 tonns	0	Dumper, 19 tonns	Fast	Lokal, intet behov
Radon- og fuktmembran for byggep	498	m^2 x	1,2	mm	1,4t - 0,97%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
XPS isolasjonsplate, 33 mm, 300KP	498	m^2 x	150	mm	8,4t - 6%	180	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Dampsperre i plast, 0.2 mm (Tomm	498	m^2 x	0.2	mm	0,22t - 0,2%	110	Trailer, 40 tonns	0	Trailer, 40 tonns	Fast	Lokal, intet behov
Ferdigbetong, normal styrke, generi	498	m^2 x	50	mm	6,4t - 5%	70	Betongbil, omtrent 8m3	0	Betongbil, omtrent 8m3	Fast	Norge IEA2018

Appendix E: Input Values in SIMIEN for the TEK17 Concept

AREA OF ROOFS	
NW Glass	160 m^2
NW Roof	189.89 m^2
NW total	349.89 m^2
SE Glass	33.5 m^2
SE Roof	189.89 m^2
SE total	223.39 m^2
Area total glass	193.5 m^2
Area total roof	379.78 m^2
Area total	573.28 m^2

AREA OF WALLS				
	NW	NE	SW	SE
Area glass	249.96 m^2	32.7 m^2	188.66 m^2	46.58 m^2
Area wall	0 m^2	155.21 m^2	0 m^2	263.95 m^2
Area total	249.96 m^2	187.91 m^2	188.66 m^2	310.53 m^2

AREA OF FLOORS					
	Basement	1st floor	2nd floor	3rd floor	Total
Volume	1412.3 m^3	2633.27 m^3	985.5 m^3	516.1 m^3	5547.17 m^3
Area	497.3 m^2	491.85 m^2	304.1 m^2	223.6 m^2	1516.85 m^2

NUMBER OF WINDOWS & DOORS										
	Large windows 2.15 m^2 (1.05x1.43 m)	Small windows 1.47 m^2 (1.05x1.40 m)	Long window 1.25 m^2 (0.5x2.5 m)	Door 1 2.3 m^2 (1x2.3 m)	Door 2 2.5 m^2 (1x2.5 m)	Door 3 2.1 m^2 (1x2.1 m)	Door 4 3.32 m^2 (1.2x2.77 m)	Door 5 3.6 m^2 (1.3x2.77 m)	Double 1 6.7 m^2 (2.37x2.77 m)	Double 2 4.3 m^2 (1.56x2.77 m)
NE wall	6	2	1	1	1	1				
NW wall							2		1	
SE wall	7					1				2
SW wall								2		

Description				Value	Unit	Reasoning/Reference
ENERGY SUPPLY						
Energy supply	Electricity from the grid	Data for energy source	System efficiency space heating	0.82		Value from SIMIEN
			System efficiency domestic hot water (DHW)	0.98		Value from SIMIEN
			System efficiency heating coils	0.88		Value from SIMIEN
			Coefficient of Performance (COP) space cooling	2.5		Value from SIMIEN
			Coefficient of Performance (COP) cooling coils	2.5		Value from SIMIEN
			CO_2 emissions	130	g/kWh	Value from SIMIEN
			Energy price	0.4264	NOK/kWh	Calculated
		Percentage of energy covered by electricity	Space heating	20	%	Assumed value
			DHW heating	20	%	Assumed value
			Heating coils ventilation	20	%	Assumed value

			Cooling coils ventilation	20	%	Assumed value
			Space cooling	20	%	Assumed value
			Electricity (lighting, equipment, fans and pumps)	100	%	Chosen value
	Heat pumps	Data for energy source	System efficiency space heating	2.45		Value from SIMIEN
			System efficiency domestic hot water (DHW)	2.6		Value from SIMIEN
			System efficiency heating coils	2.67		Value from SIMIEN
			Coefficient of Performance (COP) space cooling	2.5		Value from SIMIEN
			Coefficient of Performance (COP) cooling coils	2.5		Value from SIMIEN
			CO_2 emissions	130	g/kWh	Value from SIMIEN
			Energy price	0.8	kr/kWh	Value from SIMIEN
		Percentage of energy covered by electricity	Space heating	60	%	Assumed value
			DHW heating	60	%	Assumed value

			Heating coils ventilation	60	%	Assumed value
			Cooling coils ventilation	60	%	Assumed value
			Space cooling	60	%	Assumed value
			Electricity (lighting, equipment, fans and pumps)	0	%	Chosen value
	Solar	Data for energy source	System efficiency space heating	33.84		Value from SIMIEN
			System efficiency domestic hot water (DHW)	40.00		Value from SIMIEN
			System efficiency heating coils	36.85		Value from SIMIEN
			Coefficient of Performance (COP) space cooling	2.5		Value from SIMIEN
			Coefficient of Performance (COP) cooling coils	2.5		Value from SIMIEN
			CO_2 emissions	130	g/kWh	Value from SIMIEN
			Energy price	0.8	kr/kWh	Value from SIMIEN
			Space heating	20	%	Assumed value

Western Norway University of Applied Sciences

		Percentage of energy covered by electricity	DHW heating	20	%	Assumed value
			Heating coils ventilation	20	%	Assumed value
			Cooling coils ventilation	20	%	Assumed value
			Space cooling	20	%	Assumed value
			Electricity (lighting, equipment, fans and pumps)	0	%	Assumed value
The building	Heated floor area			1516.8	m^2	Calculated from drawing
	Heated air volume			5547.2	m^3	Calculated with values and measurements from the drawing
	Infiltration	Leakage number		0.80	1/h	TEK17: § 14-3 (1) a)
		Shielding class		Moderate shielding		Educated assumption
		Facade situation		More than one wind exposed facade		Educated assumption
	Furniture/interior			2	Wh/m^2K	Educated assumption
	Operating days			All days		Educated assumption

	Cold bridge	Normalized cold bridge		0.090	W/m²K	TEK17: § 14-3 (2)
NORTH–EAST						
Outer wall, NE	Total area			187.91	m²	Calculated from drawing
	In data construction	Custom construction	Total u-value	0.3	W/(m²K)	TEK17: § 14-3 (1) a) Calculated
		Heat storage in inner layer		13	Wh/(m²K)	Value from SIMIEN
	Orientation/ horizon	Orientation		NE		Measured from drawing
		Horizon		45	Degrees	Measured from drawing
Window, NE: Large	Number of (equal) windows			6		Counted from drawing
	Window size	Width		1,43	m	Measured from drawing
		Height		1,50	m	Measured from drawing
		Frame: length/width		0,05	m	Assume standard value
	Heat loss properties	Custom total U-value for the window construction		1.2	W/(m²K)	TEK17: § 14-3 (1) a)
	Heat gain properties	Variable, manually controlled				Chosen variable

Window, NE: Small	Number of (equal) windows		2		Counted from drawing
	Window size	Width	1,40	m	Measured from drawing
		Height	1,05	m	Measured from drawing
		Frame: height/width	0,05	m	Assume standard value
	Heat loss properties	Custom total U-value for the window construction	1.2	W/(m²K)	TEK17: § 14-3 (1) a) Multiconsult
	Heat gain properties	Variable, manually controlled			Chosen variable
Window, NE: Long	Number of (equal) windows		1		Counted from drawing
	Window size	Width	0.5	m	Measured from drawing
		Height	2.5	m	Measured from drawing
		Frame: height/width	0,05	m	Assume standard value
	Heat loss properties	Custom total U-value for the window construction	1.2	W/(m²K)	TEK17: § 14-3 (1) a) Multiconsult
	Heat gain properties	Variable, manually controlled			Chosen value
	Number of (equal) doors		1		Counted from drawing

Door, NE: Door no 1	Door size	Width	1	m	Measured from drawing
		Height	2.3	m	Measured from drawing
		Area	2.3	m^2	Calculated from drawing
	Heat loss properties	Custom total U-value for the door construction	1.20	$W/(m^2K)$	TEK17: § 14-3 (1) a)
Door, NE: Door no 2	Number of (equal) doors		1		Counted from drawing
	Door size	Width	1	m	Measured from drawing
		Height	2.5	m	Measured from drawing
		Area	2.5	m^2	Calculated from drawing
	Heat loss properties	Custom total U-value for the door construction	1.20	$W/(m^2K)$	TEK17: § 14-3 (1) a)
Door, NE: Door no 3	Number of (equal) doors		1		Counted from drawing
	Door size	Width	1	m	Measured from drawing
		Height	2.1	m	Measured from drawing
		Area	2.1	m^2	Calculated from drawing

	Heat loss properties	Custom total U-value for the door construction		1.20	W/(m²K)	TEK17: § 14-3 (1) a)
N O R T H – W E S T						
Outer wall, NW	Total area			249.96	m²	Calculated from drawing
	In data constructio n	Custom construction	Total u-value	0.7	W/(m²K)	TEK17: § 14-3 (1) a) Calculated
		Heat storage in inner layer		0.8	Wh/(m²K)	Value from SIMIEN
	Orientation/ horizon	Orientation		NW		Drawing
		Horizon		315	Degrees	Drawing
Door, NW: Door no 4	Number of (equal) doors			2		Counted from drawing
	Door size	Width		1.2	m	Measured from drawing
		Height		2.77	m	Assume standard height
		Area		3.32	m²	Calculated from drawing
	Heat loss properties	Custom total U-value for the door construction		1.2	W/(m²K)	TEK17: § 14-3 (1) a)
	Number of (equal) doors			1		Counted from drawing

Door, NW: Double 1	Door size	Width		2.37	m	Measured from drawing
		Height		2.77	m	Assume standard height
		Area		6.5	m^2	Calculated from drawing
	Heat loss properties	Custom total U-value for the door construction		1.2	$W/(m^2K)$	TEK17: § 14-3 (1) a)
SOUTH–EAST						
Outer wall, SE	Total area			310.53	m^2	Calculated from drawing
	In data constructio n	Custom construction	Total u-value	0.29	$W/(m^2K)$	TEK17: § 14-3 (1) a) Calculated
		Heat storage in inner layer		13	$Wh/(m^2K)$	Value from SIMIEN: Lettklinker
	Orientation/ horizon	Orientation		SE		Drawing
		Horizon		135	Degrees	Drawing
Window, SE: Large	Number of (equal) windows			6		Counted from drawing
	Window size	Width		1.43	m	Measured from drawing
		Height		1.50	m	Measured from drawing

		Frame: length/width	0.05	m	Assume standard value
	Heat loss properties	Custom total U-value for the window construction	1.2	W/(m²K)	TEK17: § 14-3 (1) a) Multiconsult
	Heat gain properties	Variable, manually controlled			Chosen value
Door, SE: Door no 3	Number of (equal) doors		1		Counted from drawing
	Door size	Width	1	m	Measured from drawing
		Height	2.1	m	Assume standard height
		Area	2.1	m^2	Calculated from drawing
	Heat loss properties	Custom total U-value for the door construction	1.2	W/(m²K)	TEK17: § 14-3 (1) a)
Door, SE: Double 2	Number of (equal) doors		2		Counted from drawing
	Door size	Width	1.56	m	Measured from drawing
		Height	2.77	m	Assume standard height
		Area	4.32		Calculated from drawing

	Heat loss properties	Custom total U-value for the door construction		1.2	W/(m²K)	TEK17: § 14-3 (1) a)
SOUTH – WEST						
Outer wall, SW	Total area			188.66	m²	Calculated from drawing
	In data construction	Custom construction	Total u-value	0.7	W/(m²K)	TEK17: § 14-3 (1) a) Calculated
		Heat storage in inner layer		0.8	Wh/(m²K)	Value from SIMIEN
	Orientation/ horizon	Orientation		SW		Drawing
		Horizon		225	Degrees	Drawing
Door, SW: Door no 5	Number of (equal) doors			2		Counted from drawing
	Door size	Width		1.3	m	Measured from drawing
		Height		2.77	m	Assume standard height
		Area		3.6	m³	Assume standard value of 20%
	Heat loss properties	Custom total U-value for the door construction		1.20	W/(m²K)	TEK17: § 14-3 (1) a)
BASEMENT						

Basement	Size	Floor area		497.3	m^2	Measured from drawing
		Outer circumference		96.8	m	Measured from drawing
		Thickness of walls		0.3	m	Measured from drawing
	Constructio n	U-value		0.18	$W/(m^2K)$	TEK17: § 14-3 (1) a)
		Heat storage in inner layer		63	$Wh/(m^2K)$	Value from SIMIEN: Very heavy construction (concrete > 100 mm)
	Ground/soil conditions	Thermal conductivity		2.00	W/(mK)	Value from SIMIEN: clay/silt
		Heat capacity		556	$Wh/(m^3K)$	Value from SIMIEN: clay/silt
INTERNAL LOAD						
Internal load	Lighting	During operating time	Mean power	3.7	W/m^2	SN-NSPEK 3031:2020, Table A.6
			Heat gain	100	%	SN-NSPEK 3031:2020, Table A.6
		Outside operating time	Mean power	0.4	W/m^2	SN-NSPEK 3031:2020, Table A.6

			Heat gain	100	%	SN-NSPEK 3031:2020, Table A.6
		Operating time		7/52	Days/weeks	Open every day
	Technical equipment	During operating time	Mean power	5.42	W/m²	SN-NSPEK 3031:2020, Table A.3
			Heat gain	100	%	SN-NSPEK 3031:2020, Table A.3
		Outside operating time	Mean power	0.89	W/m²	SN-NSPEK 3031:2020, Table A.3
			Heat gain	100	%	SN-NSPEK 3031:2020, Table A.3
		Operating time		7/52	Days/weeks	Open every day
	Tap water	During operating time	Mean power	1.92	W/m²	SN-NSPEK 3031:2020, Table A.2
			Heat gain	0	%	SN-NSPEK 3031:2020, Table A.2
		Outside operating time	Mean power	0	W/m²	SN-NSPEK 3031:2020, Table A.2
			Heat gain	0	%	SN-NSPEK 3031:2020, Table A.2
		Operating time		7/52	Days/Weeks	Open every day
	Heat gain people	During working hours		5	W/m²	SN-NSPEK 3031:2020, Table A.5

		Outside working hours	0	W/m²	SN-NSPEK 3031:2020, Table A.5
		Operating time	7/52		Open every day
HEATING SYSTEM					
Heating system	Capacity heating system	Maximum power output per m²	50.0	W/m²	Value from SIMIEN
		⇒ maximum power output	75.8	kW	Automatically calculated in SIMIEN
		Convective portion of maximum power output	0.5	°C	Value from SIMIEN
	Operating strategy	Set temperature during working hours	21	°C	Value from SIMIEN
		Set temperature outside of working hours	19	°C	Value from SIMIEN
	Operating strategy summer	Set temperature during working hours	19	°C	Value from SIMIEN
		Set temperature outside of working hours	16	°C	Value from SIMIEN
		Summer months	May - September		From SIMIEN
VENTILATION					
Ventilation	Type		Balanced ventilation		Chosen system

	Air volume	Supply air during operating time	8.15	m^3/hm^2	Chosen value
		Supply air outside operating hours	2.00	m^3/hm^2	Chosen value
		Extract air in operating time	8.15	m^3/hm^2	Chosen value
		Extract air outside operating hours	2.00	m^3/hm^2	Chosen value
	Supply air temperature (constant)		19.0	°C	Chosen value
	Components	SPF-factor	1.50	$kW/m^3/s$	Chosen value
		Heat recovery efficiency	82	%	Chosen value

Appendix F: Calculation of Energy Cost

Year	Average cost in øre	Incline
2022	38	
2023	39,3	1,33
2024	40,7	
2025	42	
2026	41,4	
2027	40,8	
2028	40,2	-0,6
2029	39,6	
2030	39	
2031	39,2	
2032	39,4	
2033	39,6	
2034	39,8	
2035	40	0,2
2036	40,2	
2037	40,4	
2038	40,6	
2039	40,8	
2040	41	
2041	41,2	
2042	41,4	
2043	41,6	
2044	41,8	
2045	42	
2046	42,2	
2047	42,4	
2048	42,6	
2049	42,8	
2050	43	
2051	43,2	
2052	43,4	
2053	43,6	
2054	43,8	
2055	44	
2056	44,2	
2057	44,4	
2058	44,6	
2059	44,8	
2060	45	
2061	45,2	
2062	45,4	
2063	45,6	
2064	45,8	
2065	46	
2066	46,2	
2067	46,4	
2068	46,6	
2069	46,8	
2070	47	
2071	47,2	
Average	42,644	

Appendix G: Results of the Energy Simulation Conducted in SIMIEN

	Saved energy per year
Roof	kWh
Stone wool	0
Aerogel	2731
Wood fibre	2580
Wall	
Stone wool	4552
EPS	2428
Glass wool	4552
Window	
Reuse	−4856
Reuse, change to energy glass	−1366
Triple pane window with gas filling	1366
Door	
Reuse	−6069
New 1.2	0
New 0.8	1821
Slab on ground	
XPS	0
EPS	3035
Glasopor	1669

Appendix H: Results of the CO_2 Estimates Conducted in One Click LCA

	Emissions	Comments
Roof	Tonnes CO_2 eq	
Stone wool	9	
Aerogel	19	
Wood fiber	7.9	
Concrete wall		
Stone wool	8.2	Exterior reinforced rough plaster will be required, but this was not available in the One Click LCA's database.
EPS	9.4	
Glass wool	5.1	
Window		
Reuse	-	Value could not be found.
Reuse, change to energy glass	0.86	The value only includes new glass.
Triple pane window with gas filling	6.7	
Door		
Reuse	-	Value could not be found.
New 1.2	3	
New 0.8	4.4	
Slab on ground		
XPS	17	
EPS	21	
Glasopor	13	

Appendix I: Results of the Cost Estimates Conducted in Holte SmartKalk

	Cost
Roof	NOK
Stone wool	761 477
Aerogel	1 857 815
Wood fibre	901 298
Wall	
Stone wool	938 299
EPS	963 919
Glass wool	940 903
Window	
Reuse	202 395
Reuse, change glass	262 395
Triple pane window with gas filling	97 722
Door	
Reuse	277 530
New 1.2	206 060
New 0.8	222 530
Slab on ground	
XPS	796 984
EPS	822 402
Glasopor	705 128

Appendix J: Total Costs and Total Emissions

	Saved energy per year	Cost	Saved cost from saved energy	**Total cost:** Cost minus saved cost from saved energy	Emissions	Saved emissions from saved energy	**Total emissions:** Emissions minus saved emissions from saved energy
Roof	kWh	NOK	NOK for 50 years	NOK	tonnes CO_2 eq	tonnes CO_2 eq for 50 years	tonnes CO_2 eq
Stone wool	0	761 477	0	761 477	9.0	0.00	9.00
Aerogel	2731	1 857 815	58230	1 799 585	19.0	2.32	16.68
Wood fibre	2580	901 298	54995	846 303	7.9	2.19	5.71
Wall							
Stone wool	4552	938 299	97050	841 249	8.2	3.87	4.33
EPS	2428	963 919	51760	912 159	9.4	2.06	7.34
Glass wool	4552	940 903	97050	843 853	5.1	3.87	1.23
Window							
Reuse	−13353	202 395	−284680	487 075	-	−11.35	11.35
Reuse, change glass	−3793	262 395	−80875	343 270	0.86	−3.22	4.08
Triple pane window with gas filling	3793	97 722	80875	16 847	6.7	3.22	3.48

Door							
Reuse	−6069	277 530	−129400	406 930	-	−5.16	5.16
New 1.2	0	206 060	0	206 060	3.0	0.00	3.00
New 0.8	1821	222 530	38820	183 710	4.4	1.55	2.85
Slab on ground							
XPS	0	796 984	0	796 984	17.0	0.00	17.00
EPS	3035	822 402	64700	757 702	21.0	2.58	18.42
Glasopor	1669	705 128	35585	669 543	13.0	1.42	11.58