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Life Cycle Assessment of an Ambitious Upgrading of an Apartment Building

An Environmental Approach on Upgrading Projects

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Problem Description

Purpose:

There is a growing interest of constructing sustainable buildings in Norway. Current buildings use significant amounts of energy inefficiently. This study analyzes the carbon footprint of an ambitious upgrading of an apartment building using Life Cycle Assessment methodology. Emissions saved per year from improved energy efficiency will be identified, in addition to the main focus of environmental impacts from construction materials. The analytical work is highly relevant for current trends in this nation and others. Finally, discussions and recommendations regarding future upgrading projects will be stressed based on findings.

Main contents:

1. A life cycle inventory analysis of the ambitious upgrading of the building apartment.
2. Conduct an environmental impact assessment of the project - what key parameters and activities contributed the most?
3. Compare use of the LCA methodology with the tool Klimagassregnskap.no in construction projects.
4. Based on the analysis, the discussion will provide recommendations for future rehabilitation projects and impacts from construction materials.

Preface

This study represents my master thesis in the MSc Industrial Ecology Program. The thesis is written at the Department of Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU), spring 2016.

There is currently a significant amount of older building apartments constructed around 1950-1970. The majority of these operate with inefficient energy solutions and poor insulation capacities. The situation causes great opportunities to perform in ambitious upgrading to reduce energy use hence total emissions from the construction sector.

The significant energy reduction achieved in the ambitious upgrading of Stjernehus apartment building was imposing, however emissions embodied in construction materials remained as an interesting case to solve. The objective of this thesis was to assess environmental impacts from the upgrading of the apartment building located in Kristiansand. The analysis has been interesting to work with.

Special thanks go to my supervisor Christofer Skaar from NTNU, my co-supervisor Reyn O'Born from University of Agder, Olav Rønningen og Eivind Torsvik from Kruse Smith, and Odd Helge Moen from Sorlandet Boligbyggelag for good guidance and cooperation throughout the spring semester.

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Abstract

The overall aim of this study is to assess the carbon footprint of an ambitious upgrading process of an apartment building that was classified as a low-energy building, class 1 in 2015. Using Life Cycle Assessment methodology, environmental impacts caused by the project are examined with a focus on global warming potential (CO_2-eq). In addition, LCA results will be compared with a previously performed analysis of the building where Klimagassregnskap.no was used to predict greenhouse gas emissions.

In order to identify environmental impacts from the ambitious upgrading there was firstly a need to collect data for all materials used, and related construction and transportation processes. When the data was gathered and treated, materials were allocated to shell components and processes. Further, the model was linked to the background database ecoinvent version 2.2, and the LCA software Arda was used to process the data. The ReCiPe method, and hierarchist midpoint was utilized for impact assessment. The NORDEL electricity mix was applied for electricity consumption.

Results from the LCA shows that total greenhouse gas emissions emitted from the upgrading project were 439 ton CO_2-eq. The calculation model includes impacts from production of construction materials including transportation to site, energy and diesel used during construction, and end of life treatment (see section 4.1 for EPD terminology). As the main objective of this life cycle assessment was the construction materials, the emissions related to energy consumption during user phase was considered separately from the system boundaries. Emissions from energy use decreased by 84% after the upgrading - from 164 ton CO_2-eq/year for the whole building apartment, to 25 ton CO_2-eq/year.

The study presents two variants of the LCA model. The first in chapter 4 reflects the complete inventory list, and the second model has a limited scope to be comparable with results in Klimagassregnskap.no. The comparison in chapter 5 shows that Klimagassregnskap.no calculated a total of 156 ton-CO_2 emissions from the upgrading, while the adjusted LCA model found 237 ton CO_2-eq. Furthermore, payback times of emissions caused by construction materials was found to be 3.3 years, according to the LCA model, and 1.3 years for Klimagassregnskap.no. Thus the project is environmentally profitable shortly after because of significant energy savings per year. The comparison identifies benefits and limitations with the two assessment tools in chapter 6.2.3.

Former studies show that emissions from construction materials in new energy efficient buildings can be significant. For ambitious upgrading of older buildings, this is found to be minor in comparison to energy saved. Thus such projects are supported by this study, from an environmental perspective. Nevertheless, for such projects to occur and be profitable, there is a need to hold a long-term perspective on economic value and consider societal and environmental values in addition.

Sammendrag

Det overordnede målet for denne masteroppgaven er å beregne karbonfotavtrykket av en ambisiøs oppgradering av en boligblokk. Bygningen i Sør-Norge ble klassifisert som et lavenergibygg, klasse 1 i 2015. Ved hjelp av livsløpsanalyse metodikk er miljøkonsekvenser som følge av prosjektets prosesser undersøkt, med fokus på klimagassutslipp. I tillegg vil LCA resultater sammenlignes med en tidligere utført analyse av boligblokken hvor Klimagassregnskap.no ble brukt til å forutsi utslipp av klimagasser. Sammenligningen identifiserer fordeler og begrensninger med de to analyse verktøyene.

For å identifisere miljøpåvirkninger fra den ambisiøse oppgradering var det først behov for å samle inn data for alle materialer brukt, samt relaterte bygg- og transport prosesser. Etter all data var samlet inn og behandlet, ble materialene allokert til bygge komponenter og -prosesser. Videre ble modellen koblet til databasen ecoinvent versjon 2.2, deretter ble LCA programvaren Arda anvendt til å behandle data. ReCiPe metoden, og hierarchist midpoint ble brukt til konsekvensutredning (impact assessment). Elektrisitetsmiksen NORDEL ble benyttet for strømforbruk.

LCA resultatene viser at totale klimagassutslipp fra oppgraderingen var 439 tonn CO_2-ekvivalenter. Beregningsmodellen inkluderer virkningen fra produksjon av byggevarer, inkludert transport til stedet, energi og diesel brukt under byggingen, og avfallsbehandling (se kapittel 4.1 for EPD terminologi). Siden fokuset i denne livsløpsvurderingen var byggematerialene, ble utslipp relatert til energiforbruket i bruksfasen vurdert separat fra systemgrensene. Utslipp fra energibruk ble redusert med 84% etter oppgraderingen - fra 164 tonn CO_2-ekvivalenter/år for hele bygget, til 25 tonn CO_2-ekvivalenter/år.

For å kunne utføre en rettferdig sammenligning med resultatene fra det alternative analyse verktøyet (Klimagassregnskap.no) ble innholdet i den originale LCA modellen redusert. Klimagassregnskap.no beregnet at oppgraderingen resulterte i 156 tonn CO_2-ekvivalenter, og den justerte LCA modellen viste 237 tonn CO_2-ekvivalenter. Disse var mindre detaljert og -utslippsintensive enn den fullstendige LCA modellen. Videre ble tilbakebetalingstiden for utslipp forårsaket av byggematerialer funnet å være 3,3 år, i henhold til LCA modellen. Dette tilsier at prosjektet var lønnsomt for miljøet allerede etter denne perioden på grunn av energien spart per år. Klimagassregnskap.no beregnet 1,3 år – en enda mer optimistisk tilnærming (se kapittel 5.3).

Tidligere studier viser at utslipp fra byggematerialer i nye energieffektive bygninger kan være betydelige. Dette studiet viser at dette ikke er tilfelle for ambisiøse oppgraderingsprosjekter av eldre bygg. Utslipp fra byggematerialer har liten betydning i forhold til hvor mye energi som kan bli spart hvert år, dermed støtter denne studien lignende prosjekter ut i fra et miljøperspektiv. Til tross for potensiell utslippsreduksjon for byggsektoren kan det være utfordrende å møte økonomiske krav i slike prosjekter. For at ambisiøse oppgraderinger skal forekomme lønnsomme, er det behov for å holde et langsiktig perspektiv på økonomisk verdi, samt inkludere samfunnsmessige og miljømessige verdier.

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1. Introduction

1.1 Background

In December 2015 the Paris Climate Conference (COP21) held 190 nations to negotiate on a legally binding agreement for emission reductions. 174 countries and the European Union (EU) have now signed the Paris agreement with the aim of not exceeding a global warming of 2 degrees. The goal is set to avoid dramatic changes in the natural environment, which are highly possible to occur if global warming exceeds this limit. This is a challenging task and needs global cooperation and engagement from all nations (United Nations, 2015).

An important element in this challenge is emissions from the building sector as that accounts for 5 Gt CO_2-eq/year. If one includes emissions from energy consumption in addition, it is then estimated to 10.6 Gt CO_2-eq/year. Thus the amount of energy used by the building sector is significant – 33% of the global total in 2004 (Barker T. and G.J. Heij, 2007). The recognized Intergovernmental Panel on Climate Change (IPCC) report discusses this where mitigation practices of importance are firstly reducing energy consumption and shifting to renewables. An important factor to achieve this is to design buildings in an efficient manner according to local climate and particular opportunities (Barker T. and G.J. Heij, 2007).

The Committee of Emission Reduction in Norway (Utslippsutvalget) assessed fundamental measures to lower emissions and states that heating practices in buildings need to be altered. Creating ambitious construction standards, eco-labels for buildings, and monetary support are important elements to act on this area (Randers et al., 2006). Today, 40% of all greenhouse gas emissions from Norway are caused by the construction industry and this knowledge has led to standardization of low energy use buildings and houses (Mork, 2016). Examples of these will be stressed in chapter 2.1.

As society experiences pressure from climate change, both consumers and suppliers become continuously more conscious of the importance of reducing emissions. The industry must satisfy their demand and consider environmental aspects in construction projects in the future. Environmental assessment tools to support project documentation are utilized more frequently. There are various manners to calculate greenhouse gas (GHG) emissions and other environmental impacts and it is therefore important to stress strengths and limitations of such tools.

A few publications exist concerning emissions from construction materials utilized in energy efficient buildings (see chapter 2.2). However, there is a lack of literature regarding ambitious upgrading and apartment buildings specifically. Nevertheless, Holen (2014a) has generated an analysis of the same apartment building as this study assesses (presented in 3.2). Holen used a different assessment tool to identify GHG emissions of the upgrading process, and this paper includes an interesting comparison of the results. An ambitious upgrading means a high quality, complete rehabilitation that considers the environment in a long-term perspective (SINTEF

Byggforsk and NBBL, 2015). The gain of performing in such an upgrading is increasingly recognized, and analytical work such as this thesis can enhance current practices.

The building apartment assessed is a significant example of an old (built 1965), energy intensive building that was upgraded to a low-energy building. The housing cooperative Stjernehus has 60 apartments and is located in Kristiansand, southern Norway. Energy is saved from improved insulation and energy source is changed from mainly oil heating to district heating. Several elements of the building where shifted to improve thermal insulation capacity, thus various construction materials were required in the rehabilitation project which caused environmental impacts.

1.2 Objectives

The main objective of this thesis is to assess the carbon footprint of an ambitious upgrading of an apartment building in Kristiansand. In addition, the results shall be compared with a previous assessment study of the same building where a different tool (Klimagassregnskap.no) was used to analyze GHG emissions. Recommendations regarding future upgrading projects will be presented. The following questions shall be answered:

1. What are the life cycle environmental impacts generated from the ambitious upgrading process?
    - What construction material groups hold the major carbon footprints?
    - How significant is the GHG emissions from construction materials in comparison to energy saved in the operation phase?
2. How do these results differ from the previous GHG assessment of the apartment building (Holen, 2014)?
3. How do different assumptions of energy sources and lifetime of components influence results?
4. How can this analysis provide decision-making support for planners and designers of future upgrading projects?

    - What are the main motive and current constraint for future ambitious upgrading projects?
    - How to reduce environmental impacts of construction materials?
    - How should the building industry approach the environmental assessment tools Klimagassregnskap.no and LCA?

1.3 Scope of study

In order to identify environmental impacts generated from the ambitious upgrading process of Stjernehus, a complete Life Cycle Assessment (LCA) shall be conducted. All construction materials and related processes are sorted into shell components that are calculated using software. The results must then be analyzed and presented in a comprehensive manner to illustrate what processes caused the highest environmental impacts. The time before emissions released by construction materials are payed back by energy reduction will clearly illustrate the benefits with upgrading. Both a contribution analysis and a sensitivity analysis will be completed to show what activities in the processes that affect total results the most, and how sensitive results are for each process. Furthermore, the LCA model needs to be adjusted to fit the assessment model in Klimagassregnskap.no. Results will be compared with those of Klimagassregnskap.no to identify benefits and limitations with both. To reflect further on results, particular LCA modelling choices are altered in a scenario analysis to observe the effect (e.g. lifetime, el mix). Finally, findings will be discussed and recommendations are drawn from these.

1.4 Structure of study

This thesis is divided in eight chapters. The following chapter consists of an introduction to the study including background and objectives. The literature in chapter 2 contains an overview of important theory to obtain great comprehension of the topic and existing literature. Following, in chapter 3, the LCA methodology used in this study shall be explored, in addition to a presentation of the apartment building Stjernehus, and information on data sources. Chapter 4 shows results, including life cycle inventory list (result of data gathering), and life cycle impact assessment results. Furthermore, in chapter 5, the results are compared with Holen's (2014a) results where Klimagassregnskap.no was used to identify greenhouse gas emissions. Main findings and recommendations are discussed in chapter 6, including uncertainties and future work. Lastly, chapter 7 contains a conclusion, and references are listed in chapter 8.

2. Literature

It is important to gain an overview of previous research on relevant topics as a basis for the new study. The literature review has increased understanding of the subject, hence enhanced knowledge, and contributed to develop ideas on relevant research questions to explore. This review describes the literature that will assist in answering the objectives in 1.2, and will be the basis for the LCA conducted in this thesis. Firstly, there will be an overview of environmental programs in the building sector in Norway including that of upgrading projects. The analysis tool Klimagassregnskap.no will be presented, which has been used in such programs. Furthermore, theory on environmental impacts from construction materials will be presented, followed by the modelling choices lifetime of components and electricity mix which must be considered in environmental assessments. Literature on LCA of buildings are increasingly published, however research on rehabilitation projects is limited. This is also the case for apartment buildings in particular.

2.1 Life Cycle Perspective in the Building Sector

2.1.1 Environmental Programs in Norway

Different efforts to consider environmental impacts in the construction sector are increasingly current in Norway. Examples of knowledge and innovation platforms in Norway are Framtidens Byer (Future Cities) (Regjeringen.no, 2014), Lavenergiprogrammet (the low-energy program) (lavenergiprogrammet.no, 2016), and the Research Centre on Zero Emission Buildings (ZEB) (zeb.no, 2016), who cooperate with the government, research institutions and the construction industry. In addition, environmental awards of buildings such as Svanemerket, BREEAM and LEED are emphasized further (Solli, 2015). Environmental documentation of materials, Environmental Product Declarations (EPDs), are increasingly requested, especially in the construction sector in Norway (EPD-Norge, 2016). The terminology of EPDs will be applied in this study when setting system boundaries (see 3.3.2 and 5.1). This documentation and the tool of Life Cycle Assessment (LCA) generate the possibility to categories buildings according to environmental impacts, and energy efficiency in the user phase. In relation to environmental efforts there are ambitious building standards in Norway, and one of them is the “low-energy, class 1” (see 2.1.2 below). The latter standard was applied in the building apartment analyzed in this study.

The initiatives hold a life cycle perspective when considering environmental impacts and costs - if resources (e.g. time, finance, data) are available. Considering the increased attention to environmental aspects in the building sector, assessment tools are significant to quantify and document realistic results. This exemplifies the importance of including the different life stages of products and processes, such as extraction of metals, manufacturing of materials, transport to construction site, construction energy, rehabilitation processes, and waste treatment in end of life (EOL).

2.1.2 Ambitious Building Standards in Norway

Ambitious standards regarding energy saving in buildings are increasingly used, particularly in larger cities for new offices and schools (Mork, 2016). The standards require documentation of environmental impacts and thus environmental assessment tools such as life cycle assessment (LCA), Klimagassregnskap.no, or ISY Calcus. SIMIEN is also used to calculate energy saved in buildings (Ronningen, 2016). The relevant standards are defined below.

TEK 10

In order to build in Norway there is a need to satisfy the regulation for technical requirements in buildings (TEK 10). The regulation covers several important areas such as visual quality, universal design, security for environmental impacts, grounds, construction safety, security with fire, energy, and health and environment (Direktoratet for Byggkvalitet, 2015). The energy measures consist of frame requirements that regards thermal insulation capacity of outer walls, windows and doors, roof and floor [measured in W/(m^{2}K)], thermal bridge, and heat recovery from ventilation, among others. The ambitious upgrading of the apartment building studied is built according to TEK 10 and the low-energy standard class 1 below.

Low Energy Standard, class 1 & 2

The Stjernehus apartment building that will be analyzed, was upgraded from an energy intensive building to “Lavenergi” (low-energy), class 1 (stricter than class 2). Documentation practices of low-energy class 1 follows NS 3700 – the Norwegian standard for low energy buildings and passive houses. The total energy demand for heating in a house built after this standard is 50% lower than a house built after the technical regulations in 1997 (Husbanken, 2011). Low-energy class 1 and 2 are Norwegian standards that emphasize passive efforts to reduce energy consumption. Insulation and heat recovery are examples frequently used. Energy demand can be the doubled of a building after the passive house standard described below. However, housings with the low energy standard demand merely 20-25 per cent of what older buildings use (corresponds with findings in this study). To compare with new buildings based on the TEK 10 standard, the low energy buildings need around 25 per cent less energy delivered (varies depending on type of building) (SINTEF Byggforsk and NBBL, 2015). The standards have requirements for u-values for windows and doors, thermal bridging value, SPF-factor for ventilation, leakages figure and average heat recovery per year (Skogheim, 2014).

Passive house standard

This standard has the same principal as those above and follows the Norwegian standard NS 3700. The main difference is that the delivered energy demand is lower. These buildings use about 10 per cent of what an older building consume. It can be challenging to upgrade older buildings to the ambitious passive house standard. The buildings often consist of significant elements that are difficult to replace (SINTEF Byggforsk and NBBL, 2015).

In order to meet standard requirements, there are different manners to calculate energy need in a building. In table 1 below the different calculating points for energy standards are presented. These methods are illustrated in the Norwegian Standard (NS) 3031 (Boligprodusentene, 2014).

Table 1: Calculating points for energy standards – defining terms (Boligprodusentene, 2014).

Calculating points for energy standards	**Defining**
Heat loss (energy measures)	Calculated heat loss from the building
Net energy demand	Calculated energy demand to keep the building heated, without considering abilities of heating system
Delivered energy	Calculated energy demand for the building also considering abilities of the heating system
Weighted delivered energy	Calculated energy demand for the building with (environmental) weighing of energy goods

In the table below the energy delivered is used as a calculating point to differentiate between the TEK 10 standard, and the more ambitious NS 3700 which also presents the low-energy standard, class 1. Energy delivered is the energy that needs to be distributed from an external source. In most cases that is the energy that needs to be purchased. It takes the heating system efficiency into account (Boligprodusentene, 2014).

Table 2: Comparison of the energy standards NS 3700 and TEK 10 (Standard Norge, 2013, Direktoratet for Byggkvalitet, 2015).

Standards for energy delivered requirements [kWh/m²/y]		
	NS 3700	*TEK 10*
% of renewable energy required	50 %	40 %
Total energy delivered	*101.2*	*115*

The energy budget in table 2 above is designed for buildings with a low-energy standard, class 1 (as for the studied apartment building), 2- and passive house. Thus these standards follow the NS 3700 standard regarding energy delivered. The standard has requirements for energy demand, calculation criteria and necessary documentation in order to for buildings to be classified. In addition, heat loss figures are emphasized, net heating and cooling demands, energy demand for lightening, and minimum requirements for components, systems and leakage values. The energy calculation software SIMIEN was utilized for the apartment building analyzed in order to document that the different energy requirements are met (Skogheim, 2014).

2.1.3 Considering Klimagassregnskap.no

It can be time consuming and challenging to consider environmental impacts of a project. In practice the organization in charge may lack resources to generate a complete assessment. Therefore, the Norwegian state's key advisor in construction, Statsbygg, offers a free online tool for the construction sector to predict GHG emissions of future projects. Civitas has been the key designer of the tool which is based on international and national standardizations such as the International Organization for Standardization (ISO), and Norwegian Standard (NS) (Statsbygg and Civitas, 2014). Klimagassregnskap.no is intended to be a user friendly tool that can be applied by most people related to the building sector in Norway. Calculations can also be included in the ranking system Building Research Establishment Environmental Assessment method for Norway (BREEAM). The system determines particular characteristics of buildings related to external and internal environments (Holen, 2014a).

The construction sector in Norway has increasingly emphasized environmental aspects and there are several manners to measure environmental impacts in projects. All pilot projects in the governmental programs Framtidens Byer (Future Cities) and Framtiden Bygg (Future Buildings) were required to use Klimagassregnskap.no. The tool acted as an integrated part of planning and design. Thus it is not the purpose that it will calculate exact GHG emissions, but results can predict emissions from a project in a cradle to gate perspective. In addition, it has modules for transportation habits and energy use in the operation phase (Statsbygg and Civitas, 2014). Total CO_2-eq. for the whole project is the outcome of the tool.

To simplify comparison of emissions from buildings, one can generate a reference building model to compare the new or upgraded building with. The reference building is commonly in line with current regulations. Pilot projects, such as the apartment building studied, should manage a reduction of 50 % GHG emissions in comparison to the reference building. The emissions include all of the CO_2 equivalent gases presented in the Kyoto Protocol - FN's climate convention: Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH_4), Hydrofluorocarbons (HFC), Perfluorocarbons (PFC), Sulfur hexafluoride (SF_6) (Holen, 2014a).

2.1.4 Upgrading of Older Buildings

There have recently been increased efforts to upgrade older buildings to increase quality and decrease energy use (Kjølle et al., 2013). The potential is great for reducing national GHG emissions by upgrading old buildings – it can cause a 20% reduction in total energy use in

Norway, according to Thunes (2016). He also argues it would take 50 years to upgrade old buildings to a satisfying environmental standard. It is beneficial in two manners: (i) to reuse components, and (ii) reduction of energy use in buildings (Thunes, 2016). Enova (2012) argues the greatest potential lays in apartment buildings and small houses. Holding a life cycle perspective, the benefits of upgrading or providing maintenance are indeed several, as long as basic construction work is stable. The lifetime of a building varies significantly depending on factors such as quality of materials, ground, climate and use (Enova, 2012).

The poorer quality of a building, the more willingness to upgrade a home. In some cases, it is necessary to conduct maintenance activities. In these cases an ambitious upgrading should be performed to both save later efforts and energy consumption (Kjølle et al., 2013). As ambitious upgrading of buildings are encouraged by the Norwegian state, a strategy for increasing such rehabilitation projects is currently in work. In the table below, ambitious upgrading projects are treated as a product, and are still in the introduction phase, according to Kjølle et al. (2013). Thus ambitious upgrading to decrease energy consumption is new to the market. This also concerns universal design of buildings. As presented in table 3, the frequency of upgrading will increase from introduction phase, to growth, and lastly to volume “sale” (horizontal column). In order to reach a new phase, it must be attractive, competitive, affordable and accessible (vertical column).

Table 3: Framework for ambitious upgrading (Kjølle et al., 2013).

	Introduction phase	Growth phase	Volume phase
Attractiveness	→	→	→
Competitiveness	→	→	→
Affordability	→	→	→
Availability	→	→	→

As notified, initiatives from the government offer financial assistance for ambitious upgrading. Apartment buildings such as Stjernehus have residents that all need to agree on increased public debt after a rehabilitation of their home. The decision-making process of such projects is time consuming and challenging, and often reliable on financial support (Moen, 2016). A study generated by Enova (2016) showed that the great barrier today was the lack of economic profitability (discussed in 6.2.1). Thus it is vital for residents to see benefits with upgrading. The mode for change of the residents is also crucial in such projects. The low electricity price in Norway is an element who limits the profitability of rehabilitation projects, as illustrated later in figure 33 (Enova, 2012).

2.2 Emissions from Construction Materials

The Research Centre on Zero Emission Building (ZEB) has found that emissions from construction materials in an energy efficient new building can equal the energy saved in the entire user phase of a building. Of the total emissions from materials, one third can come from maintenance (i.e. upgrading) of components such as exterior walls, roof and windows (Dokka et al., 2013). In low energy buildings, emissions from building materials can cause up to 50% of the total. Thus construction materials utilized in energy-efficient buildings cause more emissions in total than those used in older buildings, as illustrated in figure 1 below. Therefore, it is unfortunate to focus merely on energy reduction in operation phase. Rather, one should measure total GHG emissions in a life cycle perspective (Kristjansdottir, 2014).

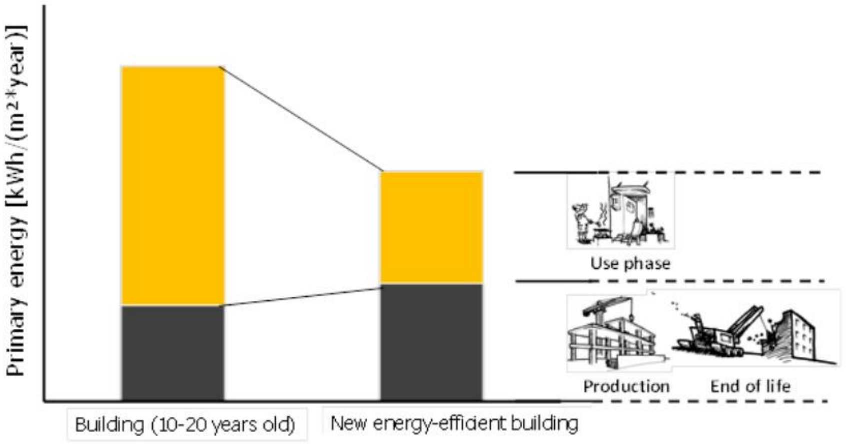


Figure 1: Comparison of emissions from construction materials, and from energy in use phase (Kristjansdottir, 2014)

This research emphasizes the importance of holding a life cycle perspective when quantifying environmental impacts of a building. In this manner one will comprehend total emissions from all materials, including upgrading or maintaining quality, energy consumed by residents, and waste treatment of materials in end of life (EOL).

Blengini and Di Carlo (2010) conducted a detailed Life Cycle Assessment of an energy efficient house and found that the maintenance process had a significant share of total life time emissions. This is because materials in general is the most significant contributor, seen in total, according to the study. Therefore, recycling construction materials used in buildings is a great opportunity to reduce environmental impacts. In comparison to the materials, the construction and transportation of materials are minor emission contributors (Blengini and Di Carlo, 2010).

Lolli (2014) found that energy efficient buildings require construction materials that are more emission intensive. He stresses the importance of considering embodied energy in materials. LCA methodology should be used to measure accurate amounts of embodied energy in future building stock. Thus in order to measure the energy needed for a material in a life cycle perspective (embodied energy), there is a need to use advanced environmental assessment tools. The embodied energy may be as critical as energy consumption in the operation phase. Location and energy sources in production of the materials are the most significant factors, according to Lolli (2014).

The national Green Building Alliance and the consultancy firm Context AS have developed a Green Material Guide to assist architects, advisors and builders. The report assesses several construction material groups and presents the GHG emissions and resource basis, among other factors. There is also an overview of what environmental documentation the material has. This includes the Ecolabel, the Scandinavian Svanemerke, PEFC, FSC, NAAF and EPD. The guide is helpful for decision-making regarding sustainable construction materials (Bramslev and Hagen, 2015). Nevertheless, various stakeholders influence the choice of materials and the exact amount needed is not known prior to construction. In order to comprehend total environmental impacts of a project, LCA methodology can be applied as a tool (see chapter 3.1).

There are several factors to consider when choosing construction materials for building projects. Leland (2008) has written a report on projecting for reuse and recycling in buildings and listed important principles for materials in this context:

Table 4: Important factors to consider when choosing materials (Leland, 2008).

To optimize possibilities for reuse and recycling of construction materials
- Use materials that can be recycled and have few ingredients to make sorting easier
- Use components of moderate size that hold a low weight
- Use components with standard dimensions. Building systems can enable reuse in other buildings.
- Use resistant materials that can withstand reuse
- Avoid surface treatment that limit possibilities of recycling

2.2.1 Lifetime of Components

Brand (1994) argues traditional designs of buildings are built with a low-cost standard that people recognize and can easily modify. By using this design, people are more expected to change components and elements of a building to meet their needs. The figure below illustrates Brand’s (1994) argument that the different changes of all components lead to a building that is constantly modified. The components are shifted as a trend that will continue over time to meet the need of the building’s function. As all the components in the figure are dependent on each other, an integrated trend will be to change every layer continuously. Thus the lifetime of materials will be shortened because of cultural patterns.

"Because of the different rates of change of its components, a building is always tearing itself apart." Brand (2014: 13)

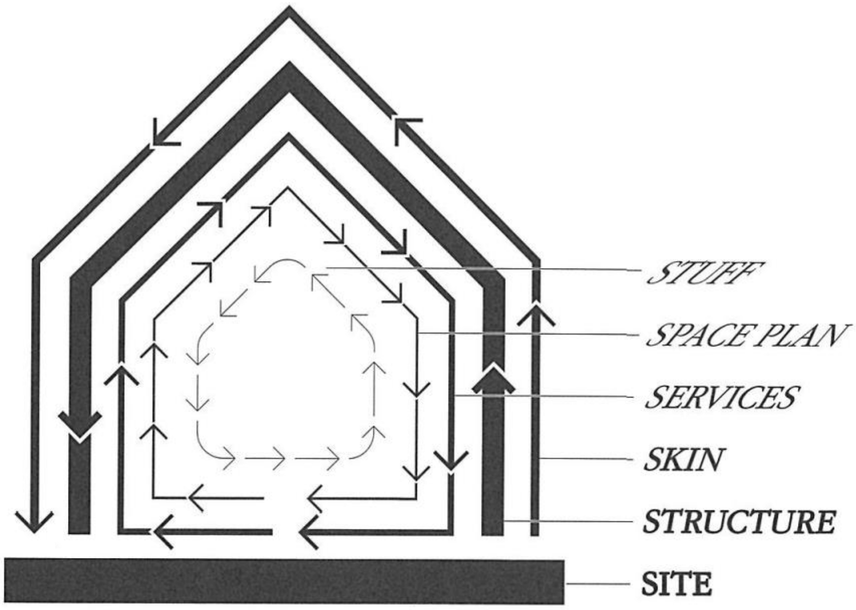


Figure 2: "Sharing layers of change" (Brand, 1994).

Lifetime of construction materials has a significant effect on environmental impacts. Different materials have normed values for lifetime, but these can differ in reality. Several factors influence lifetime such as climate, construction habits, patterns of use, and esthetics. The importance of each factor is dependent upon a building's function (Plesser and Kristjansdottir, 2015)

Kampesaeter et al. (2009) used data from a thesis to comprehend realistic lifetimes of material groups. By interviewing relevant actors, the author examined that the difference between technical and functional lifetime of construction materials differ quite significantly. The technical lifetime refers to the time before the material or product decay, depending on factors such as quality, design, use and maintenance. The functional lifetime depends on different claims of function that can in practice shift rapidly with for instance new residents. It seems that the latter lifetime is often lower than the technical (Kampesaeter et al., 2009).

Figure 3 is generated based on Bjørgberg's (2010) system (Evjenth et al., 2011). If sustainable buildings are emphasized and developed, the lifetime of materials will increase because of improved functionality. Point one illustrates the point of standard and functionality when a building is constructed, point two presents the improved standard because of maintenance activities. The third line presents the main purpose of the figure - if a building is constructed more sustainable it will sustain longer without the need of rehabilitation activities as often (Evjenth et al., 2011).

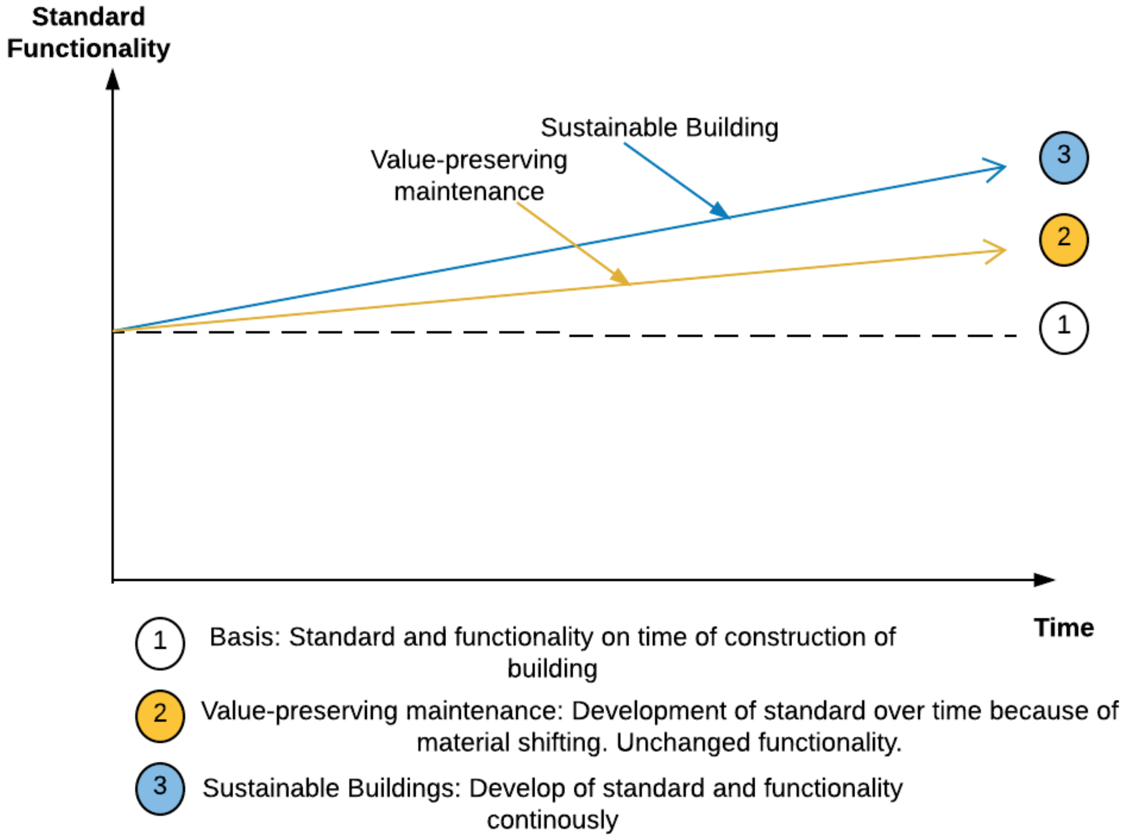


Figure 3: Illustrating good investment potentials in sustainable buildings, based on Bjorberg (2010) in Evjenth et al. (2011).

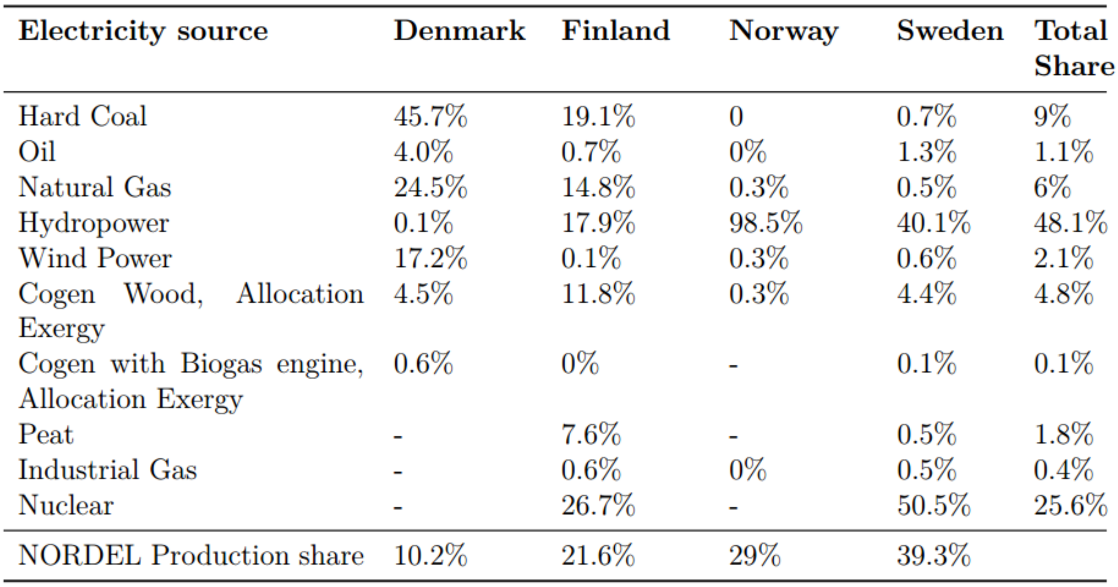
2.3 Energy for buildings

According to Thunes (2016), 40% of all energy is used for buildings. Older buildings consume a significant amount of energy in comparison to low-energy (also shown in this study). The electricity mix - the combination of energy sources, can differ significantly depending on location. Hence the great variance in emissions related to energy use. Renewable energy has a lower carbon footprint, while burning of fossil fuels to generate energy cause great emissions and increase the global warming potential. The studied apartment building previously received energy from GRID and oil boilers, but changed to local district heating after the upgrading.

2.3.1 Electricity mix from GRID

Norway produces mostly renewable hydro power, however is connected with the rest of Europe through an electrical GRID network. This is because Norway is a part of NordPool – a Nordic electricity exchange (Rauboti and Vinjar, 2013). Thus although Norway produces mainly renewable hydropower, 99% in 2000, it does not mean the consumption mix is equal as the production mix. Relevant electricity mixes for Norway is the Norwegian-, the NORDEL-, and the UCTE electricity mix (Dahlstrøm, 2011). The NORDEL energy mix regards the Nordic countries in Europe. Details on nations and energy sources are illustrated in the table below. The European el mix contains less renewable today, however the goal is to increase the share by 20-30% by 2020 (European Comission, 2015).

Table 5: The NORDEL mix content (Spiegel, 2014).



Electricity source	Denmark	Finland	Norway	Sweden	Total Share
Hard Coal	45.7%	19.1%	0	0.7%	9%
Oil	4.0%	0.7%	0%	1.3%	1.1%
Natural Gas	24.5%	14.8%	0.3%	0.5%	6%
Hydropower	0.1%	17.9%	98.5%	40.1%	48.1%
Wind Power	17.2%	0.1%	0.3%	0.6%	2.1%
Cogen Wood, Allocation Exergy	4.5%	11.8%	0.3%	4.4%	4.8%
Cogen with Biogas engine, Allocation Exergy	0.6%	0%	-	0.1%	0.1%
Peat	-	7.6%	-	0.5%	1.8%
Industrial Gas	-	0.6%	0%	0.5%	0.4%
Nuclear	-	26.7%	-	50.5%	25.6%
NORDEL Production share	10.2%	21.6%	29%	39.3%	

For this study, the NORDEL mix is applied in the operational phase calculations, and for the construction activities during the upgrading. When possible, this mix was also chosen for production of materials. This is because most construction materials utilized in the upgrading project seem to have been produced in the Nordic countries. The relevant electricity mixes are assessed in a scenario analysis in chapter 6. This study will illustrate the significance of identifying what electricity mix is applied in production of materials, and used in the operation phase. This is important because the carbon footprint between the el mixes differ.

2.3.2 District heating

The concept is based on using energy that is left from various processes that would be waste if a district heating system had not utilized it. This practice reduces total use of energy resources, and acts as energy efficiency at a system level. A district heating system distributes hot water from energy centrals to users. It is infrastructure that can gain heat from various sources, and possibly from uncommon, futuristic sources (fjernkontrollen.no, 2015). In the figure below, the share of district heating source for Norway is presented.

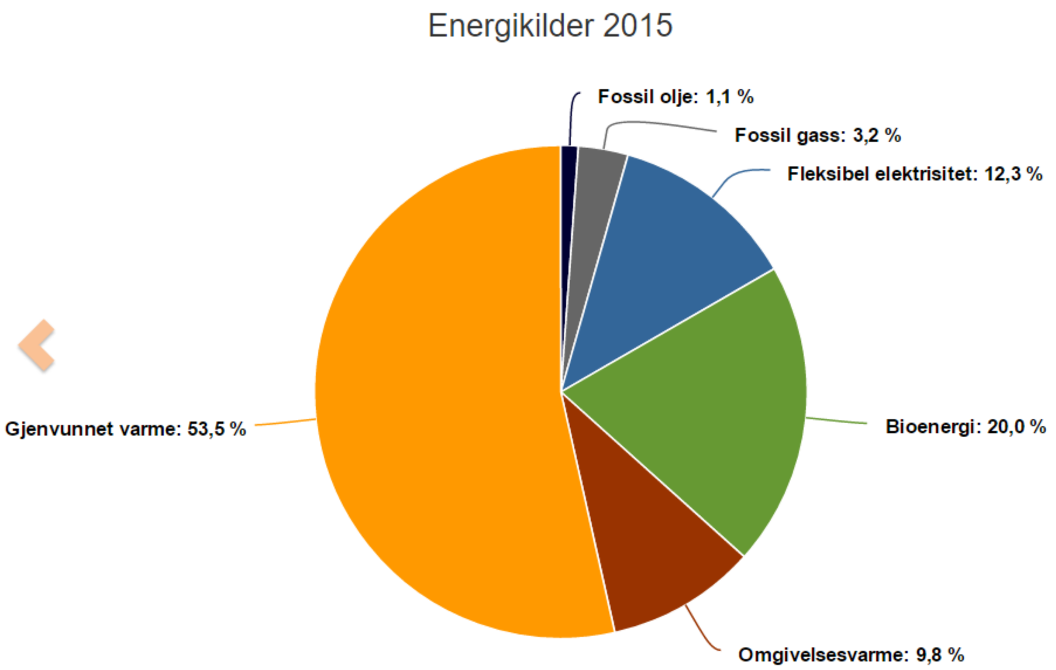


Figure 4: The district heating shares for Norway (fjernkontrollen.no, 2015).

The district heating energy sources in Norway today can range from heat recovered (53.5% - mainly from waste incineration), 20% of total from bioenergy, 9.8% from ambient heat, 12.3% from flexible electricity, and also from oil and gas, depending on location in Norway. Three different scenarios from Kristiansand, Stavanger and Harstad are presented in chapter 6, where GHG emissions with different district heating mixes are calculated. The relevant mix for this case, Kristiansand, is shown in life cycle inventory, chapter 4.

3.Methodology

In this study the method Life Cycle Assessment (LCA) is used to quantify environmental impacts (focus on global warming potential in CO_2-eq) of the ambitious upgrading of an apartment building. The LCA software program Arda (assisted by Matlab) is used for all calculations (see 3.1.5). MS Excel is used to both treat data prior to impact assessment, and to analyze results and generate presentable tables and figures. In addition to LCA methodology, semi-structured interviews were carried out as part of the data collection.

3.1 LCA methodology

A LCA assesses environmental impacts from a process or a product's life. A complete assessment includes all life stages from cradle (extraction of raw materials) to grave (waste treatment). All life stages can be significant in terms of environmental impacts (Baumann and Tillman, 2004). Thus all need to be accounted for to obtain a fair, realistic comprehension of the process or product's impact on the natural environment. Life cycle thinking is illustrated in figure 5 below (LinkCycle, 2013).

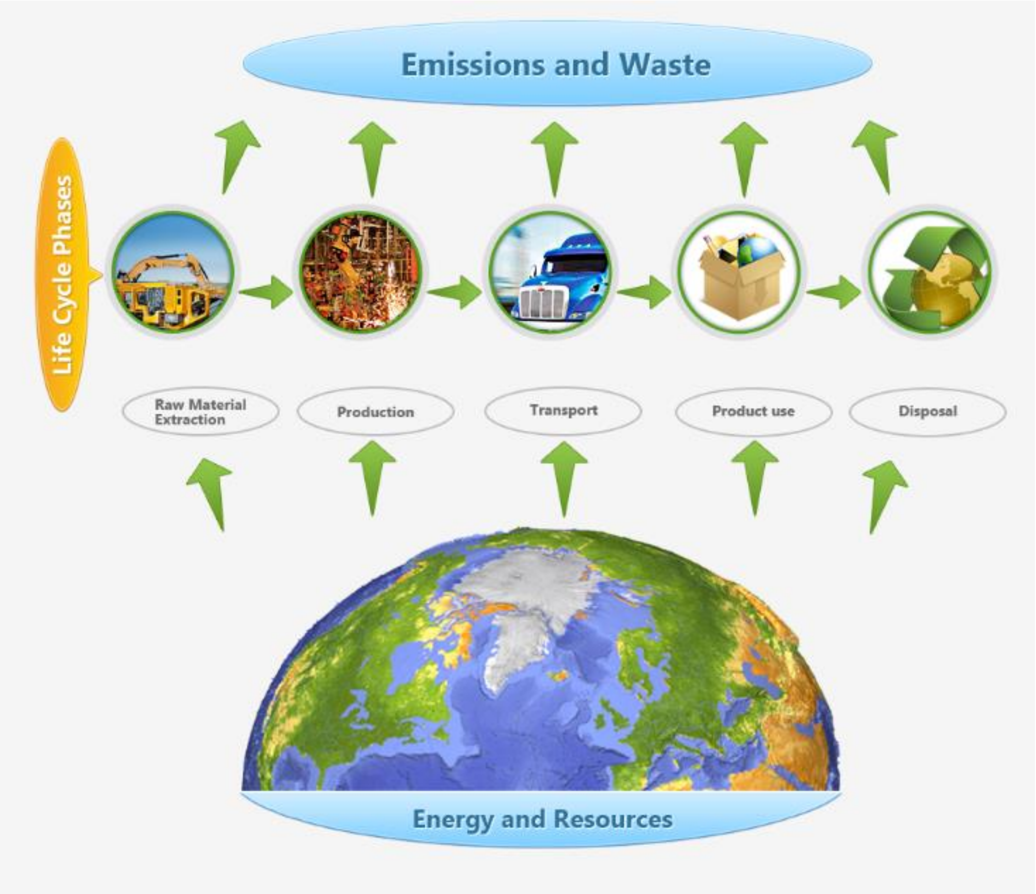


Figure 5: Illustrating the scope of Life Cycle Assessment studies. Source: (LinkCycle, 2013).

The tool can assist in (ISO 14040, 2006):

- "*Identifying opportunities to improve the environmental performance of products at various points in their life cycle*
- *Informing decision-makers in industry, government or non-government organizations*
- *The selection of relevant indicators of environmental performance*
- *Marketing"*

The International Organization for Standardization (ISO) defined the LCA framework in the 14040 standard (ISO 14040, 2006). The four phases in an LCA study are illustrated in the figure below and shall be explored in this chapter: Goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), and interpretation.

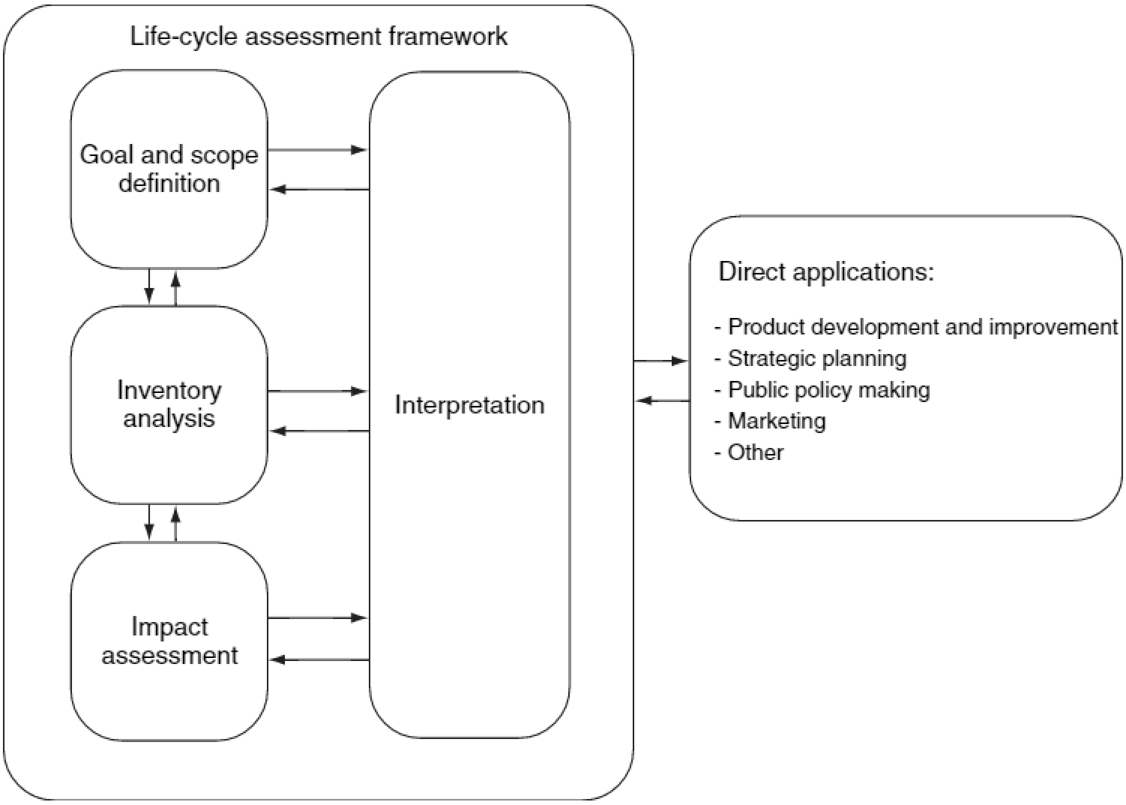


Figure 6: Phases of an LCA (ISO 14040, 2006).

LCA does not commonly include social and economic aspects, these are covered by social LCA (S-LCA) and Life Cycle Costing (LCC). By applying environmental LCA one can make informed decisions that regards the natural environment (Baumann and Tillman, 2004).

3.1.1 Goal and Scope

The goal of a LCA shall state the purpose for conducting the study, and who it will be communicated to. Defining the scope includes determining model characteristics such as functional unit, choosing impact categories, and system boundaries. The scope should also consider data requirements, assumptions and limitations. Nevertheless, modifications of the scope may be necessary to meet the original goal as data and information is collected in step 2 (ISO 14040, 2006).

When the goal is stated and the system defined, the functional unit (FU) needs to be determined. A system can have several functions and one must be selected based on the goal and scope. The FU quantifies the functions in order to obtain a concrete "case to solve". When two systems are compared, it is vital to hold the same functional unit to hold a common basis for comparison. The system boundaries in addition determine grasp and limitations of study, thus inventory type and quantities are considered for the calculation. When setting system boundaries one should consider raw materials, manufacturing, transportation, use and maintenance of products, disposal, and recovery of process wastes and products (ISO 14040, 2006). A LCA of merely one life stage can also be conducted (e.g. finding EOL impacts of a product).

3.1.2 Inventory Analysis

A life cycle inventory of the defined system is created by collecting and calculating data. All input and outputs shall be accounted for in relation to the functional unit. Inputs are all materials and energy used in the system, while outputs are products, co-products (e.g. district heating), and waste. Outputs also include the environmental impacts such as emissions to air, discharges to water and soil. The inventory can be divided in groups based on researcher's interests, depending on the goal and scope of the LCA. In some cases, this first step may be revised after investigation in step two – the inventory analysis (Curran, 2008).

Data collection can be a significantly time consuming process as various suppliers and information sources often need to be involved. To follow the LCA planning this should therefore be considered when defining goal and scope, and also documented in the study report. Allocation is also significant as most industrial processes yield more than one product and aim to recycle used materials to gain raw materials as input in a process. Thus these are common practices, however it should be considered in the beginning of the LCA as the procedures might be resource-intensive (ISO 14040, 2006).

3.1.3 Impact Assessment

The purpose of the impact assessment is to turn the life cycle inventory to information about environmental impacts deriving from emissions and resource use (Baumann and Tillman, 2004). The first step is classification where inventory parameters are sorted to the relevant environmental impact. CO_2 for instance, contribute to global warming potential. Characterization is step two where the degree of contribution to each impact category is calculated. In this manner one can identify what inventory that contributes the most to each category. The impact categories have different units, and the global warming indicator is CO_2-

eq. Thus, all emissions contributing to this impact must be converted to this unit. There are also two additional steps which are optional - normalization and weighting. However, these are not covered in this study. Impact assessment is vital when performing an LCA. Nevertheless, there are uncertainties and limitations in the characterization step.

The LCA generated in this study utilized the impact assessment method ReCiPe. This method performs the steps identified above - classification and characterization. These transforms the list of inventory into a limited amount of indicator scores (Goedkoop et al., 2012). As a basis for modelling, the method uses an environmental mechanism which can be interpreted as a series of effects that together create damage to ecosystems or resource depletion, for instance.

ReCiPe can quantify midpoint and endpoint LCA indicators. The eighteen midpoints are robust category indicators (based on data from IPCC and scientific models), but can be challenging to comprehend. The three endpoints are uncertain (based on data from WHO and own models), but simple to understand. The latter three are damage to human health, to ecosystem, and resource loss (Goedkoop et al., 2012). The user can choose which one that will be assessed. The endpoints are not included in this thesis.

The figure 7 illustrates how results from the inventory analysis are calculated to midpoint categories, and optionally to endpoints.

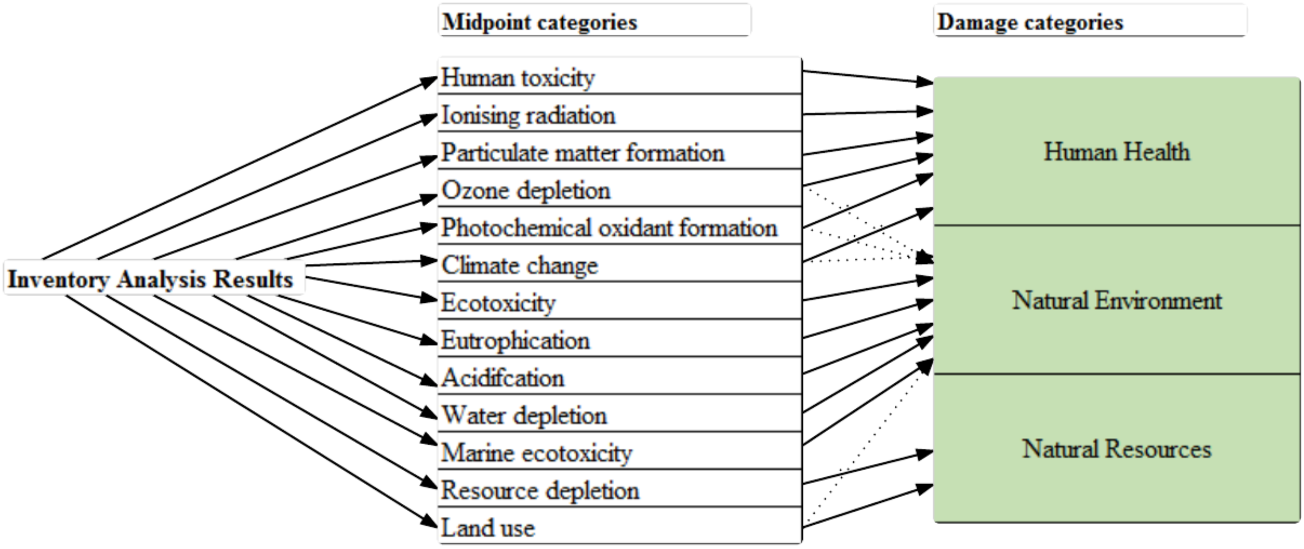


Figure 7: LCA methodology; from inventory, to midpoint categories, to damage categories.

3.1.4 Interpretation

In the last step of an LCA, one interprets the results of the life cycle inventory and impacts assessment. This is in order to comprehend significant findings, and present them in an understandable manner. Values are gathered, evaluated, and compared prior to figures and tables are produced for the readers. The results can guide or support decision-makers, however it is important that modelling choices and assumptions made are shown as well (Curran, 2008).

3.1.5 LCA tools used

Arda

The Industrial Ecology research group at NTNU developed the LCA software Arda that is used for educational and professional purposes. The software allows the user to produce their foreground matrix and connects this with ecoinvent v.2.2 – the background database. Arda is integrated with the impact assessment methodology, ReCiPE (see 3.1.3). Software used as assistance for Arda is MS Excel and Matlab. Excel was used to generate the LCA model and analyze results after impact assessment. Matlab is used in impact assessment.

Ecoinvent v. 2.2

Conducting an LCA is data intensive work and collecting the data can be time consuming - also experienced in this study. Data with high quality is needed in order to produce a good analysis. Accumulated knowledge from previous LCA studies must be built to construct a life cycle inventory. This is completed in the foreground system with an available database (such as ecoinvent) which comprises all relevant background processes. The ecoinvent center aims at delivering transparent international LCA data to their users – both research institutions and consultancies. The background database is a project between institutions in Europe and has the most complete and greatest quality of LCA databases for Europe (Strømman, 2010). The latest functional version for this study was v.2.2, released in 2009, although version 3.1 was released in 2014. Ecoinvent contains several process categories including metals, wood, transport, energy supply, plastics, basic chemicals, waste treatment services, fuels, and heat production. It is built with over 20 years of experience (Ecoinvent, 2016). As the only con recognized, the database might seem fragmented in its structure, according to Strømman (2010). This means that emissions from processes are split into several different sub-processes.

3.2 Presentation of Case: Stjernehus housing cooperative

The ambitious upgrading of Stjernehus was a pilot project in cooperation with Framtidens Byer (Future Cities), Lavenergiprogrammet (the low-energy program) and Norwegian architects National Association. The project was conducted in 2014-2015 in the city of Kristiansand, southern Norway (see map below). The apartment building built in 1965 was assumedly the coldest in the south of Norway and needed to save energy for both costs and comfort. The goal was to change electricity source from oil boilers to district heating. The upgrading also included replacing old shell components with new quality materials. The building is located in Kristiansand's "skyline" area with 11 floors and 60 apartments and it was therefore a focus on the architectural design in the rehabilitation (Husbanken, 2014). The focus of this study is the rehabilitation process and particularly the construction materials consumed to upgrade to low energy, class 1. The pictures below present the case building Stjernehus before, and after upgrading.

Figure 8: Picture of the apartment building Stjernehus before the rehabilitation (Hasenmüller, 2014).

Figure 9: Picture of apartement building Stjernehus after the upgrading (Hasenmüller, 2014).

The pictures illustrate the great change after the upgrading. Notice the asbestos sheets that was shifted with fiber cement tiles on all exterior walls, the 60 new balconies, and all the new windows.

In the tables and picture below, key information on Stjernehus is presented. This includes old and new energy characteristics, area, and a map that presents the location of Stjernehus in Kristiansand.

Table 6: Site characteristics for Stjernehus (Hasenmüller, 2014).

Area	**Stjernehus housing cooperative**
Heated area	3750 m2
Per apartment	63 m2

Table 7: Energy characteristics for Stjernehus (Hasenmüller, 2014).

Energy	**Old**	**New**
Net energy	297 kWh/m2/y	88 kWh/m2/y
Delivered energy	337 kWh/m2/y	97 kWh m2/y
Energy label		LabelB
Heating grade		Green
Main energy source	Oil heating	District heating

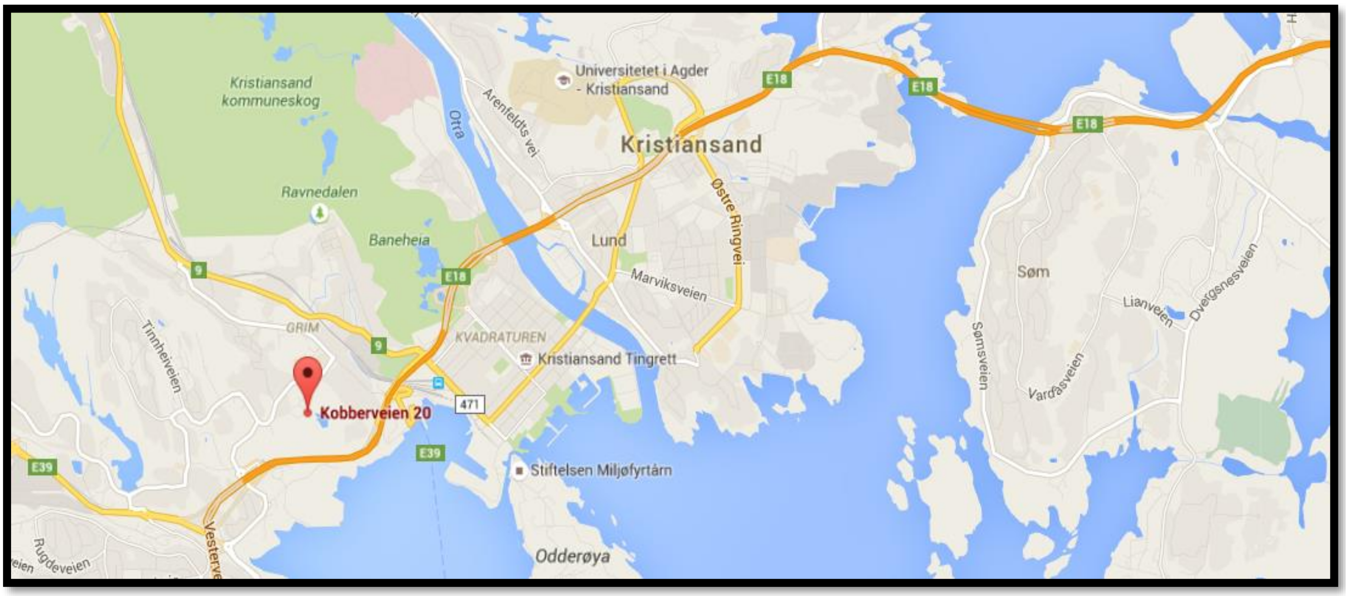


Figure 10: Location of Stjernehus housing cooperative in Kristiansand.

The table 8 lists issues prior to the upgrading and what measures that were performed.

Table 8: Issues before- and measures in the upgrading (Hasenmüller, 2014).

Issues prior to upgrading	Measures in upgrading
• Significant thermal bridge in the concrete construction • Great necessity of heating • Need for maintenance	✓ Insulation of walls, floor, roof ✓ Removal of thermal bridges ✓ Asbestos removal of facade panels ✓ New cover of the facades ✓ Change doors and windows ✓ New, glassed balconies ✓ Assemble balanced ventilation with heat recovery ✓ Replacing oil boilers with district heating ✓ Adaption in relation to universal design

3.3 Goal and Scope

The main goal and scope of this thesis is to identify the carbon footprint of the ambitious upgrading of Stjernehus building cooperative.

3.3.1 Functional Unit

The functional unit is the *upgrading process of one building block built in 1965 to a low energy class 1 in energy use with 3750 m2 of useful floor area. Construction- and end of life phase are included with a material life time of 60 years*. 1 year of operation is excluded from the FU, however shown separately to consider energy emissions saved. In the energy calculations, it is assumed that residents consume the exact values stated in the energy budget (see table 7).

An alternative functional unit could be 1 m^2 in order to compare with other studies.

[Value/3750m^2(/60y) = values per 1 m^2(/year) for comparison]

3.3.2 System Boundaries

The system boundaries determine what life cycle stages that are included in the LCA and how these processes interact (Baumann and Tillman, 2004). In this model the production and end of life management are included. This includes production of construction materials, transportation to site, energy and diesel used during construction, and EOL treatment of materials, including transport to waste treatment plant. The boundaries are illustrated in EPD terminology in table 9 below. The user phase is not part of the main model because the focus is on the building materials used in rehabilitation. The energy consumption in the user phase is however quantified separately.

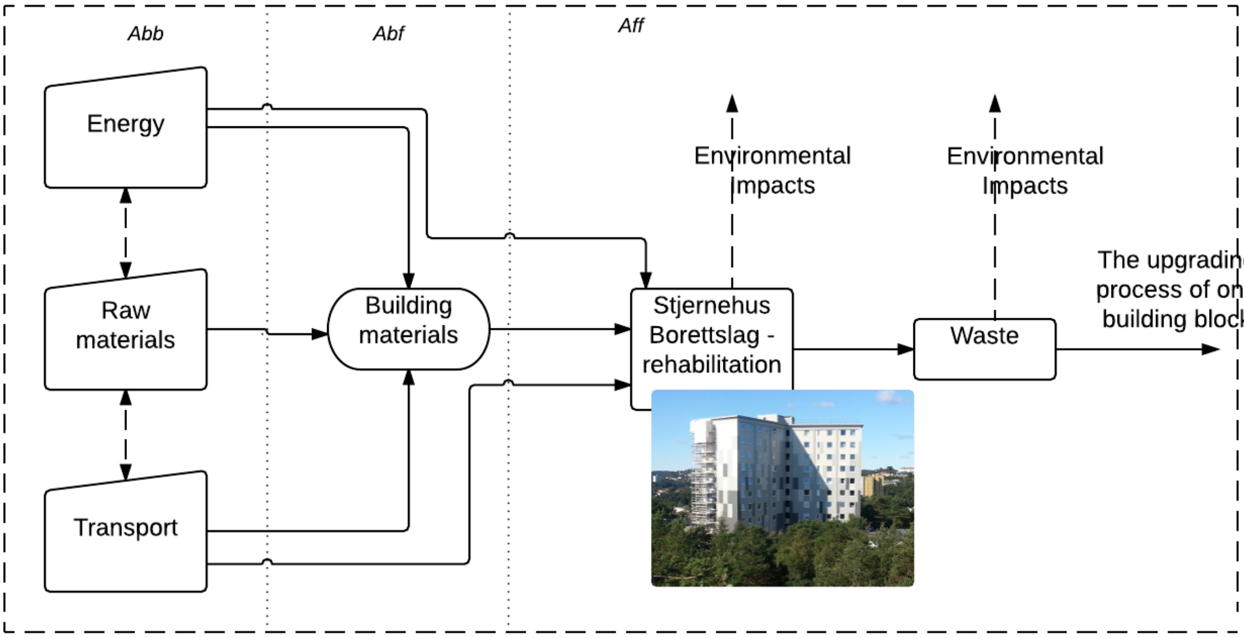


Figure 11: The system boundary in this LCA study of the upgrading of Stjernehus apartment building.

EPD Terminology

The Environmental Product Declaration program in Norway (EPD-Norge, 2016) has a standard format for defining system boundaries as illustrated below. By adapting the EPD program format the study illustrates a different perspective of the system boundary of the LCA. The phases and elements within those that are included for this study is colored. The module names A1 and so, are generated by the EPD program to make comparisons between products easier. For example, if EPDs of two windows cover the same phases and elements, the construction components can be compared fairly (EPD-Norge, 2016). The two different marking colors used the table below is explained.

Orange: Separate from the system boundary.

Blue: Phases included in the system boundary.

Table 9: Adapting the EPD standard format for drawing system boundaries.

Phase	**Product**	**Construction, installation**	**User phase**	**End-of-life**
Element	Raw materials	Transport	Energy consumption	Disassembly
	Transport	Construction, installation		Transport
	manufacturing			Waste treatment
				Finalization
Module	**A1-A3**	**A4-A5**	**B1-B7**	**C1-C4**

For LCA comparisons, the table above simplifies the evaluation regarding life stages included. In LCA comparisons there is a need to hold an equal system boundary for both entities in order to present a fair judgement (Solli, 2015). The system boundary illustrated in figure 11 and table 9 above differs from the model in Klimagassregnskap.no (Holen, 2014a). The LCA generated in this study includes more processes of the upgrading. In addition, applied data was based on invoice, thus more detailed data were available for this study. In chapter 5, a comparison between these analyses are presented with a limited scope LCA. Thus there was a need to adjust system boundaries to perform a comparison with the model in Klimagassregnskap.no (see 5.1).

3.4 Data Sources

3.4.1 Interviews

In order to perform an LCA of the Stjernehus upgrading there was firstly a need to gain comprehension of various processes in the project, important actors, and details of construction materials. Unstructured interviews with Sorlandets Boligbyggerlag and Kruse Smith were completed. In addition, other contacts that were involved in the project including material and power suppliers, were communicated with via e-mail. The most significant data gathering was for all construction materials used in the upgrading process. This data was provided by the entrepreneur for the apartment building, Kruse Smith. In the table below, all contacts for data collection are listed.

Table 10: List of all contacts for data gathering.

Contacts	**Topic**
Kruse Smith	Material list and Suppliers
Sorlandets Boligbyggelag	Details of building and energy report (Sweco)
Holen, Josefine	Author of thesis about Stjernehus using Klimagassregnskap.no
Agder Energi	District heating sources in Kristiansand
Balco AS	Suppliers of the balconies
Lindab AS	Subcontractor of materials for ventilation
Ulstein Blikk AS	Supplier of ventilation materials

3.4 2 Data treatment

All data collected on materials and energy were allocated to a LCI unit process using an Excel template for Arda. The unit processes will be presented in the next chapter. Ecoinvent v2.2 is the database used to quantify environmental impacts from each material, as discussed previously in this chapter.

The data on all construction materials used in the upgrading was provided in a different unit than required in the background database. The material list received was in different units, mostly m^2 or m^3, however kg was commonly required by ecoinvent. Thus there was a need to convert most of the materials into kg. This was a time consuming job, however vital for the study to be generated. Materials' density was relatively easy accessible on product documentation and websites. However, when a material consisted of several components (e.g. glass wool and plastics) each material needed to be split in two as the densities differ for each material.

4.Results

4.1 Life Cycle Inventory Analysis

In this step of the LCA, all the data collected is sorted in a model. Materials are categorized and listed in order for ReCiPe to allocate and calculate environmental impacts (see 3.1.3 on impact assessment). Thus this chapter presents the data used in the LCA model, including assumptions and estimates made during collection. Each section presents each life phase. Data is divided in the processes exterior walls, roof, balconies, ventilation, doors & windows production, EOL for all materials, energy at construction site, and transportation of materials. The content of each is presented below.

A lifetime of 60 years is assumed for all materials used in the Stjernehus upgrading. Nevertheless, as it is challenging to predict this modelling choice, a scenario analysis is conducted in chapter 6, which tests the effects on total emissions with shorter lifetimes of 20- and 30 years.

4.1.1. Construction phase

All materials and related processes required for the upgrading of Stjernehus are listed below including main materials for each group. In the sections below a more detailed list of inventory is presented.

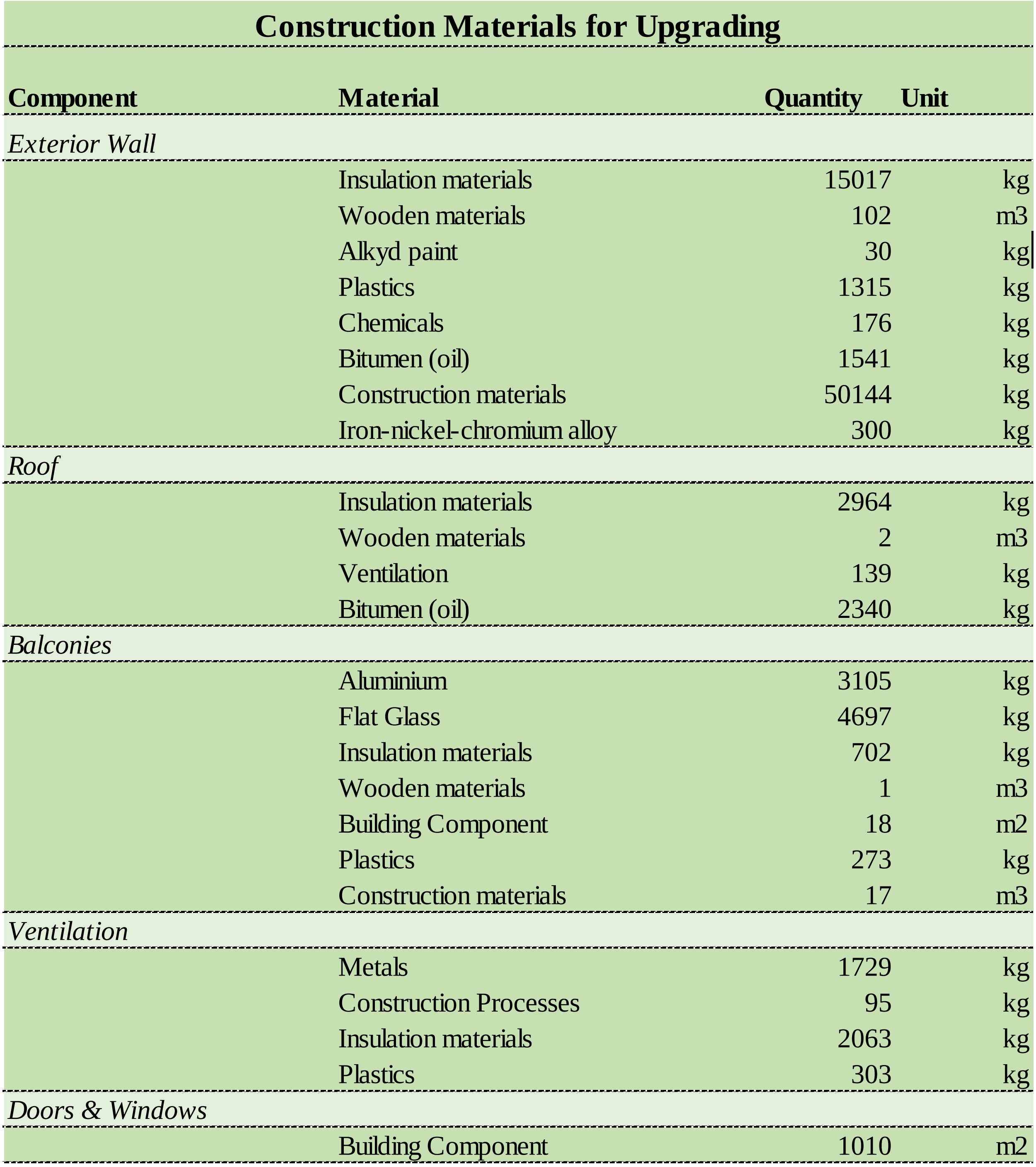
Table 11: Shell components of the upgrading process including main materials.

Shell components	**Main materials**
Exterior walls	Insulation (rockwool), softwood, polyethylene, fibre cement, concrete
Roof	Insulation, fibreboard, bitumen
Balconies	Aluminium, glass, steel, rockwool, bitumen, concrete
Ventilation	Steel, zinc, iron, rockwool, polycarbonate
Doors & windows	PVC, wood, aluminium, glass
Energy, construction site	Electricity NORDEL mix, diesel
Transportation, materials	Diesel to lorry fleet

Materials for construction

The data of materials used in the upgrading was provided by construction engineer, and project leader Torsvik from Kruse Smith (Ronningen and Torsvik, 2016). The material list is based on invoice, thus it is detailed and accurate and used in the calculation model. Notify that the list shown in table 12 below is narrowed to produce a more presentable inventory list. Thus, elements of insulation materials for instance, are summarized to one category of insulation. Electrical work during the project was small and is not included.

Table 12: Inventory list of construction materials used in the Stjernehus upgrading project.



Construction Materials for Upgrading

Component	Material	Quantity	Unit
Exterior Wall			
	Insulation materials	15017	kg
	Wooden materials	102	m3
	Alkyd paint	30	kg
	Plastics	1315	kg
	Chemicals	176	kg
	Bitumen (oil)	1541	kg
	Construction materials	50144	kg
	Iron-nickel-chromium alloy	300	kg
Roof			
	Insulation materials	2964	kg
	Wooden materials	2	m3
	Ventilation	139	kg
	Bitumen (oil)	2340	kg
Balconies			
	Aluminium	3105	kg
	Flat Glass	4697	kg
	Insulation materials	702	kg
	Wooden materials	1	m3
	Building Component	18	m2
	Plastics	273	kg
	Construction materials	17	m3
Ventilation			
	Metals	1729	kg
	Construction Processes	95	kg
	Insulation materials	2063	kg
	Plastics	303	kg
Doors & Windows			
	Building Component	1010	m2

Energy at construction site

The electricity bill from the electricity supplier LOS showed the total amount consumed during construction phase (Ronningen, 2016). The electricity mix NORDEL was chosen in the LCA modelling (see section 2.3.1). Furthermore, diesel burnt in machines at site has previously shown to hold a great impact on results (Dahlstrøm, 2011, Spiegel, 2014). Therefore, the diesel consumption was estimated by the entrepreneur (Ronningen and Torsvik, 2016).

Table 13: Energy used at construction site.

Energy, construction site			
	Electricity, production mix NORDEL	45280	kWh
	Diesel, burned in building machine	48750	MJ

Transport

Transportation of materials from production to construction site is important to include as diesel consumption releases a great amount of GHG emissions. A list of supplier addresses was provided from SBBL (Moen, 2016) and furthermore from the entrepreneur, Kruse Smith. A web page search was necessary in some cases to find location of production sites in order to calculate distances from production to store, and store to Stjernehus apartment building. Google maps was used to find distances. As the majority of construction materials used are produced in Scandinavia, the mode of transportation chosen in the ecoinvent database was lorry 3.5-20t, fleet average. The transport distances were calculated to the unit used in ecoinvent - ton/km.

Table 14: Transportation of materials to construction site.

Transportation of materials			
	Transport, lorry 3.5-20t	688	tkm

4.1.2 Operation phase

The focus of this thesis is the construction materials used in the upgrading, thus the energy consumption in the operation phase is not included in the total GHG emissions in section 4.2 (the main LCA model). However, in order to measure payback time of the materials' emissions, the energy saved per year after upgrading is considered. Furthermore, if lifetime expectancies decreased for some of the materials, the extra emissions would have been added to the use phase as it accounts for using the apartment.

The figure 12 below shows the energy budget to use when aiming for a building with passive house standard, or low energy class 1 or 2. The values are set according to the Norwegian standard NS 3700 (Standard Norge, 2013).

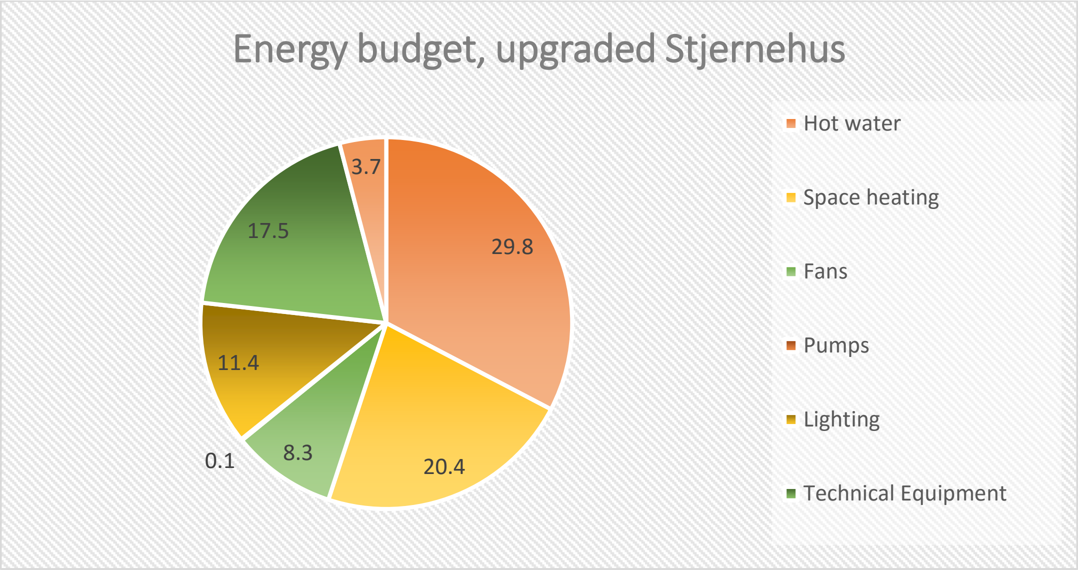


Figure 12: Energy budget for the upgraded Stjernehus building according to Standard Norge (2013).

The upgrading to an energy efficient building apartment lead to a significant reduction in energy use per year. Previously the building received energy mainly from oil boilers which caused high emissions. The main source of energy in Stjernehus after the rehabilitation is district heating as illustrated in figures 13 and 14 below. In order to calculate the reduction of GHG emissions there was a need to identify energy sources in the district heating. At fjernkontrollen.no one can easily choose town of interest and the sources of energy for each area in Norway will appear in a figure as illustrated below (fjernkontrollen.no, 2015).

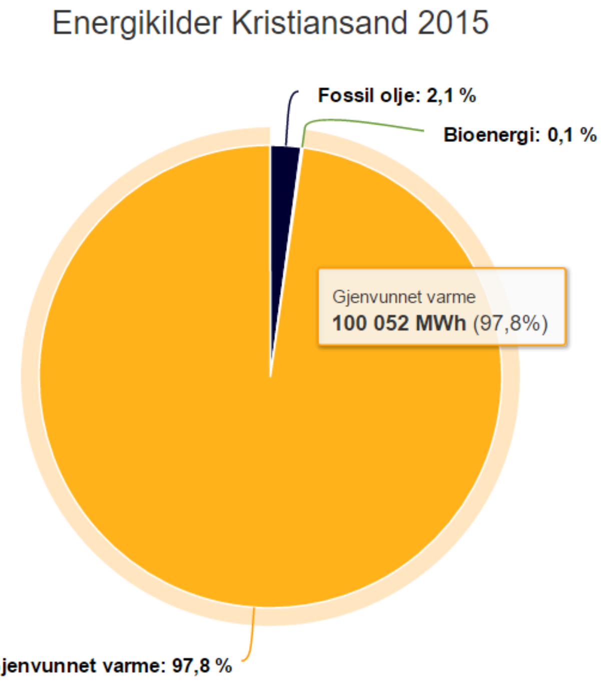


Figure 13: Energy sources from district heating in Kristiansand (fjernkontrollen.no, 2015).

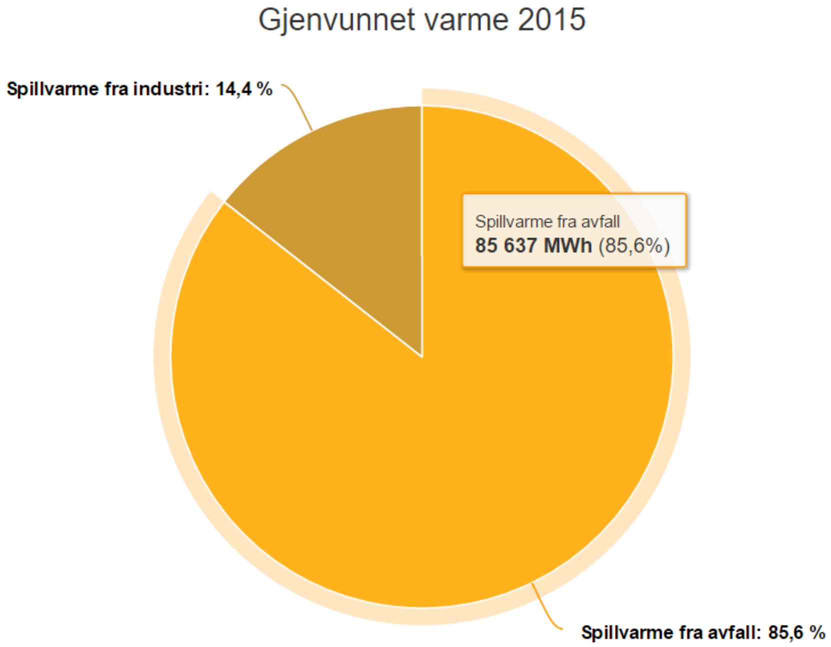


Figure 14: Sources within recovered heat (fjernkontrollen.no, 2015).

Table 15 presents the district heating mix for Kristiansand, thus also for Stjernehus apartment building. 97.8% of delivered energy is from recovered heat from waste incineration and a local industrial plant. Although the energy sources currently used are preferable in an environmental perspective, the production of energy is not completely emission free (see chapter 4.2.2).

Table 15: Energy consumption for Stjernehus building apartment after rehabilitation (Skogheim, 2014, fjernkontrollen.no, 2015).

District heating mix, Stjernehus, 2015	share	*kWh/ m^2 /year*
Bio energy	0.1 %	0.1
Fossil oil	2.1 %	1.4
Recovered heat	97.8 %	64.6
Sum	100 %	*66.0*
+ Electrical GRID, Nordel		37.8
Total energy delivered after upgrading		**102.4**

As one may observe in table 16, the main energy source was oil prior to rehabilitation of Stjernehus. Thus an important measure in the upgrading project was to shift energy sources to district heating and exclude energy from fossil fuels.

Table 16: Energy consumption for Stjernehus prior to rehabilitation (Enova, 2016, Holen, 2014b).

Energy use, Stjernehus, 2012	*kWh/ m^2 /year*
Energy from oil heating	222.5
Energy from electricity	114.5
Toal energy delivered prior to upgrading	**337**

4.1.2 End of Life

End of life (EOL) management for all inventory is treated as one process rather than allocating EOL to each material group (e.g. x kg to exterior walls, and x kg to roof). Both informational access and time were constraints to generate a more complex model of EOL. In the table below all materials included in the EOL process are listed.

Table 17: Materials to end of life management.

Materials to EOL Management	
Wood	Steel
Plasterboard	Iron
EPDM Rubber	Zinc
Facade panels	Rockwool
Roof	Plastic
Concrete	PVC Windows

In table 18 below the inventory list of end of life is shown, including EOL paths chosen in the LCA model. An example of modelling method is the “EOL, steel”, where all steel parts from different components are summarized to this one process.

Table 18: Inventory list of materials included in the end of life processes, including the EOL paths.

EOL materials			*EOL path*
EOL, Wood materials untr	28168	kg	municipal incineration
EOL, Wood fiber, roof	1366	kg	final disposal
EOL gypsum plaster	2534	kg	to sorting plant
EPDM sort rull à 30 m	1549	kg	municipal incineration
Zenit fasadeplater	47600	kg	to sorting plant
Isola mestertekk	2340	kg	municipal incineration
EOL, Wooden materials	17959	kg	municipal incineration
EOL, Concrete	26278	kg	to sorting plant
EOL, glass	5839	kg	to sorting plant
EOL, steel	4748	kg	municipal incineration
EOL, iron	283	kg	to sorting plant
EOL, Zinc	11	kg	municipal incineration
EOL, Rockwool	20275	kg	final disposal
EOL, Plastic	275	kg	to sorting plant

As seen to the right in table 18, there are three different EOL paths assumed for the materials. Figure 15 presents the share of each. The assumptions were based on common practices in the construction sector in Kristiansand. However, both current and future EOL paths are uncertain – practices vary, and may change in the near future (see chapter 6.3.1 about uncertainties).

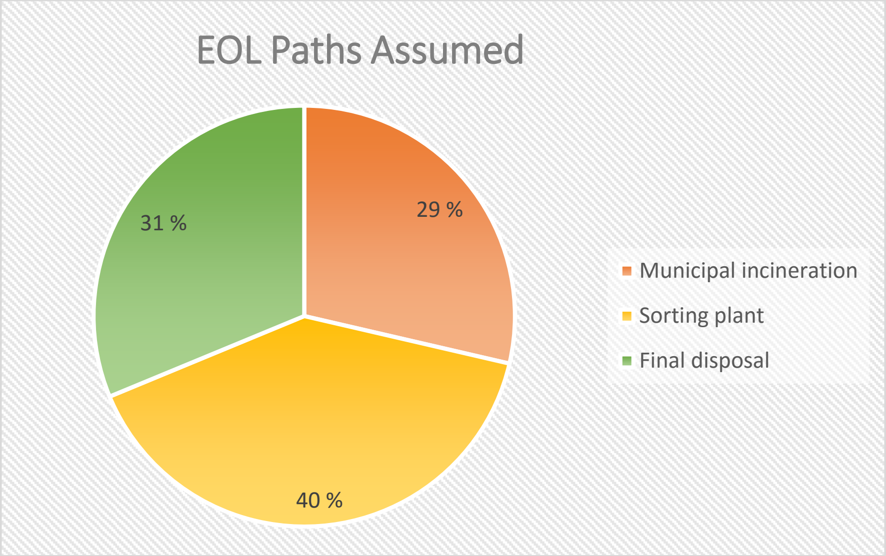


Figure 15: Materials' waste treatment in end of life, from the LCA model

Transportation of waste materials are included in the EOL process. Distance in the model is from construction site to the local waste treatment plant in Kristiansand. This background process is shown in table 19.

Table 19: Transportation of materials in the end of life phase.

EOL transportation		
Transport, lorry 3.5-7.5t	58	tkm

4.2 Life Cycle Impact Assessment

This section presents results from the environmental impacts assessment of the Stjernehus upgrading. The life cycle inventory (in 4.1 above) is calculated to midpoint indicators using the ReCiPe method. This transforms the inventory list into a limited amount of indicator scores. The midpoint categories have different units and can therefore not be directly compared. In this study, the main focus is on the climate change impact category illustrating global warming potential (CO_2-eq). Effects on each impact category from each shell component is also found and presented in 4.2.3.

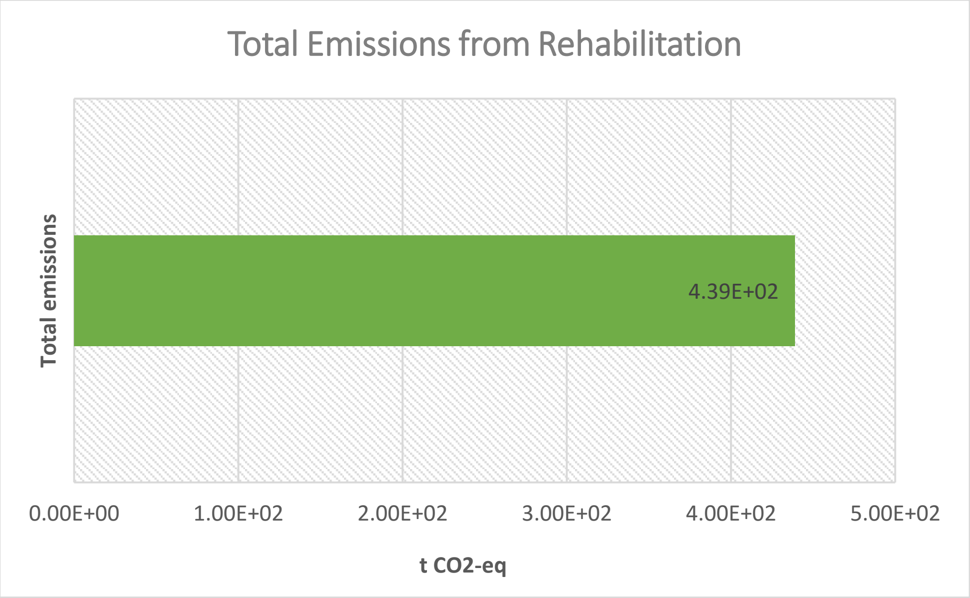


Figure 16: Total emissions from the upgrading project according to LCA results.

Figure 16 above presents total global warming potential (GWP) from the ambitious upgrading of Stjernehus. Thus all substances from construction processes that contribute to GWP are converted to CO_2-eq and summarized. This includes manufacturing of materials, transportation, energy at construction site, transportation in end of life, and waste treatment of materials.

Figure 17 below presents the share of emissions caused by each foreground process in the LCA model. Emissions caused by EOL of materials are summarized and treated as one process, hence the significant emissions in this category. Emissions from construction materials will be explored further in the next section.

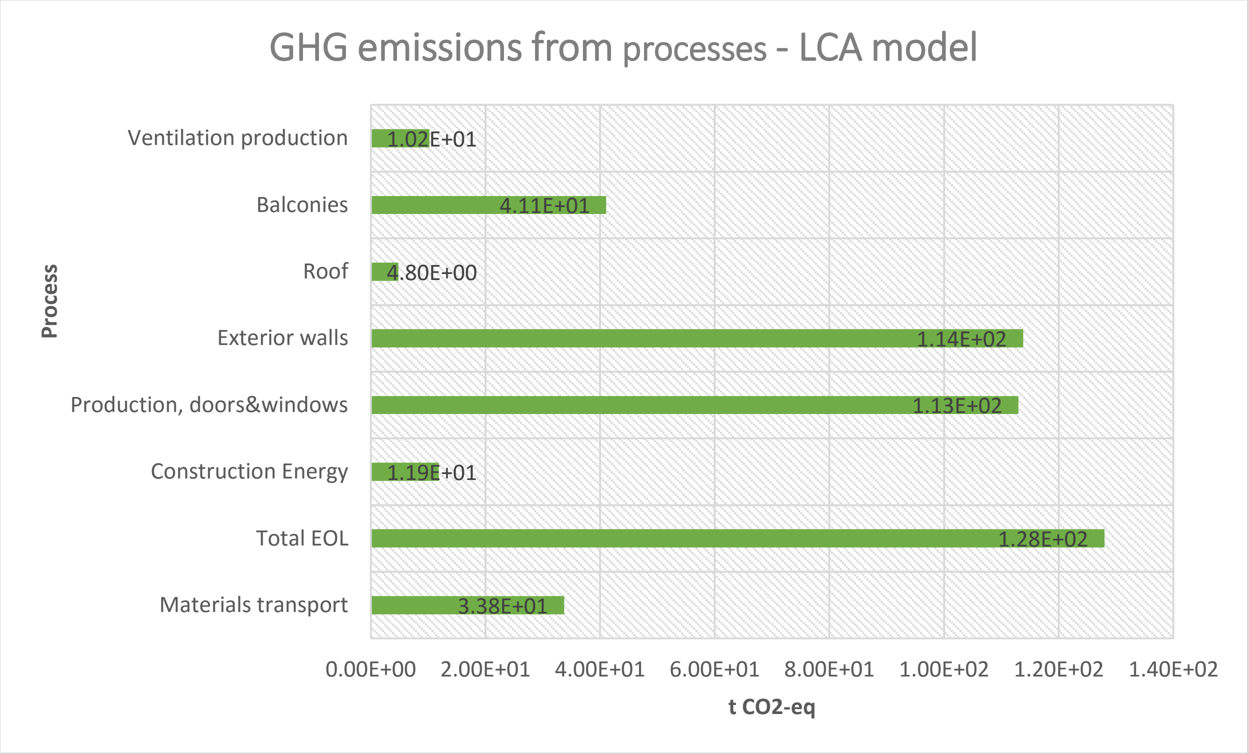


Figure 17: Global warming potential (CO_2-eq) of the different shell components and processes.

4.2.1 GHG emissions from construction materials

In order to reduce emissions from the building sector there is a need to approach it in a life cycle perspective (Kristjansdottir, 2014). The best manner will be to use construction materials with a low carbon footprint (Leland, 2008). Nevertheless, it is important to stress the thermal insulation capacity of materials as well, as this saves emissions in the operation phase of a building (discussed in chapter 6.3.2).

The figure below illustrates the share of emissions deriving from the construction phase and the waste treatment (EOL) of materials. Embodied energy, resource use and waste treatment in combination lead to total emissions.

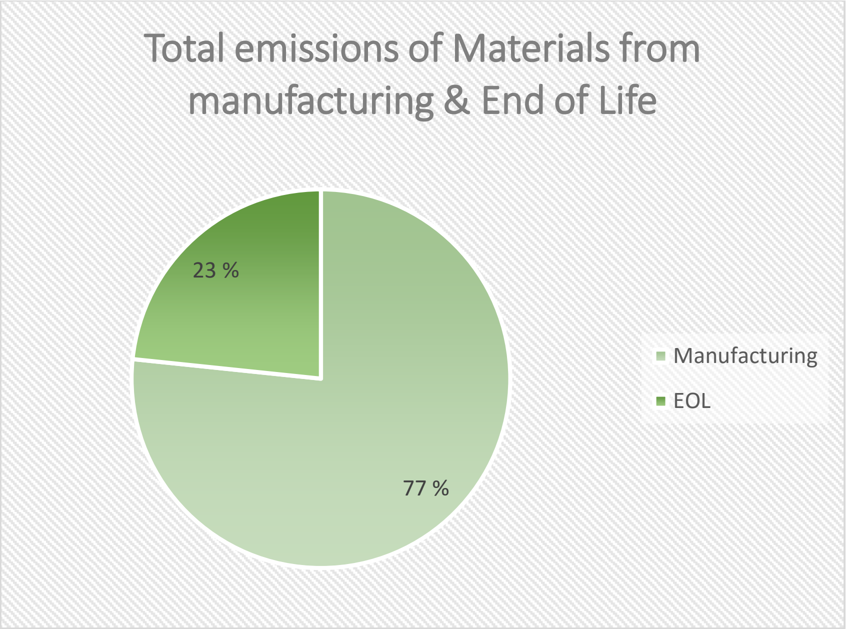


Figure 18: Greenhouse gas emissions of materials from construction and EOL processes.

The figure below illustrates the share of emissions deriving from each shell components (construction material groups). The emissions reflect a cradle to gate perspective, thus the calculation does not include EOL of materials.

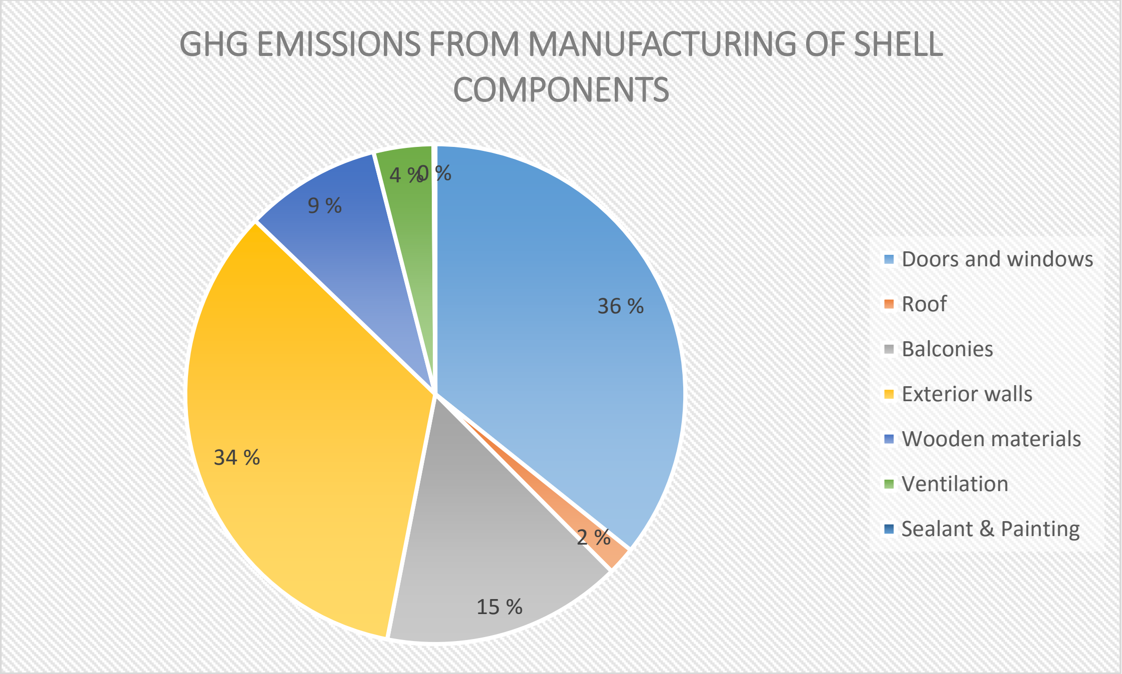


Figure 19: Share of GHG emissions from construction materials.

The doors & windows process is high mainly due to the PVC window sills which require production of polyvinylchloride (PVC), steel, zinc cover, and embodied energy in production and end of life. This is found in the structural path analysis where value chains of emission intensive activities are presented. The figure 20 below presents clearly that both production and end of life treatment of the PVC window sills are emission intensive processes. Notice that the quantity of windows in total for the project was 395, while the amount of doors was 123.

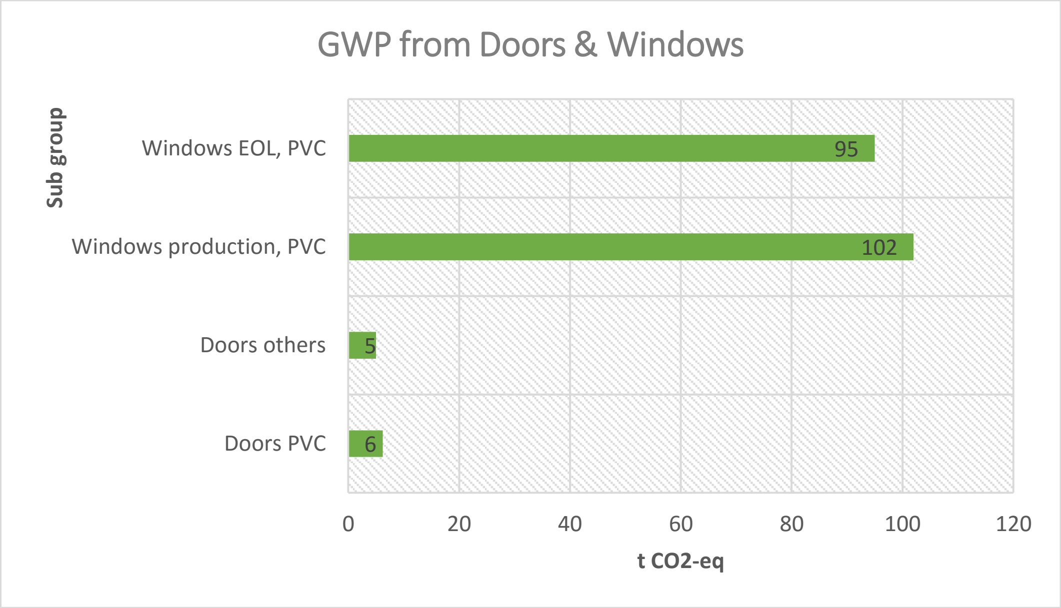


Figure 20: Emissions caused by the doors & windows process, divided in sub groups.

In order to observe what materials that cause the greatest impact for each shell component, the LCA model was adjusted as shown in figure 21. Thus the material list was allocated in a different manner and shell components were shifted with the materials showed below.

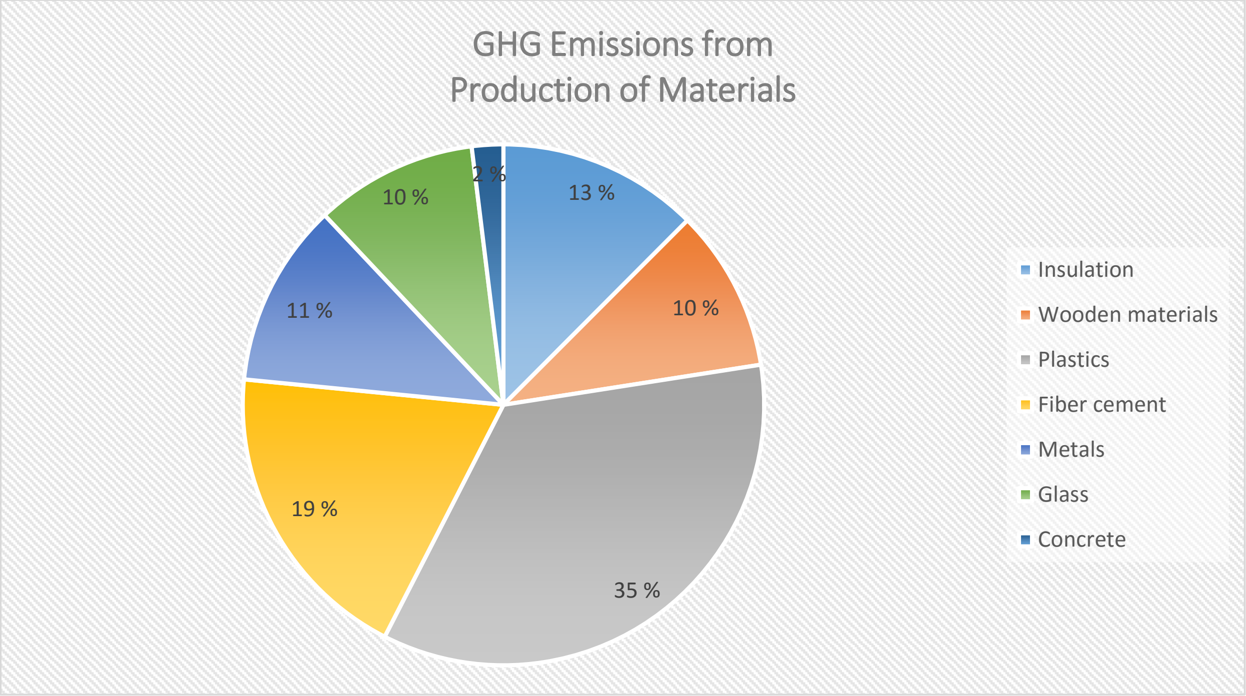


Figure 21: Modeled differently: Version of the Stjernehus rehabilitation to consider materials in shell components.

In figure 17 in the beginning of this section one can observe the share of emissions for each material components. As found, windows and exterior walls are significant processes, however, it does not identify what materials (e.g. plastics, metals, concrete) of the components that caused the major environmental impact. In figure 21 above this is shown by modelling differently. Considering figure 17, which showed the significant impact from plastic window sills, it is not surprising that plastics effect total emissions the most. Furthermore, fiber cement is a great contributor as well as the tiles for exterior walls were made out of this material (significant amounts required to cover all walls). Metals accounted for 11% of total emissions and includes zinc, iron, steel, copper and similar. Concrete is normally causing notable emissions in construction project, however in the upgrading case there was no need to add a lot more, hence merely causing 2% in the figure above.

4.2.2 Energy use

The NS 3700 standard shows requirements (in kWh/m^2/y) for calculations of energy delivered for heating in passive house-, and low-energy building standards (see 3.2 for details). Total delivered should not exceed 101.2 with about 60% coming from district heating and 40% from electrical GRID (Standard Norge, 2013). The TEK 10 standard is less ambitious in terms of emission reduction over a building's lifetime with 115 kWh/ m^2/y. This requirement is for apartment building in particular (Direktoratet for Byggkvalitet, 2015). To provide a perspective of energy use prior to upgrading: Stjernehus demanded double as much energy delivered as the limit of TEK 10.

Before rehabilitation, the energy delivered was 337 kWh/m^2/year (Enova, 2016). By utilizing the LCA method the emissions per year was calculated to be 164 ton CO_2-eq per year. Currently, the delivered energy is 102.4 kwh/ m^2/year (Skogheim, 2014) with emissions per year 25 ton CO_2-eq. That is a reduction of 70% in energy and 84% in GHG emissions per year (see figure 22 below). Thus it is highly beneficial to both reduce energy demand and energy source in upgrading projects to reach significant emission reductions. The graph below illustrates development of emissions over time with the old Stjernehus energy use (energy delivered, see table 1 in chapter 2) and after the energy upgrading.

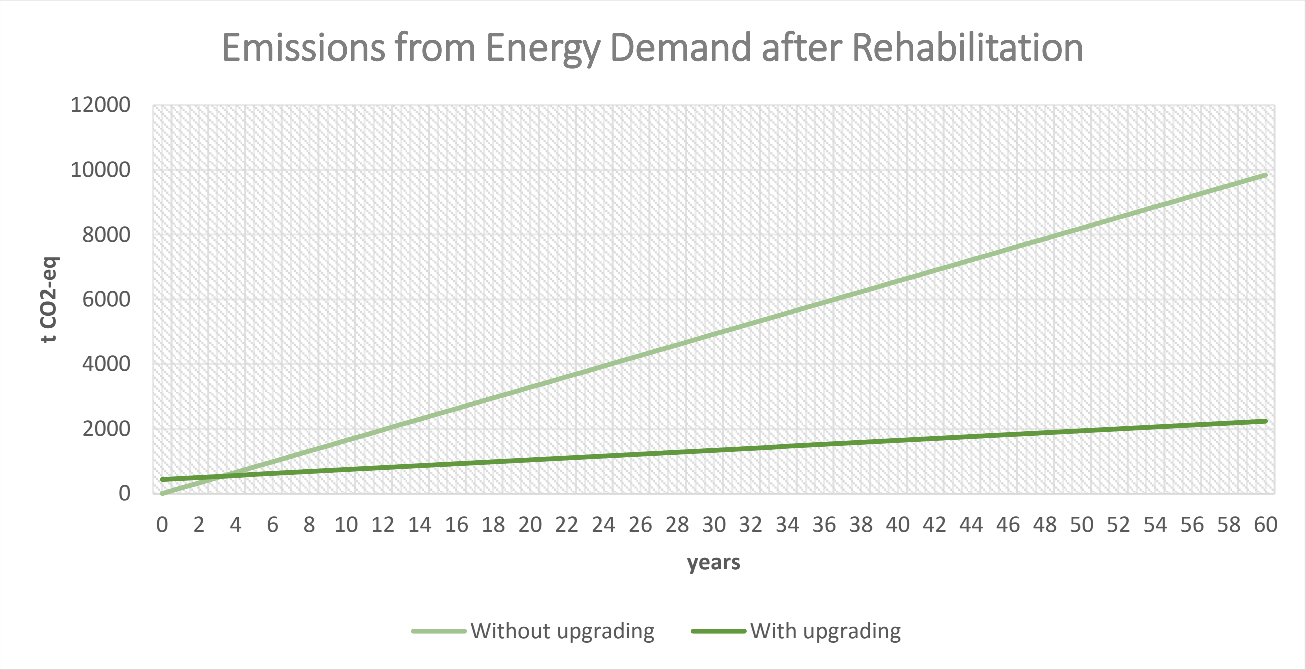


Figure 22: Future emissions from energy demand with and without rehabilitation, including construction emissions.

The dark green line starts at 439 t CO_2-eq in year 0 as these are the emissions caused by the upgrading. In chapter 5, further examining of energy use shall be presented, including comparisons and payback time of emissions.

4.2.3 Environmental impacts

Greenhouse gas emissions are the main focus of this study, however the LCA methodology accounts for several impact categories. Seventeen midpoints are shown in this section. The upgrading of the apartment building effects several elements in nature because of materials and energy needed. Figure 23 illustrates total environmental impacts. Notice that units differ for all environmental impacts. The values for each category are added to the Appendix C.

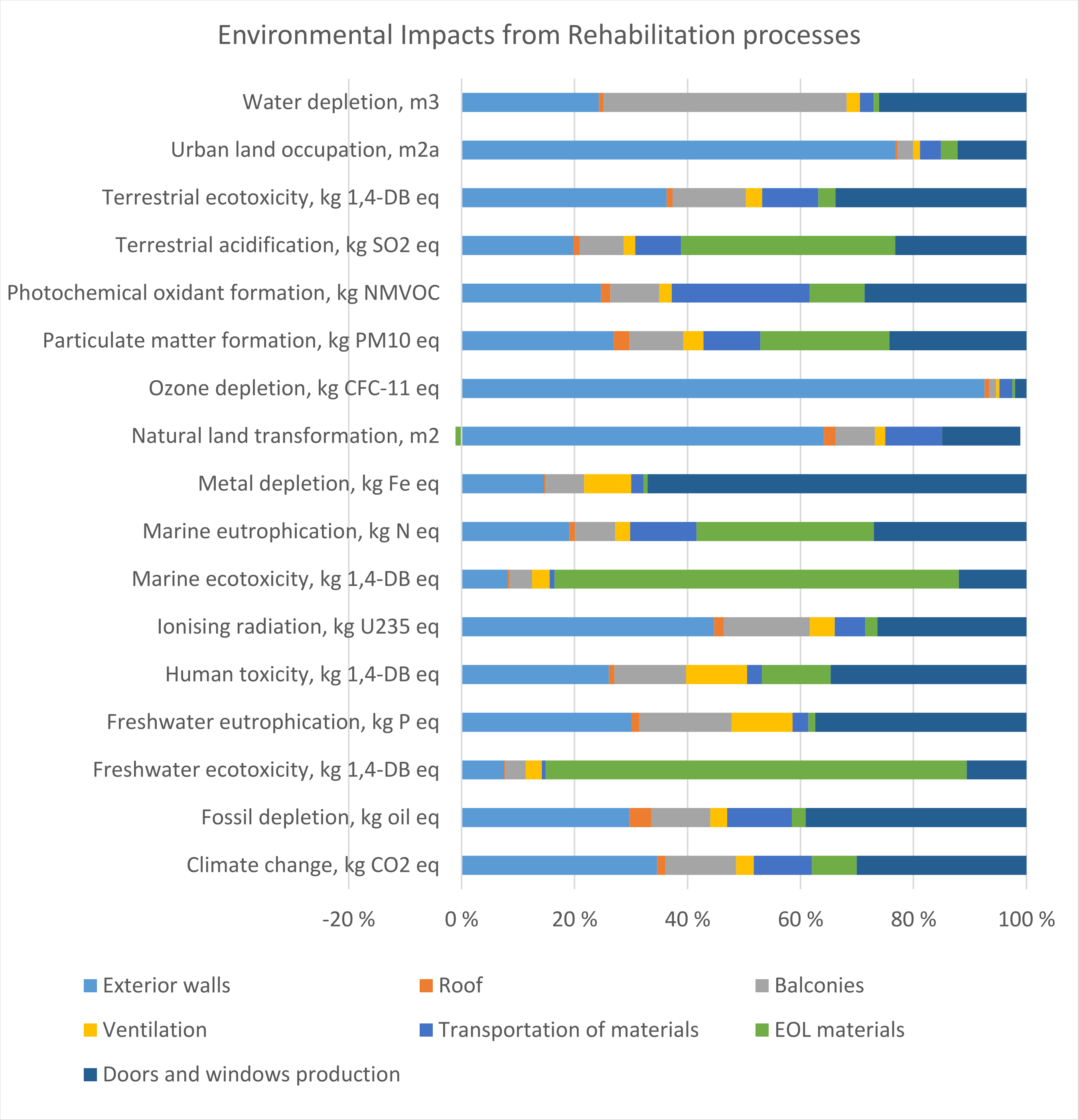


Figure 23: Environmental impact categories affected by processes from the upgrading project. Values in Appendix.

The figure above shows effects on 17 impact categories from each shell component and related processes. These are marked with colors and listed in the bottom. The material groups only include the manufacturing phase, not the end of life. The latter phase is collected as one process presenting total environmental impacts from EOL of all materials.

Not surprisingly one can see that the two processes exterior walls and doors & windows production dominate for the majority of impact categories. This is shown throughout this chapter. Exterior walls particularly influence urban land occupation, ozone depletion, and natural land transformation. In the structural path analysis, it was found that fiber cement facing tiles were the greatest contributor to exterior walls. This require cement production, which emits CO_2 in the clinker production and therefore effect ozone depletion. Cement production require great amounts of land and resources (e.g. limestone) (WBCSD, 2002). By examining the value chain in this manner, one can identify why exterior walls effect these three impacts significantly. The metal depletion is most affected by the windows & doors process. As identified earlier, steel, zinc and other metals are required to produce PVC window sills and will thus effect metal depletion.

The EOL process in figure 23 above seems to damage the natural ecosystem of marine and freshwater. The figure shows that the categories marine- and freshwater ecotoxicity, terrestrial acidification, and marine eutrophication are affected significantly by this shell component. As for balconies, this process consists of several materials which require water in the manufacturing phase, such as concrete and aluminum, and thus impacts water depletion quite significantly. However, in most impact categories balconies were less important as the process was relatively minor in comparison to others. In addition, the balcony process includes several materials that will spread to each impact category and thus will hold little effect for each.

4.2.4 Sensitivity Analysis

It is of interest to identify what activities in the value chain contributing the most to GHG emissions in the Stjernehus upgrading project. A sensitivity analysis measuring GWP (CO_2-eq) is conducted to examine how total impacts are altered when particular parameters change. Thus a sensitivity analysis measures the sensitivity of change in the parameters.

Table 20: Sensitivity analysis of all processes in the upgrading project.

Process	**Change in Model (%)**	**Change in Results (%)**
Exterior Walls	1 %	**0.20 %**
Roof	1 %	**0.01 %**
Balconies	1 %	**0.08 %**
Ventilation	1 %	**0.02 %**
Doors & Windows, production	1 %	**0.40 %**
End of Life, all Materials	1 %	**0.05 %**
Transportation of Materials	1 %	**0.07 %**
Energy at Construction Site	1 %	**0.02 %**
Operation of Building Apartment	1 %	**0.06 %**

The following processes in table 20 are altered by one per cent to observe the effect each had on total emissions emitted. The two most significant contributed processes are marked in red in the column to the right. One can see that doors and window production is the process with the highest impact of all (0.4% change in final results). This is also found earlier in this chapter. Furthermore, activities that affect GWP the most are the PVC production and disposal of PVC to municipal incineration (see section 6.2.2). The production of exterior walls is also accountable for a significant amount of total emissions and affect the results by 0.2%. The exterior walls were a great part of the rehabilitation process as insulation materials are important to create thermal insulation capacity and save energy in user phase.

4.2.5 Advanced Contribution Analysis

The advanced contribution analysis examines what activities and substances that contribute the most to each environmental impact. For instance, the analysis shows that the activity transportation of materials contributes 8% of the total to GWP. For the impact category human toxicity, it shows that 4% is caused by disposal of PVC window sills to municipal incineration. Manganese to water is the substance which contributes the most to this category. The impact categories analyzed for this are climate change, human toxicity, particulate matter formation, terrestrial acidification, freshwater eutrophication, and metal depletion. The complete advanced contribution analysis can be seen in appendix F.

5. Comparison of Results from Klimagassregnskap.no

In this chapter, the results of the life cycle impact assessment will be compared with results from Klimagassregnskap.no, performed by Holen (2014a). The former study on Stjernehus apartment building used the latter tool to identify greenhouse gas emissions caused by the upgrading. Thus the functional units are equal and a comparison is possible. However, the original LCA model need to limit its scope as identified in 5.1 below.

The LCA methodology and the Klimagassregnskap.no tool shall be compared to assess differences in emission intensive shell components. This includes a comparison of payback time of emissions caused by the upgrading (materials' emissions vs saved energy per year). In addition, the chapter contains an interview with the environmental manager in Kruse Smith, the entrepreneur firm for the Stjernehus rehabilitation. The short interview in 5.4 regards use of LCA and Klimagassregnskap.no in practice. Benefits and limitations of the two are further mapped and discussed in chapter 6.

It is important to notice that the comparison of the two environmental assessment tools is not the main objective of this thesis. Thus an extensive comparison would require more in depth exploration of Klimagassregnskap.no and its calculation methods. The purpose of the comparison is to provide a mapping of benefits and limitations with both tools (table presented in chapter 6.2.3.)

Currently there is a lack of comparison between the Klimagassregnskap.no tool and LCA methodology. As the latter is a more resource-intensive assessment, a mapping of benefits and limitations can work as decision-making support for choosing an assessment method in projects that hold an environmental approach. This is relevant in the context of increased interests for sustainable buildings. Assessment tools can both assist in decision-making prior to construction, and provide documentation of environmental impacts of projects. More environmental assessment tools exist, but Klimagassregnskap.no has been used for all pilot projects in Framtidens Bygg (future buildings), and recognized by several in the construction sector. The tool has acknowledged limitations today, however it is continuously improved by CIVITAS (Statsbygg and CIVITAS, 2016). As Holen (2014a) conducted a GHG emission analysis of Stjernehus applying this tool, it was considered a great opportunity to compare results with an LCA impact assessment.

Klimagassregnskap.no is referred to as an LCA with limitations, mainly because it merely accounts for GHG emissions and not additional environmental impacts. In addition, it holds a limited scope and excludes the last life phase – end of life (EOL) management. The tool has been developed since 2007, and the last version number 5 was released in 2015 (Statsbygg and CIVITAS, 2016). The study by Holen (2014a) was done with the 2012 version, thus improvements in version five are not considered in this study. To obtain an understanding of the main purposes of the tools, the following definitions of LCA and Klimagassregnskap.no are provided.

"LCA is a relative tool intended for comparison and not absolute evaluation, thereby helping decision-makers compare all major environmental impacts when choosing between alternative courses of action" (Curran, 2008).

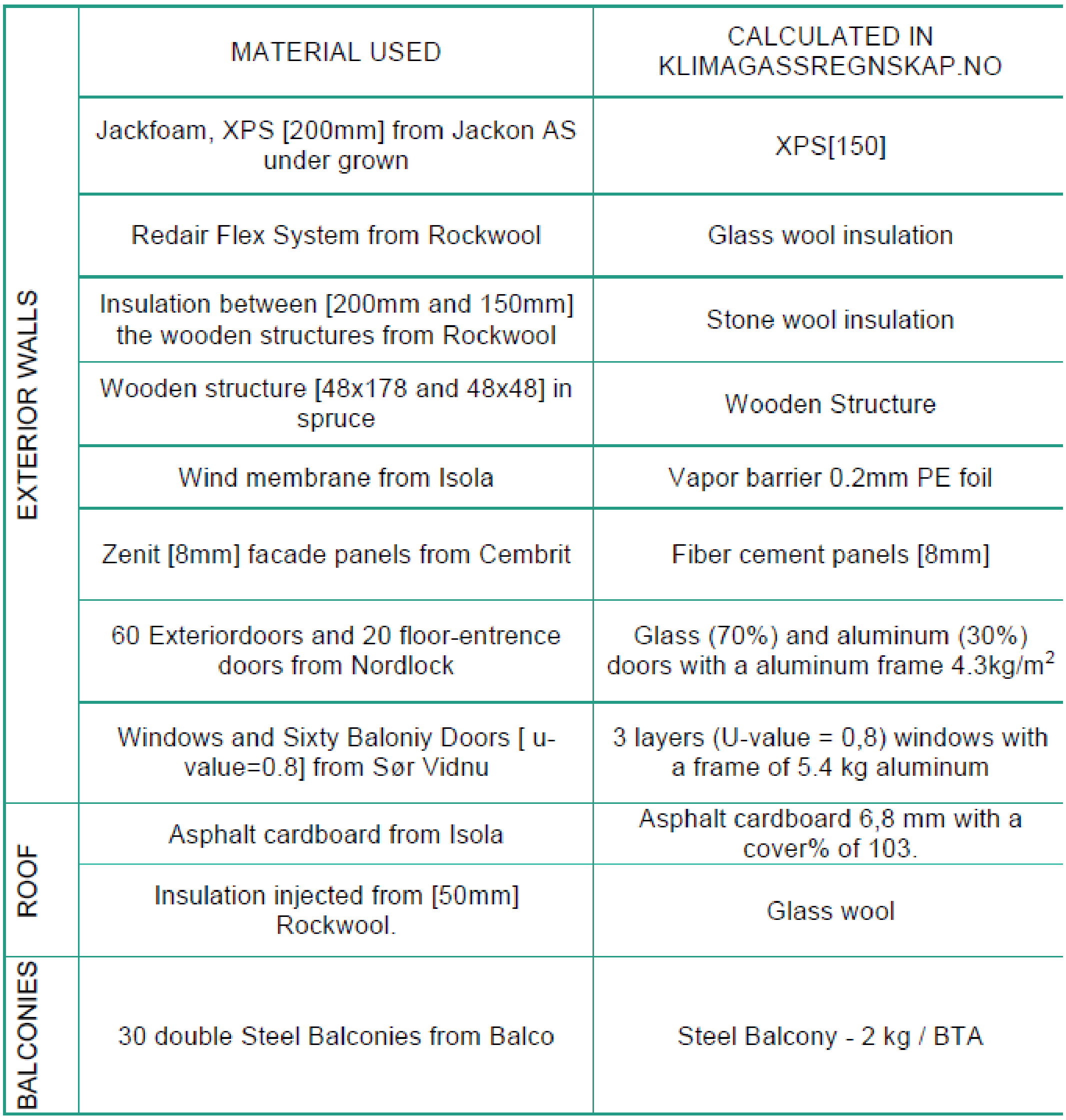
"The model Klimagassregnskap.no is a communication- and analytical tool for planning and projecting of construction projects" (Statsbygg and Civitas, 2014).

Before the results are compared, differences in modelling will be presented to interpret how GHG emissions are calculated in both cases.

5.1 Modelling Differences

If system boundaries are treated differently, the basis for comparison is not realistic (Solli, 2015). Thus life phases and key processes included must be equal (e.g. transportation, EOL). In addition, choice of electricity mix and time perspective are key parameters that can effect impact assessment results significantly. In order to compare results with Holen (2014a), the allocation method of materials to each process should therefore the same. When Holen analyzed GHG emissions applying Klimagassregnskap.no, the amount of construction materials was not complete, but partly assumed and non-detailed. The LCA generated in this study had access to a complete list of all materials used. Therefore, in order to make a fair comparison, there was a need to limit the scope of the original LCA model to fit Holen's (2014a). This model is referred to as the "remodeled LCA" in the following sections. The inventory list used in the Klimagassregnskap.no model is showed in table 21 below. This can be compared with the complete LCA inventory analysis in chapter 4.1.

Table 21: List of materials that were used in Klimagassregnskap.no in the left column, and materials that were chosen in the right column (Holen, 2014a).



	MATERIAL USED	CALCULATED IN KLIMAGASSREGNSKAP.NO
EXTERIOR WALLS	Jackfoam, XPS [200mm] from Jackon AS under grown	XPS[150]
	Redair Flex System from Rockwool	Glass wool insulation
	Insulation between [200mm and 150mm] the wooden structures from Rockwool	Stone wool insulation
	Wooden structure [48x178 and 48x48] in spruce	Wooden Structure
	Wind membrane from Isola	Vapor barrier 0.2mm PE foil
	Zenit [8mm] facade panels from Cembrit	Fiber cement panels [8mm]
	60 Exteriordoors and 20 floor-entrence doors from Nordlock	Glass (70%) and aluminum (30%) doors with a aluminum frame 4.3kg/m^2
	Windows and Sixty Baloniy Doors [u-value=0.8] from Sør Vidnu	3 layers (U-value = 0,8) windows with a frame of 5.4 kg aluminum
ROOF	Asphalt cardboard from Isola	Asphalt cardboard 6,8 mm with a cover% of 103.
	Insulation injected from [50mm] Rockwool.	Glass wool
BALCONIES	30 double Steel Balconies from Balco	Steel Balcony - 2 kg / BTA

To clarify differences of the complete LCA, the remodeled LCA, and Klimagassregnskap.no, the three models are explained below.

Klimagassregnskap.no's model: A pre-assumption model of materials used in the upgrading of Stjernehus. The tool Klimagassregnskap.no was applied to estimate GHG emissions of three shell components. The analysis was performed by Holen (2014a) in cooperation with Kruse Smith, prior to upgrading.

Remodeled LCA: In this case, the complete LCA model has been adjusted to a limited scope LCA (see figure 24). The model is changed according to Holen's model in Klimagassregnskap.no. This was necessary in order perform a fair comparison with the previous analysis of Stjernehus.

Complete LCA model: The model included a detailed material list, energy used on construction site, transportation of materials to site, and end of life treatment of materials used in the upgrading project (see 4.1 for a complete inventory analysis).

The processes removed in the remodeled LCA is shown in figure 24 below.

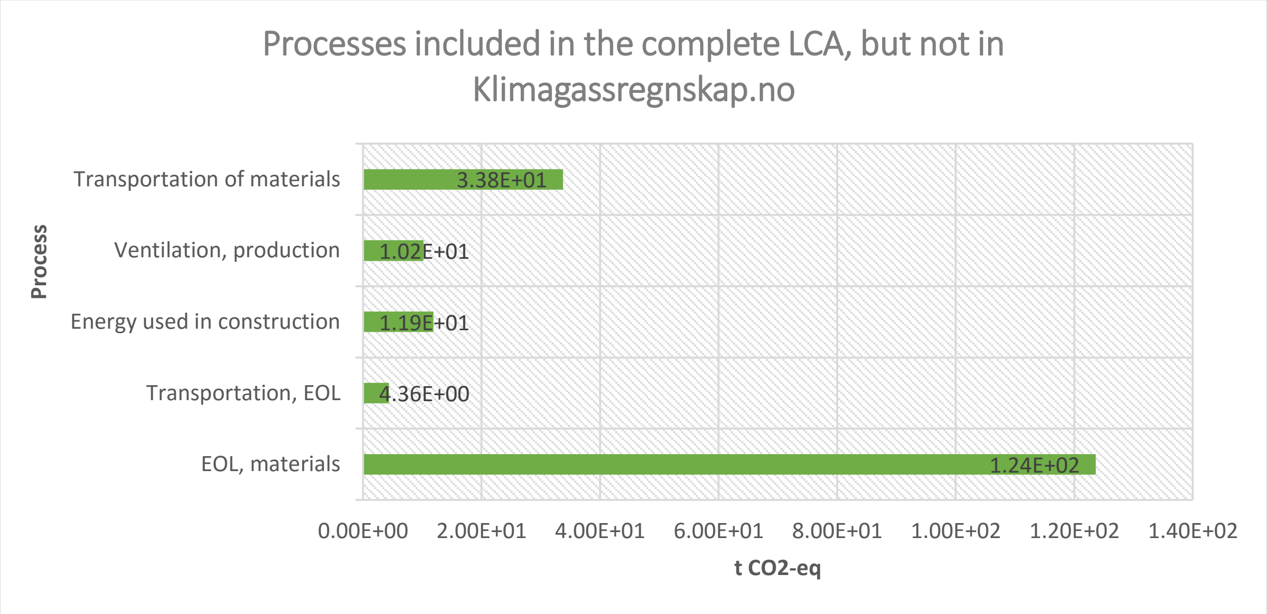


Figure 24: The processes removed in the remodeled LCA.

The processes above are included in the complete LCA (results presented in chapter 4), however not in the remodeled LCA used for comparison with Holen (2014a).

EPD Terminology

As discussed in chapter three, the program for Environmental Product Declarations has a standardized format that presents what life phases are included in an environmental assessment (EPD-Norge, 2016). In section 3.3.2 the EPD format is applied for the complete LCA model. As for the remodeled LCA, the table below reflects this model. As noted, the reason for adjusting the complete LCA model is to make a fair comparison with Holen's (2014a) model. Thus the table below reflects both the calculation model in Klimagassregnskap.no and the remodeled LCA holding (limited scope). The marking colors in the table are explained below.

Orange: Separate from the system boundary.

Blue: Phases included in the system boundary.

Table 22: The life phases included in Klimagassregnskap.no in EPD format (Holen, 2014a).

Phase	**Product**	**Construction, installation**	**User phase**	**End-of-life**
Element	Raw materials	Transport	Energy consumption	Disassembly
	Transport	Construction, installation		Transport
	Manufacturing			Waste treatment
				Finalization
Module	**A1-A3**	**A4-A5**	**B1-B7**	**C1-C4**

As seen in the table above, several life phases are not included in the Klimagassregnskap.no model or the remodeled LCA.

5.2 Results compared

This chapter compare results from the remodeled LCA performed in this study, and the analysis performed by Holen (2014a). The results present GHG emissions from the three shell components exterior walls, roof, and balconies. Nevertheless, indirect emission sources that the shell components consist of differ. That is the background data input to each shell component. This is because the models use different databases, estimates and assumptions.

Figure 25 below presents a comparison of total emissions found in Klimagassregnskap.no, in the remodeled LCA, and in the complete LCA.

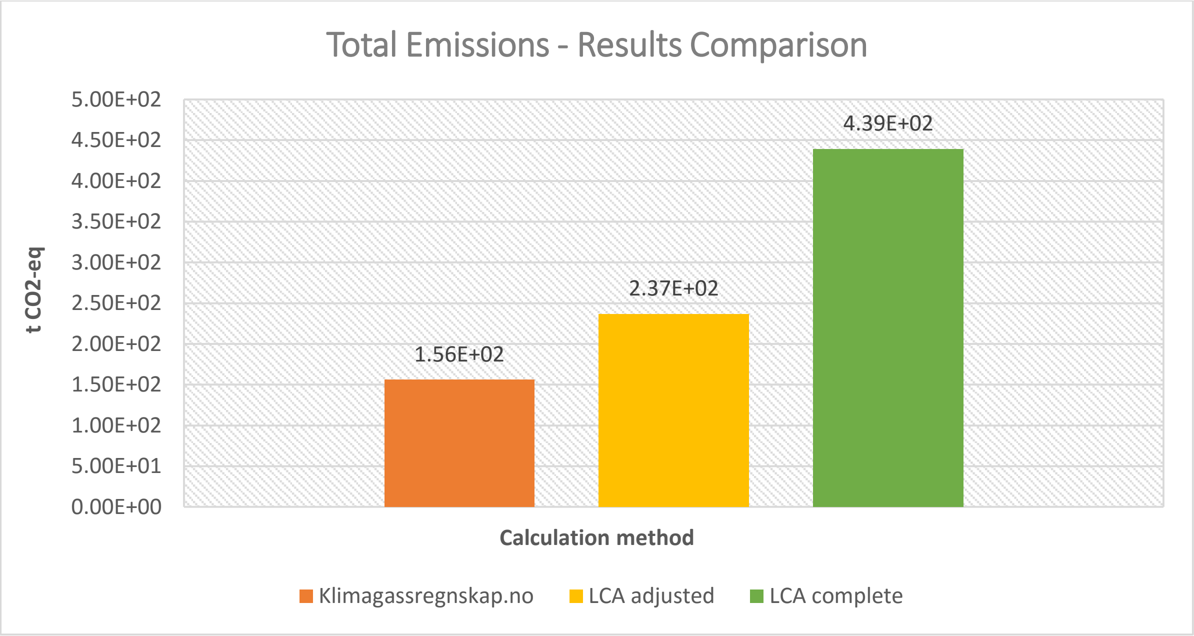


Figure 25: Total global warming potential from different calculation models.

According to the calculations performed in this study, total emissions were 52% higher with the remodeled LCA calculations than with Klimagassregnskap.no. Comparing the complete LCA generated and results from Holen (2014a), emissions differ with 180%. Thus both LCA models found that GHG emissions were higher in comparison with Klimagassregnskap.no. Differences in results are further analyzed in the figure below. Emissions from the three shell components included in all models are illustrated. For all components Klimagassregnskap.no illustrates a more optimistic approach (i.e. lower emissions).

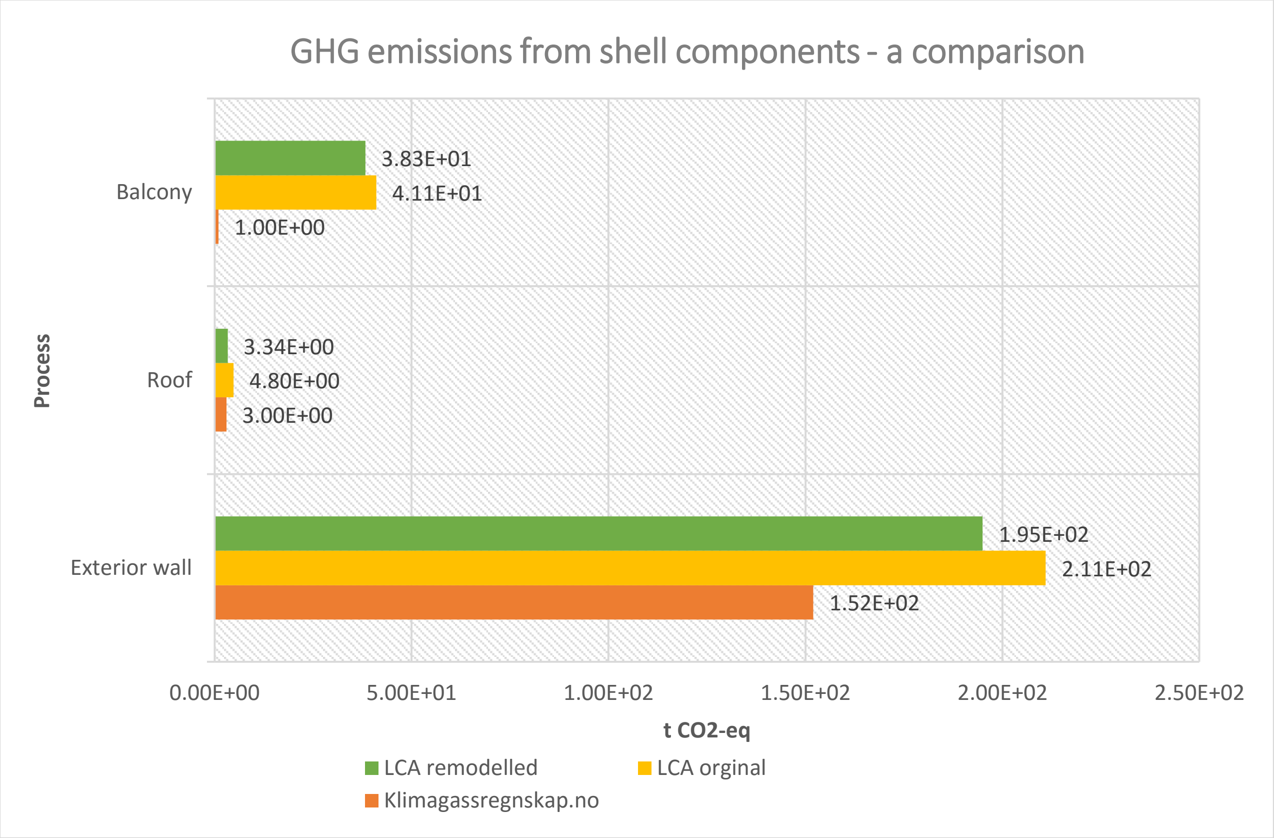
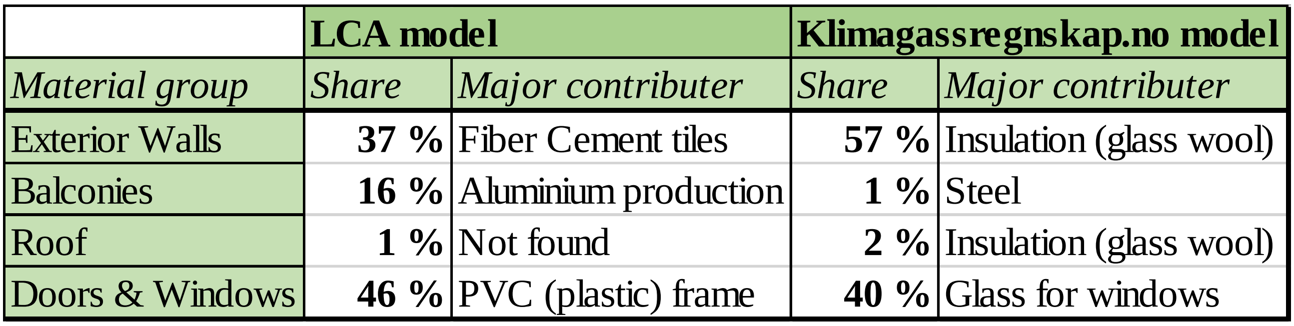


Figure 26: GHG emissions from shell components – a comparison of results from the different models.

In figure 26 above one can observe the difference in emissions for balconies. Klimagassregnskap.no models this process as per cent of total building area that are assumed to be for "balconies of steel" (16% in Holen's study) (Holen, 2014b). For the LCA, a detailed list was provided from supplier Balco AS containing all materials and measures of the balconies. The latter leads to a more realistic calculation of emissions deriving from the balconies.

The table below presents a comparison of results between the original (complete) LCA model and Klimagassregnskap.no. The table shows the share of GHG emissions from each shell component, both according to the complete LCA and Klimagassregnskap.no.

Table 23: Emission intensive construction materials from the complete LCA model and Klimagassregnskap.no.



	LCA model		**Klimagassregnskap.no model**	
Material group	*Share*	*Major contributer*	*Share*	*Major contributer*
Exterior Walls	**37 %**	Fiber Cement tiles	**57 %**	Insulation (glass wool)
Balconies	**16 %**	Aluminium production	**1 %**	Steel
Roof	**1 %**	Not found	**2 %**	Insulation (glass wool)
Doors & Windows	**46 %**	PVC (plastic) frame	**40 %**	Glass for windows

In table 23 above one can observe differences of the two tools in terms of emission intensive materials. For the plastic window sills production, the difference may seem utterly significant. The reason is that Holen (2014a) assumed a utilization of window frames of wood with aluminum, holding the same life time as PVC windows sills of 60 years. Window frames of PVC are more emission intensive than of wood, as observed in EPDs. One example from two EPDs shows a window with plastic frame that had 204 kg CO_2-eq per window produced, while one of wood had 83.7 kg CO_2-eq (Tellnes, 2015a, Tellnes, 2015b). The functional unit (FU) was equal in these Environmental Product Declarations and it was therefore rational to compare the two EPDs.

5.3 Energy comparison, & Payback Time of Emissions

Data for delivered energy is provided by Sweco, who conducted an energy report to assist Kruse Smith in their work (Skogheim, 2014). Data on energy use prior to upgrading is provided by Holen (2014b). The district heating mix for Kristiansand was found at the webpage fjernkontrollen.no (2015), as recommended by the energy company Agder Energi. The district heating mix that Holen utilized in Klimagassregnskap.no differs with small amounts because dissimilar sources were used. Furthermore, the results of emissions from energy differ because calculation methods and databases are not equal in LCA methodology and Klimagassregnskap.no. The differences will be explained below.

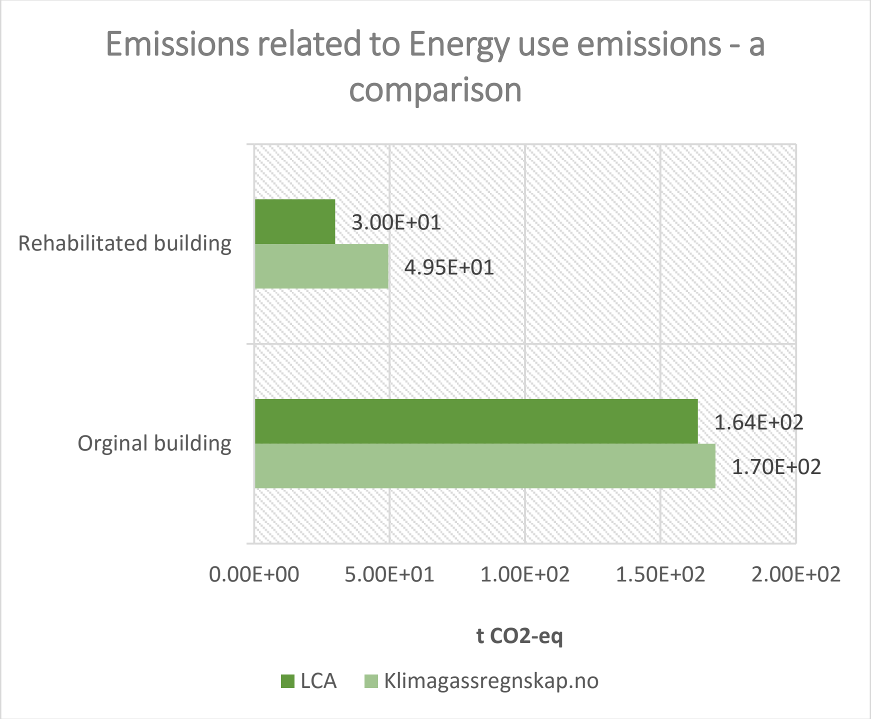


Figure 27: Emissions from 1 year use before and after rehabilitation, with different calculation models.

The modelling of the original building is equal in the LCA and Klimagassregnskap.no (the lighter green color in figure 27). This study used the data on "old energy use" from Holen (2014b). Thus the small differences of emissions from the old energy use derives from different calculation methods (ReCiPe vs Klimagassregnskap.no) and different background databases (ecoinvent vs a variety combined). Similarly, electricity from GRID used in the "new energy use", after rehabilitation, is the same in the two models. Thus, both studies concluded a use of 37 kWh/m^2/year from GRID for Stjernehus after the upgrading, however emissions were calculated differently because of specific methods and databases.

The district heating mix is not equal in the two models. Table 24 shows a comparison between the district heating mix used in the LCA model and in Klimagassregnskap.no.

Table 24: Compare the district heating mix used in the LCA and Klimagassregnskap.no calculations.

LCA		
District heating mix, Stjernehus, 2015		*kWh/m2/year*
Bio energy	0.1 %	0.1
Fossil oil	2.1 %	1.4
Recovered heat from waste	85 %	
Recovered heat from industry	14 %	64.6
	100 %	*66.0*
Klimagassregnskap.no		
District heating mix, Stjernehus, 2015		*kWh/m2/year*
Bio energy	0.4 %	0.3
Fossil oil	1.1 %	0.7
Recovered heat from waste	81 %	53.5
Recovered heat from industry	17.5 %	11.6
	100 %	*66.0*

In chapter 6 a scenario analysis with different district heating mixes will illustrate that these variations can effect results of total emissions, which is also the case in the comparison. Data sources differed when collecting information regarding district heating mixes in 2014 (Holen's analysis) and 2016 (this study). The energy company in southern Norway, Agder Energi, provided Holen (2014a) with data regarding this. Fjernkontrollen.no provided data regarding this mix for Kristiansand in 2015. Thus Holen's data was as reliable, however, fjernkontrollen.no (2015) is more updated on specific values.

The reasons for different emission values shown in the figure above is due to district heating mixes, as stated. However, the databases used are also influencing differences. The LCA study used ecoinvent, while Klimagassregnskap.no used several in combination (Statsbygg and Civitas, 2014). In addition, the use of different calculation methods is affecting results (this study uses ReCiPe, as presented earlier). In terms of databases, a NTNU professor in Industrial Ecology, Strømman (2010), argues ecoinvent has the best quality data for European purposes. The database is also highly recognized in Goedkoop et al (2012) where characterization factors are produced. Similarly, the ReCiPe method used to transform inventory to impact categories is a method commonly used in the research field, and is recognized among leading researchers (Goedkoop et al., 2012). The methodology used in the LCA of this study is therefore seen as reliable in these areas.

A comprehensive manner to illustrate the different impact results from Klimagassregnskap.no and the LCA, is to calculate payback time of GHG emissions from the upgrading. The total emissions of 439 ton CO_2-eq (complete LCA model) need to be paid back in energy savings in order for the rehabilitation to be environmentally profitable. Thus dividing emissions saved per year after upgrading with total emissions from the rehabilitation process. Was it awarding in terms of greenhouse gas (GHG) emissions to carry out the ambitious upgrading? See appendix D for complete calculation.

Table 25: Payback time of emissions calculated according to results from the LCA and Klimagassregnskap.no.

Environmental assessment tool	**Years of payback time**
Emissions calculated using LCA	*3.3 years*
Emissions calculated using Klimagassregnskap.no	*1.3 years*

In figure 28, the calculation is presented graphically. Thus the figure illustrates how much energy that is saved in the upgrading project. Emissions saved are both due to a large reduction in energy use, and shift of energy source from mainly oil boilers to district heating (waste incineration heat the major energy source). The three colored lines are firstly defined.

Red line: Old energy use. In the figure, one can observe that the red line start with 0 emissions in year 0. That is because this presents a scenario where the upgrading of Stjernehus did not occur, hence the rapid increase in emission release each year throughout a lifetime of 60 years.

Green line: Energy model according to LCA calculations. This study calculated emissions from the upgrading process by using LCA methodology and found that the upgrading released 439 ton CO_2-eq in total. These emissions are set in year 0 for the green line, and are payed back after 3.3 years with less emissions from operational energy use (saves 134 ton CO_2-eq/y).

Yellow line: Emissions related to energy use, according to the model in Klimagassregnskap.no (Holen, 2014a). Emissions from materials are lower than the LCA findingds - 156 ton CO_2-eq. Thus the yellow line starts with a lower value in year 0. Therefore, the payback time is also lower - merely 1.3 years as to be observed in the yellow line in figure 28.

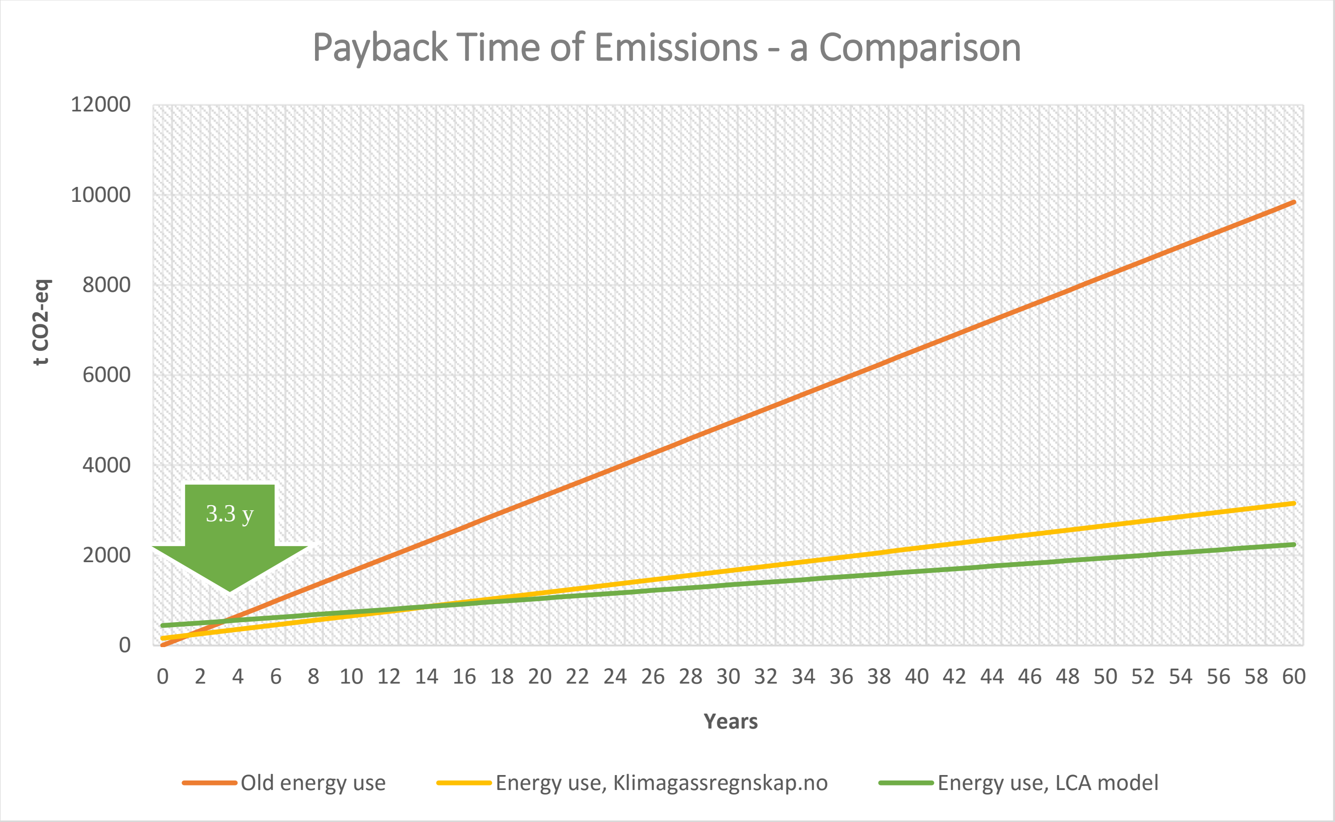


Figure 28: Payback time of emissions based on energy savings in user phase.

The amount of emissions saved per year after the upgrading can beneficially be presented per m^2 for an easier interpretation. By dividing the total value of 134 ton CO_2 with 3750 m^2 (Stjernehus' total heated area) it is found that the building saves **0.0357 ton CO_2 -eq/m^2 /year** because of increased energy efficiency.

5.4 Interview: Use of Tools in Practice

To explore environmental approaches in practice, the entrepreneur for the Stjernehus upgrading, Kruse Smith AS, was asked questions regarding their practice. Their environmental manager, Ronningen, noted that this is the organization's personal approach that will differ among entrepreneurs. The organization itself has generated internal energy- and climate accounts at company level. Direct and indirect emissions are considered and efforts to reduce these are initiated. Emission sources such as use of diesel during projects and electricity consumption are in focus, but also waste generated, flights, and use of cars are considered. The tools of LCA and Klimagassregnskap.no are two of many approaches at project level (Ronningen, 2016).

- *How can Kruse Smith use Klimagassregnskap.no as a tool in projects? How can decisions be affected by this use?*

According to environmental manager Ronningen (2016), the tool is not widely used other than in projects which has specific environmental goals such as pilot projects in Framtidens Byer (Future Built) (the program mentioned in chapter 2, that realizes best practice projects such as the upgrading of Stjernehus). Other cases are where buildings aim to become BREEAM-Nor certified, although a reduction of greenhouse gas emissions is not necessary to get certified. There are key elements to consider in order for Klimgassregnskap.no to support decision-making regarding material choice and energy demand. There must be a common, ambitious goal among stakeholders, the assessment tool must be considered at the earliest stage of planning, and there must be economic capacity to implement more environmental friendly practices. As the Stjernehus project had been planned in detail prior to use of the tool, there was no economic capacity to alter decisions significantly. However, there was an awareness that the ambitious upgrading would lower emissions significantly regardless (because of lower energy use). Thus decisions in the project was not significantly influenced by results from Klimagassregnskap.no (Ronningen and Torsvik, 2016).

- *How can Kruse Smith use a Life Cycle Assessment (LCA) of a construction product or process? How can decision be affected by this use?*

The LCA tool is considered to be more relevant at a product level. If used in BREEAM-Nor projects, one receives points for using a LCA tool to evaluate at least two material options. Similarly, if one can demonstrate that the outcome of the evaluation has influenced design or material choices. LCA seems more relevant for building material producers to use as a factual basis, in some cases to obtain an EPD, and possibly to register in ECOProduct. Furthermore, LCA is used in ambitious pilot projects such as zero emission buildings or zero energy. There are buildings where the total amount of energy used by the building (over its lifespan) is equal or lower than the amount of energy created on site. Thus LCA is generally not a topic in “ordinary” construction projects (Ronningen and Torsvik, 2016).

6. Discussion

In this chapter the main findings of the LCA results will be discussed, and recommendations will be provided based on these conclusions. The aim of this section is to answer the objectives stated in chapter 1.2.

Firstly, main findings and correspondence with literature will be discussed. Emissions from construction materials in upgrading projects will be in focus. In addition, a scenario analysis for modelling choices in LCA methodology is generated regarding lifetime, electricity mix and district heating mix. Such choices influence results significantly and it is therefore important to illustrate this by quantifying differences for the apartment building.

Furthermore, recommendations will regard future ambitious upgrading projects. First by stating benefits and challenges of ambitious upgrading, then regarding emissions from construction materials which includes the issue of problem shifting. How the environmental assessment tools compared in this study should be approached in future upgrading projects are then illustrated by showing benefits and limitations. Uncertainties in data and in the methodology will then be stated. Lastly, possible future work on relevant topics will be discussed briefly.

6.1 Main findings and correspondence with literature

6.1.1 Emissions from construction materials in upgrading projects

Kristjansdottir (2014), Blengini and Di Carlo (2010), and Lolli (2014) argue that new energy efficient buildings require more emission intensive materials. Kristjansdottir (2014) found that emissions from materials in construction, maintenance and EOL can cause as much emissions as the energy saved in operation phase. Blengini and Di Carlo (2010) argue that the maintenance process is significant and cannot be excluded from environmental assessments. The study considers new buildings with a passive house standard which require all new materials. An upgrading process itself requires a minor amount of materials in comparison to this quantity. The results in this study illustrates this by showing the short payback time of 3.3 years in terms of emissions (see chapter 5).

Emissions from materials and energy consumption in new buildings with a passive house standard can hold an equal amount of emissions over a lifetime (Kristjansdottir, 2014). This study showed that this is not the case for upgrading of older buildings. Figure 29 is a comparison with the figure in chapter 2.2 of Kristjansdottir (2014). One can observe that for the upgrading of Stjernehus, the construction materials merely caused 22%, while the energy consumption in user phase caused 78% over a lifetime of 60 years. The green share equals energy use, the yellow is emissions from end of life phase of materials, and the red shows the carbon footprint of manufacturing of materials.

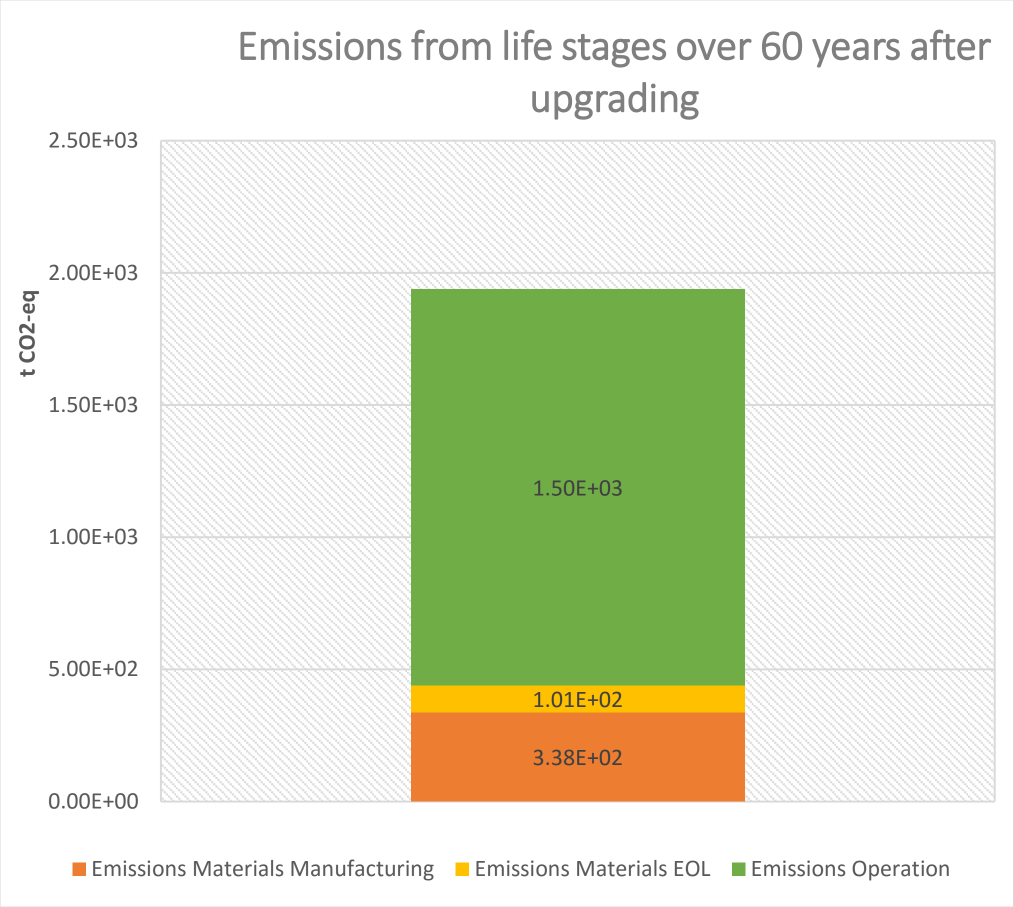


Figure 29: Comparison with Kristjansdottir (2014) figure in section 2.2.

6.1.2 Modelling choices in LCA methodology

Conducting an LCA can be challenging and several methodological choices must be considered during the modelling (Baumann and Tillman, 2004). This section presents the modelling choices that influenced total emissions the most in the upgrading project. A scenario analysis is generated to measure change in total GHG emission results. One needs to make choices regarding the characteristics of the product or process. In this discussion the key parameters considered are the expected lifetime of the product, the electricity mix utilized in the life phases, and the district heating mix. In addition, end of life treatment could have been considered as the recycling potentials are often significant in terms of environmental impacts (see 6.3 for this discussion). The results of an LCA indeed depend on these modelling choices (Plesser and Kristjansdottir, 2015).

Lifetime of materials

As argued by Kampesaeter et al. (2009), normed lifetime of materials is not always current in practice. In many cases, materials are assumed to remain longer in a building than in reality. To test the effect of such differences, a scenario analysis is generated in order to identify the impact of replacing particular construction materials during a building's lifetime. The table below illustrates what materials that are shifted in this scenario analysis. The scenario analysis covers the manufacturing of materials, not the EOL as in the results in chapter 4.

Table 26: Materials that are shifted in the scenarios below.

Construction Material replaced during 60 years	**Lifetime 1 replacement**	**Lifetime 2 replacements**
Doors	30 years	20 years
Windows	30 years	20 years
Coating	30 years	20 years
Inner walls	30 years	20 years
Thatching	30 years	20 years
Painting & Sealant	30 years	20 years
Ventilation unit	30 years	20 years

Based on the results in the figure below it is recommended to investigate lifetime of materials in particular as this knowledge may change results of total emissions significantly. There are several factors (e.g. use, aesthetics, technical quality) influencing lifetime depending on a building's purpose (Plesser and Kristjansdottir, 2015).

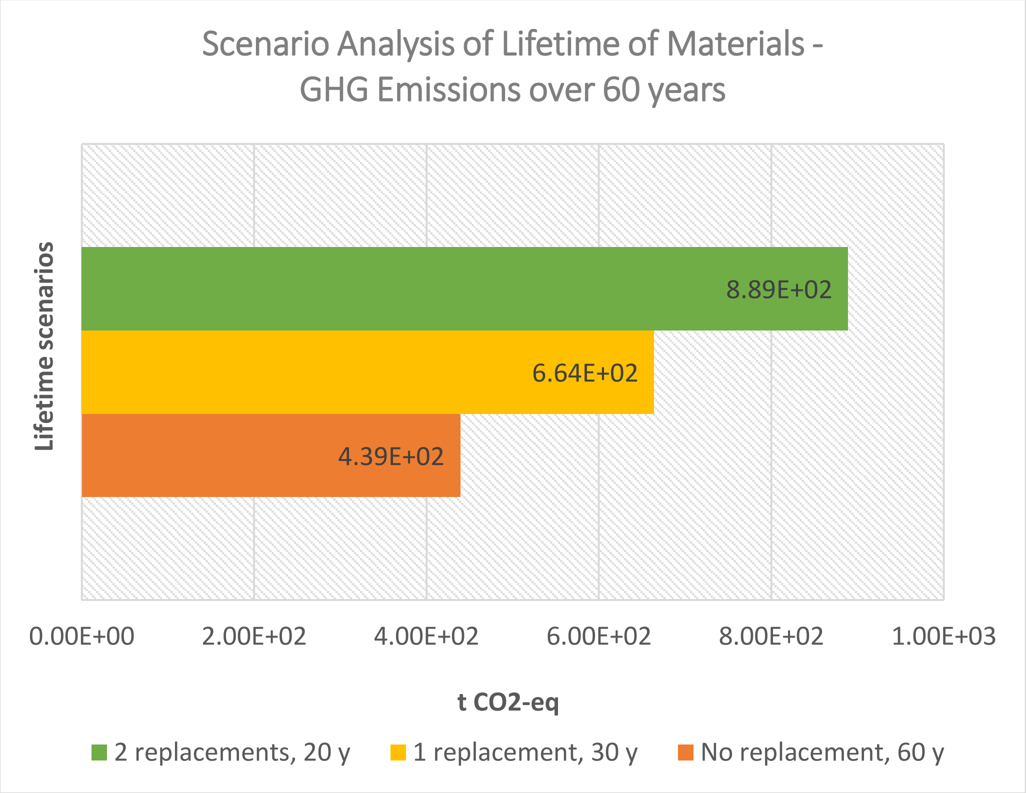


Figure 30: Scenarios where materials are shifted one or two times during 60 years.

As one can observe in figure 30, total emissions increased by 51% when particular materials were replaced one time during the 60 years. If these were replaced two times during these years (lifetime expectancy of 20 years), GHG emissions increased by 102%. It is a challenging task to recognize accurate lifetime of construction materials (Plesser and Kristjansdottir, 2015). The materials listed in table 26 could assumedly have a lower lifetime than 60 years. If such maintenance activities were to be included in total emissions calculated in this thesis, the emissions would be allocated to the operation phase.

Energy

As 40% of all energy consumed in Norway is used for buildings (Thunes, 2016), another important factor affecting the final results of an LCA is the choice of energy source and electricity mix. The energy sources from each country depend on available resources and economy (Rauboti and Vinjar, 2013). Norway is fortunate to have great access to renewable energy from hydro, but also import electricity from fossil fuel from other nations in Europe (Plesser and Kristjansdottir, 2015). The purpose of this scenario analysis is (i) to measure the effect of shifting location and district heating mix for the Stjernehus building apartment, and (ii) to change the GRID electricity mix. The table below presents the three scenarios assessing different location of Stjernehus.

Table 27: District Heating scenarios for Stjernehus, data from (fjernkontrollen.no, 2015).

Mix, orginal Kristiansand		**Mix, scenario Stavanger**	**Mix, scenario Harstad**
Bio energy	0.1 %	50 %	*99 %*
Fossil gas	0.0 %	50 %	*1 %*
Oil	2.1 %		
Recovered heat	97.8 %		
	100 %	100 %	100 %

Stavanger has a district heating mix that is heavily reliant on fossil gas (50%) compared to Harstad (99% wood chips) and Kristiansand (97.8% from recovered heat) (fjernkontrollen.no, 2015). The figure below illustrates differences in GHG emissions with the alternative district heating mixes. The results illustrate the dependence of location in decision-making regarding benefits of ambitious upgrading. Thus if Stjernehus was located in Stavanger, emissions per kWh would be significant in comparison to the other Norwegian cities below. Figure 31 clearly shows the interesting differences depending on location.

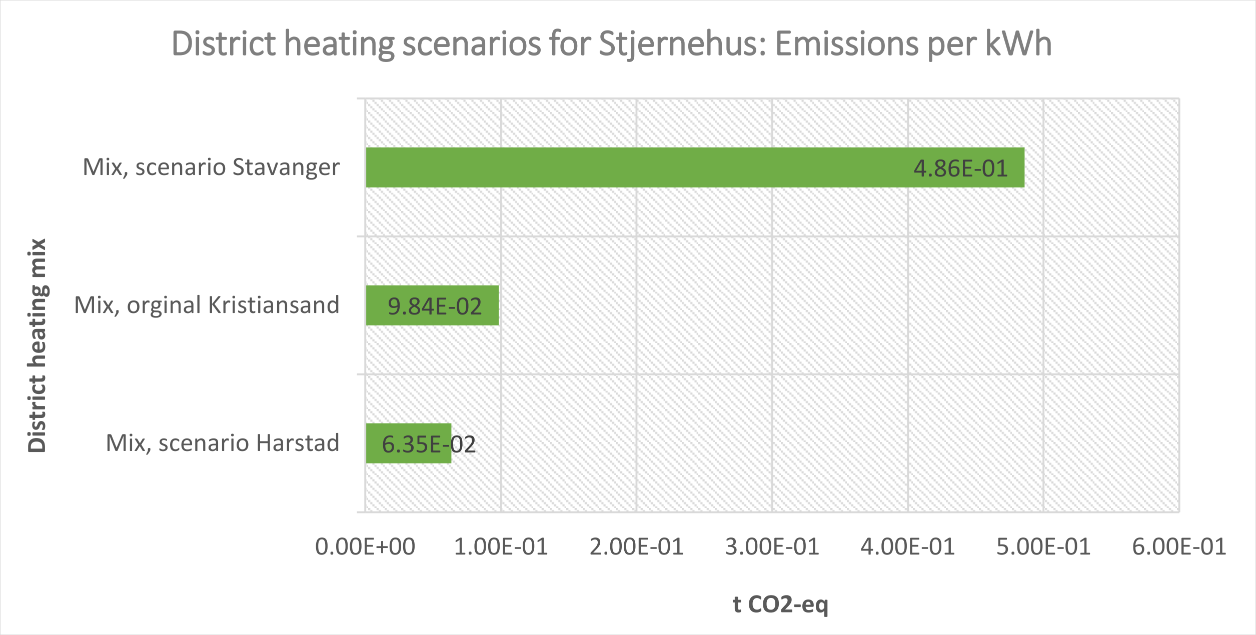


Figure 31: *CO_2 emissions from different district heating mixes*

The third scenario regards electricity mix from GRID. The relevant mixes for Norway is the Norwegian-, NORDEL, and the UCTE (EU) mix, as noted in chapter 2 (Dahlstrøm, 2011). The differences in GHG emissions per kWh is presented below in figure 32. The reason for the great variations seen is because the different mixes have a particular share of renewable, and non-renewable energy in its mix (European Comission, 2015). As observed in the figure, by using the Norwegian el mix rather than the NORDEL (Nordic countries mix), emissions per kWh are reduced by 194%, or 22 t CO_2-eq (see table 5 for full NORDEL mix content table). As for the UCTE mix, the share of non-renewable is today great in comparison to the Nordic. However, as part of the goal to decrease emissions in the European region, the mix will be improved in terms of clean energy within the next years (European Comission, 2015).

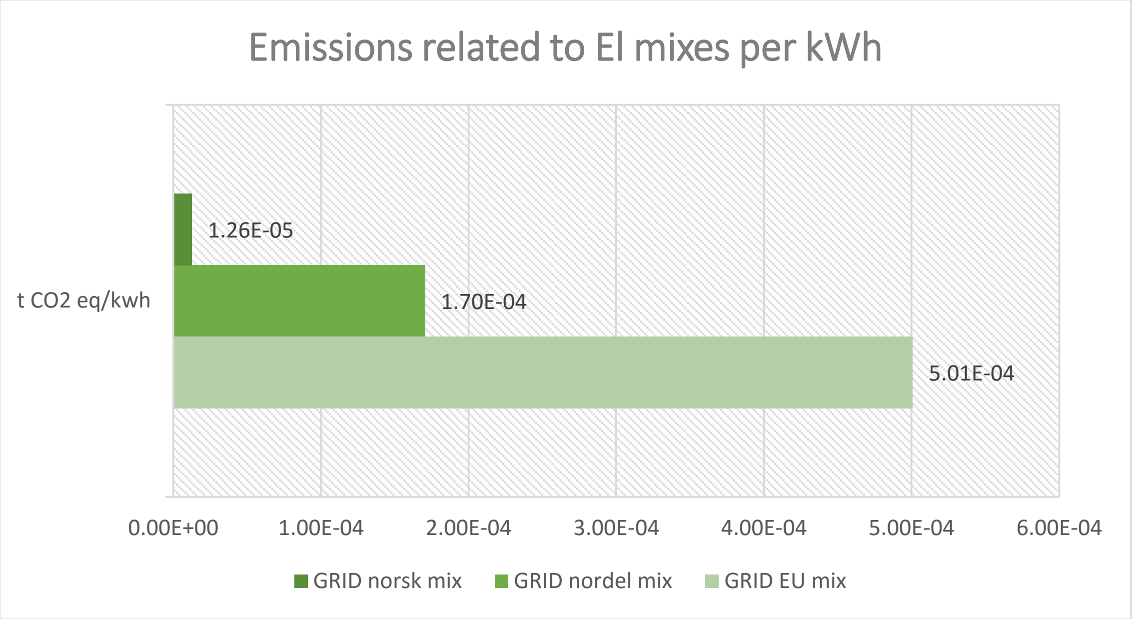


Figure 32: *El mixes from GRID - GHG emissions scenarios*

The measurement of actual amounts of energy the residents utilize today in Stjernehus is not covered in this thesis, however an estimation performed by Sweco (Skogheim, 2014) and Enova (2016) is utilized in calculations. It is therefore important to acknowledge the psychological effect of residents when their apartment building is upgraded to an energy efficient home. It is recognized that the residents spend more energy after the upgrading to a low-energy building. This is mainly because the payment is shared equally for the whole apartment building, rather than on each apartment (except the electricity from GRID). Therefore, the actual amount of electricity one uses does not have a large effect on the electricity bill. If electricity from GRID would hold a higher cost, this would be different (see also figure 33 in the next section). Thus the individuals living in Stjernehus pay a similar amount despite varied indoor temperatures (Moen, 2016). In agreement, Langseth et al. (2011) suspect these conditions in low energy buildings. Thus people may tend to increase indoor temperature and other use of electricity when their apartment is classified low energy.

6.2 Recommendations

In this section recommendations will be given to decision makers in the building industry as to how:

(i) What are the motive and current constraint for future upgrading projects?
(ii) How to reduce the environmental impacts of construction materials?
(iii) How should the building industry approach the environmental assessment tools Klimagassregnskap.no and LCA?

This guidance is to further encourage ambitious upgrading of older buildings to a low-energy standard as the energy saving potential was found to be significant in this study.

6.2.1 Future rehabilitation projects

The potential to reduce emissions from the construction sector in Norway is significant by upgrading older buildings to a low-energy, as this study has shown (Thunes, 2016). As older buildings commonly have poor insulation and use emission intensive energy sources, the energy used in operation phase lead to a great amount of emissions emitted. Thus, benefits are due to the significant reduction of 70% of energy use (kWh/y) and altering energy source from oil heater to district heating. In combination, these efforts caused a reduction of 84% in GHG emissions per year after the upgrading.

Nevertheless, it is important to consider opportunities and access of renewable energy sources. This effort is significant as to how much emissions related to energy use can decrease. The table below illustrates the difference of emissions when energy sources are changed. The values reflect change in total ton CO_2-eq from energy use per year for Stjernehus.

Table 28: Illustrating how significant energy sources are for total GWP results.

Scenarios of Energy Sources	**Change in total emissions** [t CO_2-eq]	[%]
District heating mix (org. Kristiansand)		
Mix, Stavanger	25	390 %
Mix, Harstad	-2	-55 %
El-mix (original NORDEL)		
Norwegian	-22	-194 %
UCTE	47	93 %

Economy as a constraint

The main constraint for such upgrading projects is the economic aspect (Enova, 2012). As this study found, the environmental payback time is 3.3 years, thus between 2018 and 2019 the emissions from construction materials are "covered" by the energy and emissions saved per year. In contrast, the economic payback time is significant when calculations are purely based on energy costs saved. All projects need economic budgets to secure finance for materials, energy, labor, transportation, and other costs. The economy of ambitious upgrading projects is outside the scope of this thesis, however it is important to hold awareness of the great costs of such projects. The economic payback time is found below.

Electricity prices have varied the last 5 years (LOS, 2016). The graph below illustrates differences in economic payback time with different electricity prices over 5 years. Thus one can observe that these prices effect the economic payback time for Stjernehus. The prices for

Kristiansand ranges from 0.45 NOK/kWh in 2011, to 0.22 NOK/kWh in 2015 for households (LOS, 2016). As the price was double as low in 2015 (record low) compared to in 2011, the years of payback time in form of electricity savings also ranges from 88- to 181 years as shown below.

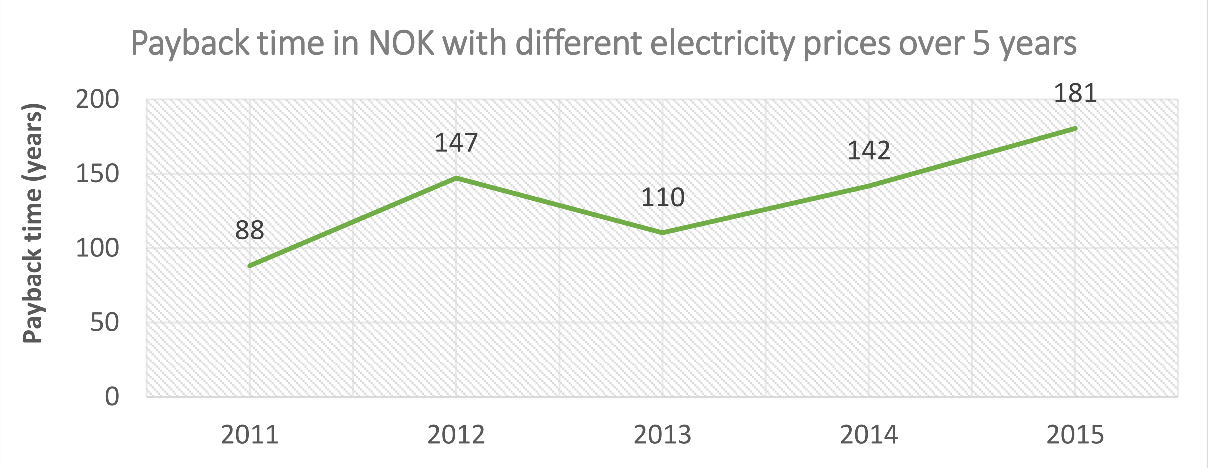


Figure 33: Payback time in NOK with different electricity prices over 5 years.

A low electricity price can lead to increased consumption of energy in Norwegian households and the building sector can experience intensification of emissions emitted in the user phase. Figure 33 illustrates that a low electricity price will increase the economic payback time, which can lead to a more pessimistic view of low-energy upgrading projects.

The environmental- and economic payback time are found to be largely contradictory when merely considering electricity savings. In order for ambitious upgrading projects to occur, there is a need to hold a long-term perspective on economic profitability. In addition, societal and environmental values need to be included in the economic budget in order for such projects to be profitable. The cooperative project Framtidens Byer (Future Cities), where Stjernehus was one of the pilot project, aimed for reducing GHG emissions and improving the quality of life in the cities involved (Regjeringen.no, 2014). In the future, more people will move to cities and there is a need to prepare and learn to build low-emission infrastructure that can cope with climate change. Such buildings will be sustainable, and need less maintenance and energy in the future as illustrated in figure 3 in chapter 2 (Evjenth et al., 2011). This value, in addition to improved physical urban environment regarding ecology, health, experience and business development, are perceived as significant and thus financed largely by the Norwegian government (Regjeringen.no, 2014). Hence there is a need to include societal and environmental values in the economic perspective in ambitious upgrading. This is illustrated in table 28.

Table 29: Payback time in NOK for the rehabilitation with additional values.

Payback time in NOK	Value	Unit
Electricity price, average	0.3	NOK/kWh
Energy saved	881250	kWh/year
=	264375	NOK/year
Total cost of rehabilitation	35	mill NOK
Payback time in NOK	132	years

\+ Climate change mitigation
\+ Improved physical urban environment
\+ Develop skills on sustainable buildings
= *Long-term values*

The three additional values generated by the project; climate change mitigation, improved physical urban environment, and develop skills on sustainable buildings are motives familiar in pilot projects such as the Stjernehus upgrading (Regjeringen.no, 2014).

Efforts to add environmental value: Emission Quotas

One effort to include environmental value by emphasizing climate change mitigation is the quota system in Europe. As the economic values determine if projects are conducted in the free market, the emissions trading scheme aims to force industries to lower their emissions to protect the natural environment. This including the construction sector. All Norwegian organizations that are part of the scheme must report their emissions to the Norwegian environmental agency, Miljodirektoratet (Miljodirektoratet, 2016). The emission limit is lower than the expected and will thus reduce total environmental emissions in Europe. The system is tightened every year by reducing climate quotas. If a company emits more than the free quotas provided, there is a need to purchase quotas on the market. The tightening will constantly increase the quota price, together with stricter environmental policies, thus the effect of the system will increase following (Hambro, 2014). In table 30 below the quota cost of emissions for the Stjernehus upgrading is illustrated (Miljodirektoratet, 2016). As for now, the price is low compared to costs and values of such projects.

Table 30: Emission quotas for the Stjernehus project.

Emission quotas for the Stjernehus project		
	Value	*Unit*
Total emissions of project	439	t CO2-eq
Emission quotas 2016	70	NOK/ton CO2
Quota for the upgrading	30721	NOK

The table illustrates merely emissions caused by construction materials and related processes, not the saved emissions per year as a results of energy efficiency. Below it is illustrated how much emission quota is saved per year after the ambitious upgrading of Stjernehus.

Table 31: Emission quotas for the Stjernehus project.

NOK saved by emission quotas for Stjernehus project		
	Value	*Unit*
Total emissions saved/year	134	t CO2-eq
Emission quotas 2016	70	NOK/ton CO2
Quota for the upgrading	9380	NOK/year

Future ambitious upgrading projects of older buildings are found to be beneficial for the environment and other social factors. Governmental initiatives such as Framtidens Byer (Future Cities) and Framtiden Bygg (Future Buildings) should therefore be emphasized in the future to gain experience and expand knowledge about sustainable buildings. Cooperation with private sector and other institutions in society are supported in order to expand both current and future knowledge to several parties.

6.2.2 Emissions from construction materials

This study has shown that particular materials used in components have a large effect on total emissions. In chapter 4 it was found that the plastic (PVC) window frames caused major GWP in both the manufacturing process and EOL treatment. When compared with results from Holen (2014) in chapter 5, it was identified that windows were responsible for less GHG emissions than the LCA calculations. The window frames were not assumed to be of PVC, in addition EOL was not included, hence the different results from the LCA model and Klimagassregnskap.no. Choosing fiber cement tiles was also causing a great amount of emissions for the exterior walls process, according the findings. The figure below illustrates the remodeled LCA that shows the amount of emissions caused by each materials.

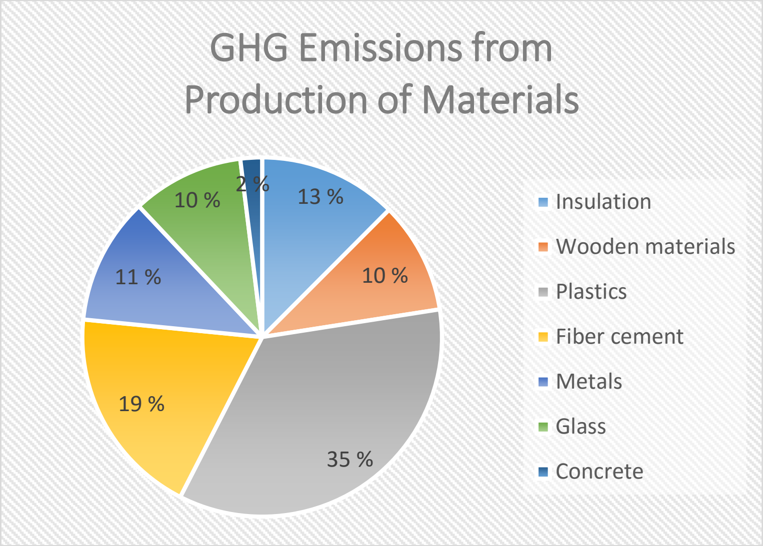


Figure 34: A modelling version of the complete LCA showing what the shell components consist of, and the impacts.

This figure illustrates the significance of materials in building components. Nevertheless, there are other factors that need to be included in the decision-making of choosing construction materials.

EOL paths

The end of life management is responsible for 23% of total construction materials' emissions, according to this study. Thus it is important to emphasize reuse and recycling continuously. By utilizing the waste as efficient as possible in the construction sector, the environmental impacts will be reduced as a result (Blengini and Di Carlo, 2010). Sorting waste and encourage proper waste treatment is significant. However, upgrading of buildings can be a major contributor for waste reduction itself. In this study the waste treatment methods were municipal incineration, sorting plant and final disposal. The share of these used for construction materials today is difficult to measure, and future sorting per cent is challenging to predict. Nevertheless, as the amount of wastes from this sector is so great, there is a need to further improve material exploitation in the future. These efforts can signify to improve quality of construction materials and thus extend the lifetime and reduce emissions in a life cycle perspective (Leland, 2008).

The possibilities of reusing or recycling are significant, and factors that increase these chances are listed in table 4 in chapter 2, Leland (2008). Among others it is recommended to use materials with few ingredients to simplify sorting. Further it is important to consider resistant materials that can withstand reuse, and to avoid surface treatment that can limit the recycling possibilities.

Lifetime of Components

As reuse and recycling are discussed above it is clearly an importance of lifetime of materials. The longer life, the less emissions for the building seen in a life cycle perspective. In table 32, one can observe interesting findings of this study. If materials merely obtain a lifetime of 30, or even 20 years, the total emissions increase significantly.

Table 32: Illustrating how significant lifetime choices are for total emissions from the upgrading.

Scenarios of Lifetime	**Change** [t CO_2-eq]	[%]
Lifetime of materials (org. 60 y)		
30 y lifetime	123	23 %
20 y lifetime	348	64 %

When a lifetime of 30 years is assumed on particular materials (see what materials in table 26 previously in this chapter), rather than originally 60 years, emissions increase by 123 ton CO_2-eq, or 23%. If materials are shifted after 20 years, one needs to add 348 ton CO_2-eq to total emissions of the upgrading, or 64% per cent. As found, the scenario results of el mix and district heating mix have greater changes in per cent, however do not contribute significantly on total emissions compared to change in lifetime of materials. Thus there was an importance to include both absolute and relative change in the scenario analysis.

Problem Shifting

It is challenging to give recommendations for materials merely based on GWP (measured in CO_2-eq). This study found environmental impacts of different construction material groups in a life cycle perspective. One of the impacts, climate change (GWP), identified emission intensive materials in building projects. However, the issue of problem shifting should not be ignored as it can shift a problem from one area to another. This is discussed in Hertwich (2005) article about rebound effects.

Materials' emissions vs thermal insulation

Exterior walls are a significant process consisting of several emission intensive elements such as fiber cement tiles and insulation. In addition, the window frames are contributing greatly, as shown earlier in this study. These findings are presented in table 33. Furthermore, one should be aware that EOL is not included in the table below and may affect the recommendations (e.g. treatment of window frames in PVC will double the current number, as found in chapter 4). Despite the importance of these observations in the table below, the information is not sufficient in terms of providing recommendations for material use in future rehabilitation projects: It does not consider u-values as an additional indicator.

Table 33: Emission intensive construction materials and major contributors.

LCA model, [Cradle to Gate]			
Foreground Process	*Major contributer*	*t CO2 eq*	*% of total materials*
Exterior Walls	Fiber Cement tiles	113.8	**42 %**
Doors & Windows	PVC (plastic) frame	98.7	**37 %**
Balconies	Aluminium production	41.1	**15 %**
Ventilation	Not found	10.2	**4 %**
Roof	Not found	4.8	**2 %**

In a life cycle perspective one can more easily experience problem displacement as the life stages depend on each other (Hertwich, 2005). One example is the windows with plastic frame that can lead to higher emissions from construction phase than wooden frames (Tellnes, 2015a, Tellnes, 2015b). However, the greater thermal insulation in a window, the more energy and emissions are saved in operation phase. This may compensate for emission-intensive construction and EOL processes. Thus, all life stages must be considered for recommendations to be reliable. Therefore, it is not necessarily recommended to choose wooden windows over PVC, that would be to ignore all life stages. When holding a long-term perspective and aiming to reduce environmental impacts over a buildings lifetime it is important to consider u-values (thermal insulation capability) (Skogheim, 2014, Solli, 2015). The purpose of the construction materials in an upgrading project is at last to save energy in the building's operation phase, in addition to provide functional user benefits.

Environmental Impact categories

In the field of industrial ecology, several environmental categories are considered to view potential rebound affects (Hertwich, 2005). The impact of one category can be low as a results of particular product or process decisions, however it may lead to great concern for another environmental impact. In this manner, the problem shifts from one category to another, and the importance of each is challenging to measure.

By observing figure 23 in chapter 4, the "environmental impacts from rehabilitation processes", problem shifting is found. Firstly, it is noted that exterior walls and doors & windows production were logically the processes that influenced the majority of categories the most. This is because these had high emissions compared to the total. Nevertheless, the total end of life (EOL) management of materials causes the most significant impact on marine- and freshwater ecotoxicity. Waste treatment, particularly land filling can cause a release of toxic substances to the soil and waters. Copper and nickel contributed the most to both of these environmental impact categories, according to the structural path analysis in this study.

Furthermore, doors & windows production seems to impact resource depletion significantly. The balconies influence the categories less than 10%, except the water depletion where the process has the highest impact. Thus, materials used for the balconies required a great amount of water during production.

By analyzing the structural path in the table below one can track the most emission intensive processes in the value chain for three impact categories: Climate change, human toxicity and freshwater ecotoxicity. Although the two recognized processes dominate the most one can identify the most emission intensive indirect processes differ among the environmental impact categories. For climate change, the two processes PVC suspension polymerized, and clinker dominate. For both human toxicity and freshwater ecotoxicity the problem shifts to zinc and steel production, and disposal of sulfidic tailings (see tables below).

Table 34: Tracking the value chain to identify the significant emission source. The number is relative to total impact (%). Climate Change (Global Warming potential).

17	Doors and windows production	window frame, plastic (PVC)	polyvinylchloride	PVC, suspension polymerised, at plant
5	Transportation of materials	transport, lorry 3.5-20t	operation, lorry 3.5-20t	
5	Exterior walls	fibre cement facing tile	portland cement, at plant	clinker, at plant
3	Doors and windows production	window frame, plastic (PVC)	polyvinylchloride	PVC, emulsion polymerised, at plant
3	Doors and windows production	window frame, plastic (PVC)	steel, low-alloyed, at plant	steel, converter, low-alloyed, at plant
2	Exterior walls	fibre cement facing tile	portland cement, at plant	clinker, at plant

Table 35: Tracking the value chain to identify the significant emission source. The number is relative to total impact (%). Freshwater Eutrophication.

4	Doors and windows production	window frame, plastic (PVC)	zinc coating, coils	zinc, primary
3	Exterior walls	iron-nickel-chromium alloy	nickel, 99.5%, at plant	disposal, sulfidic tailings, off-site
3	Doors and windows production	window frame, plastic (PVC)	steel, low-alloyed, at plant	steel, converter, low-alloyed
1	Doors and windows production	window frame, plastic (PVC)	zinc coating, pieces	zinc, primary
1	Doors and windows production	window frame, plastic (PVC)	steel, low-alloyed, at plant	steel, converter, low-alloyed
0	Doors and windows production	window frame, plastic (PVC)	polyvinylchloride	PVC, suspension polymerised

Table 36: Tracking the value chain to identify the significant emission source. The number is relative to total impact (%). Human Toxicity.

4	Doors and windows production	window frame, plastic (PVC)	zinc coating, coils	zinc, primary
3	Exterior walls	iron-nickel-chromium alloy	nickel, 99.5%, at plant	disposal, sulfidic tailings, off-site
3	Doors and windows production	window frame, plastic (PVC)	steel, low-alloyed, at plant	steel, converter, low-alloyed
1	Doors and windows production	window frame, plastic (PVC)	zinc coating, pieces	zinc, primary
1	Doors and windows production	window frame, plastic (PVC)	steel, low-alloyed, at plant	steel, converter, low-alloyed
0	Doors and windows production	window frame, plastic (PVC)	polyvinylchloride, at plant	PVC, suspension polymerised

As found in this study, the issue of problem shifting can challenge decision-making regarding choice of construction materials. All impact categories covered in chapter 4 are of significance for the natural environment and are interconnected (Hertwich, 2005). It is also important to address that the uncertainty of human toxicity and freshwater ecotoxicity is more significant than in for the climate change impact. See the next section (6.3) for further details about uncertainty.

6.2.3 Klimagassregnskap.no vs LCA

In table 37 the benefits and limitations of the two tools are outlined to comprehend the uniqueness of both. Such mapping can function as a guidance for what assessment tool to choose in different activities and consequences of choices.

Table 37: Benefits and Limitations of LCA and Klimagassregnskap.no. Source: (Holen, 2014a) and (Statsbygg and Civitas, 2014)

Environmental Assessment Tool	Benefits	Limitations
LCA	-Scientific matrix calculation of substances, allocated to processes -Several environmental impacts are calculated (e.g. human toxicity, freshwater eutrophication) -Uncertainty of results can be measured - Coherent: Uses one database (commonly ecoinvent in EU), acknowledged and updated - Flexible model – change and add as necessary	- Complexity: Large data quantities often need to be gathered -Cost: Common to purchase services from LCA expert -Uncertainty: Every parameter and model choice can alter results
Klimagassregnskap.no	-Relatively user friendly and easy accessible in comparison to LCA -Free of charge (generated by the Norwegian government) -Based on/in line with international and national standards from LCA methodology and the construction sector -Possible to use in early stage planning and can thus affect decision-making -Modelling: Easy to alter lifetime of materials -The demand will constantly drive improvements of the tool -Includes a module that calculates GHG emissions in user phase (i.e. from public transportation, cars)	-Considers merely carbon footprint, no other environmental impacts -Excludes several life cycle stages of materials -Inaccuracy: Simplified method to identify potential emission intensive building components -Several data bases used for one case, assumptions may differ in each -Limited amount of materials to choose from -Combinations of uncertainties: Uncertainty in data and missing link in data -No uncertainty test

Klimagassregnskap.no is designed to be easy to use in an early planning phase and obtain therefore several limitations (Holen, 2014a). One of the major is that system boundaries only includes construction phase, operation and maintenance. This excludes transportation of materials, installation, and end of life from the calculation of GHG emissions. As illustrated, these stages can be significant in comparison with the production phase, and in these cases results will not be realistic (Kristjansdottir, 2014). Another disadvantage is the lack of environmental impact assessment method that can show effect on various aspects in the environment – not just greenhouse gas emissions. Nevertheless, Klimagassregnskap.no has an additional module that measures emissions form transportation in user phase. This considers residents' transport habits and services to the building (Holen, 2014a).

It is important to notice that Klimagassregnskap.no is relatively new and is under constant improvement. This study has followed version 4, and has not accounted for changes in version 5 where for example presupposed lifetime calculation, and details for material use are altered (Statsbygg and CIVITAS, 2016).

6.3 Uncertainties

It is important to recognize uncertainties in both data and the methodology used in calculations. There are two types of uncertainties (Goedkoop et al., 2016):

Model uncertainties: Uncertainties can derive from subjective modelling choices. It is challenging to assess the impacts on the results, however the scenario analysis previously in this chapter provide an insight.
Data uncertainties: Uncertainties in data can be explored using statistics. In this study it will not be quantified, but discussed.

6.3.1 Uncertainty of data

Data gathering can be problematic and data availability can impact final results significantly (Curran, 2008). The data used in the LCA calculations is divided in materials, EOL, electricity and transport and discussed below.

Materials

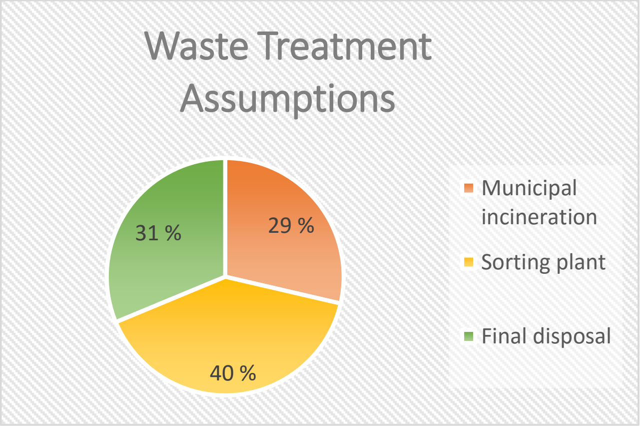
There was a need to estimate particular data collected in this study. As the material list were given in a different unit than required by the LCA software, there was a need to convert these to kg, m^3 and m^2. When materials consisted of several components there was a need to estimate the share of each part. For example, for the balcony, the share of glass, aluminum in the walls were calculated based on measures and drawings. This estimate is not perfect, however a close estimate to real values. Similarly, the insulation product "Rockwool HardRock Energy Systemtak" is built based on the "dual density" principal which means the plate has a higher density on the top and a lower on the lowest part. By achieving this the point load strength is significant because the top (with high density) divide the weight down to the lowest point

(Rockwool.no). The reason for such complexity is clearly quality. In an LCA perspective, however, it increases the complexity of measuring the product's weight, hence calculation of environmental impact.

The density is highly varied for different tree types as well (Weider and Skogstad, 1999). Hence it was challenging to determine the specific density for each material of wood and other materials utilized in the Stjernehus rehabilitation process. Nevertheless, detailed information regarding density of various wooden types were provided by SINTEF Byggforsk (Plesser and Kristjansdottir, 2015).

End of life

There are reasons for the EOL process to be uncertain. (i) As several components consist of more than one material, the share of each is estimated with information from suppliers and webpages. (ii) As data gathering for end of life processes is a time consuming process and not the main focus of this thesis, the assumptions for treatment methods were made based on previous local practice in Kristiansand. (iii) As the apartment building can exist for several decades it is difficult to predict future waste treatments. The figure below illustrates assumptions made regarding waste treatment methods of the construction materials in the end of life phase.



.

Figure 35: Waste Treatment Assumptions in the LCA model.

Energy

Several forms of energy were needed for the Stjernehus project. Electricity used at construction site were estimated by the project leader from Kruse Smith (Ronningen and Torsvik, 2016). The NORDEL el mix was chosen as energy source (see chapter 2.3.1), as Norway is a part of the NordPool – the Nordic electricity exchange. Use of diesel during the rehabilitation was similarly estimated with the help of the entrepreneur. These processes were allocated to an own foreground process called energy for construction. The most significant energy use occurs during the operation phase which was calculated separately from the scope of the upgrading project as the focus was construction materials. The values for energy delivered from GRID and district heating were estimated by Sweco using the energy calculation software SIMIEN (Skogheim, 2014). See section 4.1.2 for details on inventory.

Transportation

An address list of all suppliers for the Stjernehus project was provided by the entrepreneur Kruse Smith. In addition, the project responsible (Moen, 2016) from Sorlandets Boligbyggerlag provided necessary information. Home pages of suppliers were also reviewed to assess the value chain. In this manner transportation distances could be calculated. Because the majority of construction materials were either found or assumed to be produced in Scandinavia, a fleet vehicle for transportation was chosen in the ecoinvent database. Nevertheless, it is time consuming to assess a complete value chain of production. Thus the transport distances may be higher in reality. See appendix B for calculation of transport distances for both “transportation of materials to construction site”, and “values for calculation of transportation of EOL from construction site”.

6.4.2 Uncertainty of the methodology

The two methods used to collect data in this study was LCA methodology and interviews with the project leader in SBBL and the entrepreneur Kruse Smith. The interviews were conducted to obtain an insight in processes and elements of the upgrading project. This included materials list, address list of suppliers, energy use, and technical information that assisted in LCA modelling choices.

In the LCA modelling, the background database ecoinvent 2.2 was used to calculate environmental impacts. In the database there are limitations in the choice of nations the operations occur. Therefore, Switzerland or Europe were often chosen when Scandinavia was not existing. Additionally, it was found that the process of “windows” included both impacts from the manufacturing process and EOL. Therefore, there was a need to analyze the results to identify the share deriving from manufacturing and EOL.

The lifetime of materials is uncertain as identified in the literature review. Therefore, a scenario analysis of different lifetimes of relevant materials were generated previously in this chapter. As observed, different assumptions of lifetime lead to significant differences in total emissions.

Of the eighteen midpoint categories, some of them are dependent on regional environment. Eutrophication, acidification, toxicity, photochemical ozone formation, land- and water use are environmental mechanisms that differs between locations. Therefore, results from these impact categories cannot be completely valid as Norwegian specific customization does not exist for now. Food habits, hygiene, weather conditions, background concentrations and population density are regional specific factors that can affect the validity in the impact assessment (Goedkoop et al., 2012).

Several environmental impacts were calculated in this study and the degree of uncertainty for each impact differs. For instance, climate change (CO_2-eq) holds the most significant research and data, hence is recognized as having minor uncertainty in comparison to other categories. All impacts are effected by a changed time perspective; however particular categories are significantly sensitive to such changes. One example is metals, which will show largely different impacts in a 50, 100, or 500 year perspective (Goedkoop et al., 2012). Thus these impact categories are more uncertain than the more stable.

6.4 Future Work

As discussed, Kristjansdottir (2014) found that construction materials for new buildings with ambitious energy efficiency hold a large share of total emissions from the building in a life cycle perspective. This study found that emissions form materials for the upgrading were minor in comparison to energy saved. This study assesses the ambitious standard low-energy, class 1. Future studies can compare rehabilitation projects with different ambitions. The different Norwegian standards are listed in chapter 2. In this manner one can interpret the impact on materials’ emissions vs energy saving in user phase with the different standards.

This study has assessed environmental impacts from construction materials and related processes. Considering that such upgrading projects aim for energy saving in the user phase, it is important for designers to consider materials’ thermal insulation (u-values in operational phase). Therefore, it could be interesting to compare emissions vs thermal insulation of material groups. For example, if window frames were shifted from PVC to wood, what would be the effect on thermal insulation capacities?

An extensive scenario analysis could be carried out testing end of life treatment methods as these are uncertain in the future. In the end of life of the materials, which is in 60 years for this study, it is difficult to predict how different types of wastes are treated. Scenarios with landfill, reuse, recycling, and incineration could be interesting to assess to identify environmental impacts with the different methods. The results could influence future work on EOL paths

In housing with sufficient insulation, residents tend to increase the indoor temperature (Langseth et al., 2011). In Stjernehus, the electricity bills do not differ significantly between residents because of common bills for district heating, and low electricity prices. Thus there is no cost-effect to increased energy consumption (Moen, 2016). What would be the effect on electricity use, hence emissions, if all apartments paid fully after consumption? This can also be seen in relation with electricity prices.

This study includes an interview with the case building’s entrepreneur, Kruse Smith, regarding their approach of the tools LCA and Klimagassregnskap.no in practice. There are several manners to approach environmental aspects in the construction sector and it would be interesting to consider differences in practice, and their motives. This could be by assessing and interviewing different construction companies with differences in location, size, organizational strategy, target customers, among other factors.

The three different cultural perspectives existing in LCA methodology could be analyzed in relation to environmental impacts from an ambitious upgrading. The perspectives individualist, hierarchist, and the egalitarian reflect different assumptions and, importantly, time perspectives in LCA calculations.

7. Conclusion

The ambitious upgrading of the case building Stjernehus was a pilot project in cooperation with Framtidens Byer (Future Cities), Lavenergiprogrammet (the low-energy program) and Norwegian architects National Association and was performed in 2014-2015. The goal of this thesis was to identify the carbon footprint for the upgrading process of the housing cooperative in Kristiansand. In addition, results from two different environmental assessment tools used, Life Cycle Assessment (LCA) and Klimagassregnskap.no, were compared. Discussion and recommendations were drawn based on the analysis.

The results show that total carbon footprints of the upgrading of Stjernehus was 439 ton CO_2-eq. This includes production of construction materials, transportation to site, energy and diesel used during construction and end of life treatment of materials, including transport to waste treatment plant (in EPD terminology: A1-A5, B separate, and C1-C4). The exterior walls caused 32% of total climate change impact with fiber cement tiles as the major contributor. 34% of emissions came from window and doors production where treatment of PVC (plastic) window frames was the major contributor in the value chain.

The main objective of the LCA conducted was the upgrading process with a focus on construction materials used. Therefore, energy consumption during the operation phase was considered separate from emissions embodied in materials. Greenhouse gas emissions related to energy use by residents prior to upgrading was 164 ton CO_2-eq/year, and decreased by 84% to 25 ton CO_2-eq/year after the rehabilitation. The time before emissions caused by the upgrading project are payed back in energy savings is 3.3 years. Thus the GHG emissions from construction materials are minor in comparison to energy saved in the operation phase.

There are different advancements and manners to perform an environmental analysis of a construction project. Klimagassregnskap.no is an example tool provided by Statsbygg (the Norwegian Directorate of Public Construction and Property), estimating greenhouse gas emissions from elements of a building. The purpose of this tool is to be used in planning in projects where GHG emissions are considered from cradle to gate. LCA methodology aims to generate a complete calculation of different environmental impacts by identifying all materials and processes in a life cycle perspective. A previous analysis was performed using Klimagassregnskap.no (Holen, 2014a), and a comparison of results were conducted in this study. To perform a fair comparison, the scope of the LCA model was reduced to be comparable with Klimagassregnskap.no. (e.g. ventilation and transportation of materials were not included in the adjusted LCA model). The assessment shows that Klimagassregnskap.no calculated a total of 156 ton CO_2-eq emissions from the upgrading, while the adjusted LCA model 237 ton CO_2-eq. The results from Klimagassregnskap.no is 180% less compared with the complete LCA model (439 ton CO_2-eq). In addition, the payback time of emissions were also found to be 2 years less. Hence both the LCA- and Klimagassregnskap.no models result in an optimistic approach towards future ambitious upgrading, however the latter tool underestimates emissions from materials.

The scenario analysis found that emissions increased 22% if particular materials were changes one time during 60 years, and 64% if changed two times - that is 348 ton CO_2-eq more emitted. Thus lifetime of materials can alter total emission value significantly. The effect with different district heating mixes was measured by assuming different locations of the apartment building. If Stjernehus was located in Stavanger holding a different district heating mix, emissions per year would increase by 390%. There are also three relevant electricity mixes for Norway, the Norwegian-, the NORDEL, and the UCTE el mix. One scenario tested the effect if Stjernehus received another el mix from GRID. If the Norwegian el mix were used, and not the NORDEL, emissions per year would decreased 194%, or 22 ton CO_2-eq. Thus, modelling choices during environmental assessments can affect the results significantly.

This study supports future upgrading projects of apartment building from an environmental perspective as this can save a significant amount of energy hence emissions, per year. Nevertheless, for such projects to occur and be profitable, there is a need to hold a long-term perspective on economic value and consider societal and environmental values in addition.

A remodeling of the components showed the significance of emissions from plastics and fiber cement. Thus the choice of particular materials in the shell components effect total environmental impacts. Nevertheless, there are other factors that need to be included in the decision-making of choosing construction materials. It is recognized that materials designed for reuse or recycling are preferred in terms of reduction of environmental impacts. The end of life paths chosen for this study were landfilling, incineration, and recycling with about an equal share. It is challenging to predict future EOL scenarios as waste treatment methods may be altered in the future. To the extent possible, this aspect of materials should however be considered in decision-making. The last important aspect of materials discussed in this study is the lifetime of materials. The longer life, the less emissions seen in a building's life cycle perspective.

The issue of problem shifting is recognized in environmental assessments and add challenges to provide solid recommendations based on an assessment of environmental impacts solely. Findings in this study correspond with literature regarding problem shifting between environmental impacts. Also in terms of recommending particular construction materials, this issue is discovered. It is found that although PVC windows and exterior walls seem to hold most of the GHG emissions, these also act as significant thermal insulation contributors. Thus, leads to more energy saved in the operation phase of the building. This illustrates that recommendations regarding "environmentally friendly" construction materials should consist of several indicators. The most important are emissions in a life cycle perspective and thermal insulation capacities.

8. References

Treteknisk håndbok, Oslo, Norsk treteknisk institutt, 1999.

BARKER T., I. B., L. BERNSTEIN, J. E. BOGNER, P. R. BOSCH, R. DAVE, O. R. DAVIDSON, B. S. FISHER, S. GUPTA, K. HALSNÆS, & G.J. HEIJ, S. K. R., S. KOBAYASHI, M. D. LEVINE, D. L. MARTINO, O. MASERA, B. METZ, L. A. MEYER, G.-J. NABUURS, A. NAJAM, N. NAKICENOVIC, H. -H. ROGNER, J. ROY, J. SATHAYE, R. SCHOCK, P. SHUKLA, R. E. H. SIMS, P. SMITH, D. A. TIRPAK, D. URGE-VORSATZ, D. ZHOU 2007. IPCC - Technical Summary. *In:* GITHENDU, M. W. (ed.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment*

Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York: IPCC.

BAUMANN, H. & TILLMAN, A. 2004. The Hitch Hiker's Guide to LCA. *An orientation in life cycle assessment methodology and application.* Lund, Sweden: Studentlitteratur.

BLENGINI, G. A. & DI CARLO, T. 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings,* 42**,** 869-880.

BOLIGPRODUSENTENE. 2014. *TEK 10 - tips og råd om energiberegninger* [Online]. Boligprodusentene.

BRAMSLEV, K. & HAGEN, R. 2015. Grønn Materialguide. Grønn Byggallianse and Context AS.

BRAND, S. 1994. *How buildings learn: What happens after their built,* United States of America, Penguin Group.

CURRAN, M. A. 2008. Life-Cycle Assessment. *Human Ecology*.

DAHLSTRØM, O. 2011. *Life Cycle Assessment of a Single Family Residence built to Passive House Standard.* Master, NTNU.

DIREKTORATET FOR BYGGKVALITET, D. 2015. Veiledning om tekniske krav til byggverk. *Energi.* Direktoratet for Byggkvalitet.

DOKKA, T. H., WIBERG, A. H., LAURENT, G. & MELLEGÅD, S. 2013. A zero emission concept analysis of a single family home. *Concepts and strategies for zero emission buildings.* SINTEF.

ECOINVENT. 2016. *Differences between ecoinvent 2 & 3* [Online]. Zurich, Switzerland.

ENOVA 2012. Potensial- og barrierestudie: Energieffektivisering i norske bygg. *In:* ENOVA (ed.) *Potensial- og barrierestudie.*

ENOVA. 2016. *Dagens standard og fremtidens boliger* [Online]. [Accessed 26.04 2016].

EPD-NORGE 2016. EPDs for construction materials. EPD-Norge.no: EPD-Norge.

EUROPEAN COMISSION, E. 2015. Renewable Energy Package: new Renewable Energy Directive and bioenergy sustainability policy for 2030 *In:* COMISSION, E. (ed.) *Inception Impact Assessment.* ec.europa.eu.

EVJENTH, A., SANDVIK, P., ALMÅS, A.-J. & BJØRBERG, S. 2011. Grunnlag for, og krav om, utbedring av eksisterende bygninger. *In:* MULTICONSULT & KLUGE (eds.).

FJERNKONTROLLEN.NO. 2015. *Norsk fjernvarme oversikt* [Online]. [Accessed 30.03.2016 2016].

GOEDKOOP, M., HEIJUNGS, R., HUIJBREGTS, M., SCHRYVER, A. D., STRUIJS, J. & VAN ZELM, R. 2012. ReCiPe 2008: Report 1, Characterization. *In:* AL., G. E. (ed.) *ReCiPe.* 1st, revised ed. Den Haag: Ministerie van VROM.

GOEDKOOP, M., OELE, M., LEIJTING, J., PONSIOEN, T. & MEIJER, E. 2016. Introduction to LCA with SimaPro 8. *In:* PRÉ (ed.) *SimaPro.* California.

HAMBRO, E. 2014. *Økte klimagassutslipp fra kvotebedrifter* [Online]. [Accessed 02.05 2016].

HASENMÜLLER, B. 2014. *Oppgradering av eksisterende boligblokk* [Online]. Norske Arkitekters Landsforbund (NAL). [Accessed 10.04 2016].

HERTWICH, E. G. 2005. Consumption and the Rebound Effect: An Industrial Ecology Perspective. *Journal of Industrial Ecology,* 9**,** 85-98.

HOLEN, J. 2014a. *Case study of a retrofitting project: GHG calculation & study of decision making processes.* Masters Master, Aalborg University.

HOLEN, J. 2014b. *Model in Klimagassregnskap.no* [Online]. Klimagassregnskap.no. [Accessed 15.03 2016].

HUSBANKEN 2011. Veileder til Husbankens grunnlån. *In:* HUSBANKEN (ed.) *Retningslinjer og veiledning.*

HUSBANKEN. 2014. *Stjernehus Borettslag - oppgradering* [Online]. Husbanken.no. [Accessed 20.04 2014].

ISO 14040 2006. Principles and framework, Environmental Management - Life Cycle Assessment - ISO 14040. Geneva: ISO.

KAMPESAETER, A., BJORBERG, S. & LISTERUD, C. A. 2009. Levetider i praksis - prinsipper og bruksområder. Oslo: Multiconsult.

KJØLLE, K., DENIZOU, K., LIEN, A., EVA MAGNUS, K. B., ÅSHILD L. HAUGE,, KLINSKI, M., LÖFSTRÖM, E. & ØYEN, T. W. O. C. F. 2013. Flerfaglig analyse av casestudier i REBO – med vekt på ambisjonsnivå for universell utforming og energistandard. *Bærekraftig oppgradering av boligblokker* [Online].

KRISTJANSDOTTIR, T. E. A. 2014. A Norwegian ZEB-definition embodied emission.

LANGSETH, B., EVERETT, E. N. & HAVSKJOLD, M. 2011. Energibruk i lavenergi- og passivbygg - En sammenligning av forventet og målt energibruk. *In:* NORGE, E. (ed.) *Energibruk i lavenergi- og passivbygg* Energi Norge.

LAVENERGIPROGRAMMET.NO. 2016. *Om Lavenergiprogrammet* [Online]. Oslo: Lavenergiprogrammet. [Accessed 15.05 2016].

LELAND, B. N. 2008. PROSJEKTERING FOR OMBRUK OG GJENVINNING. *In:* LARSEN, B. (ed.). Oslo: Rådgivende Ingeniørers Forening.

LINKCYCLE. 2013. *What is life cycle assessment* [Online]. [Accessed 05.05 2016].

LOLLI, N. 2014. *Life cycle analyses of CO2 emissions of alternative retrofitting measures.* PhD, Norwegian University of Science and Technology.

LOS, E. 2016. Historiske strømpriser. *In:* LOS (ed.). los.no/los/privat/historiske-strompriser.

MILJODIREKTORATET 2016. Kvotepris for beregning av årlig CO2-kompensasjon. *In:* MILJODIREKTORATET (ed.) *CO2-priskompensasjon.*

MOEN, O. H. 05.02.2016 2016. *RE: Meeting SBBL about Stjernehus.* Type to WRÅLSEN, B.

MORK, Ø. 2016. *RE: Talk about future sustainable buildings.* Type to WRÅLSEN, B.

PLESSER, T. S. & KRISTJANSDOTTIR, T. F. 2015. Byggforskserien. SINTEF byggforsk.

RANDERS, J., ARNSTAD, E., FLÅTEN, O., HEDSTEIN, A., LEKVA, H., NORD, L., AAM, S., H. ALFSEN, K., HAGEN, K. A. & WESTSKOG, H. 2006. Et klimavennlig Norge. *In:* ENVIRONMENT, M. O. C. A. (ed.). Utslippsutvalget.

RAUBOTI, J. & VINJAR, A. 2013. *Nord Pool ASA* [Online]. [Accessed 04.05 2016].

REGJERINGEN.NO 2014. Framtidens Byer. *In:* PLANAVDELINGEN (ed.) *By- og stedsutvikling.* Kommunal- og moderniseringsdepartementet.

RONNINGEN, O. 22.04.2016 2016. *RE: E-mail communication.* Type to WRÅLSEN, B.

RONNINGEN, O. & TORSVIK, E. 2016. *RE: Meeting entrepreneur Kruse Smith, data gathering.* Type to WRÅLSEN, B.

SINTEF BYGGFORSK, O. & NBBL, O. 2015. Forberedelse og Mevirkning. *In:* BYGGFORSK, S. (ed.) *Oppslutning om oppgradering.* Oslo.

SKOGHEIM, H. 2014. Energirapport for Stjernehus BRL. Kristiansand: Sweco.

SOLLI, C. E. A. 2015. Helhetlig miljøvurdering av byggematerialer.

SPIEGEL, R. 2014. *Life Cycle Assessment of a new School Building designed according to the Passive House Standard.* Master, NTNU.

STANDARD NORGE, N. 2013. NS 3700: 2013. *Kriterier for passivhus og lavenergibygninger: Boligbygninger.* Standard Norge.

STATSBYGG & CIVITAS 2014. Brukermanual Klimagassregnskap.no. *In:* STATSBYGG & CIVITAS (eds.) *Brukermanual.*

STATSBYGG & CIVITAS. 2016. *Endringslogg* [Online]. Klimagassregnskap.no: Statsbygg and CIVITAS. [Accessed 15.05 2016].

STRØMMAN, A. 2010. Methodological Essentials of Life Cycle Assessment. Trondheim: Norwegian University of Science and Technology.

TELLNES, L. G. F. 2015a. EPD: Nordvestvinduet Innslående vindu. *EPD-Norway.* Norsk Treteknisk Institutt.

TELLNES, L. G. F. 2015b. EPD: Nordvestvinduet UltimDWH horisontalhengslet vindu. *EPD-Norway.* Norsk Treteknisk Institutt.

THUNES, J. 2016. Ved å rehabilitere gamle bygg kan vi halvere energibruken.

UNITED NATIONS, U. 2015. *COP21paris.org* [Online]. London. [Accessed 20.04 2016].

WBCSD 2002. The cement sustainability initiative. *In:* DEVELOPMENT, W. B. C. F. S. (ed.) *Dedicated to make a difference.*

WEIDER, I. & SKOGSTAD, P. 1999. *Treteknisk håndbok,* Oslo, Norsk treteknisk institutt.

ZEB.NO. 2016. *the Research Centre on Zero Emission Buildings* [Online]. [Accessed 15.05 2016].

Appendix

A. Acronyms

LCA Life Cycle Assessment

EOL End of Life

GHG Greenhouse Gas

COP21 Conference of the Parties

EU European Union

IPCC Intergovernmental Panel on Climate Change

CO_2 Carbon Dioxide

GWP Global Warming Potential

ISO International Organization for Standardization

NS Norwegian Standard

UCTE Union for the Coordination of the Transmission of Electricity

FU Functional Unit

EPD Environmental Product Declaration

SBBL Sorlandets Boligbyggelag

PVC Polyvinyl chloride

BREEAM Building Research Establishment Environmental Assessment Method

B. Transportation

Table 38: Transportation of materials to construction site; location and distances.

Producer (P)	P adress	Supplier (S)	S adress	Km P-S	Km S-site	Material	Mode	Source
	Oslo	Ulstein ventilasjon	Postboks 56 4791 Vennesla	300	32	Ventilation system	Lorry	SBBL
Rockwool	Moss	Etterisolering Agder	Buhusheia 5B, 4634 Kristiansand	268	50	Rockwool insulation	Lorry	EPD
Jackon AS	Fredrikstad	Carlsen & fritzøe	Postboks 9114 Sørlandsparken 4696 Kristiansand	290	10	Jackofoam, wooden materials	Lorry	SBBL
	Ungarn	Cembrit	Eternitveien 34,3470 Slemmestad - oslo	1870	320	Fasadeplater	Lorry&ferry	Web page
	Vaxjø, Sweden	Balco AS	Vågsbygd Ringvei 100 4626 Kristiansand	719	3.7	Balconies	Lorry	Web page
	Kristiansand	ABC-tak AS	Olav Trygvasons vei 2, 4633 Kristiansand S	0	6.8	Roof	Lorry	SBBL
	Lithuania	Sør-vindu	Prestegårdsskauen 8, 4790 Lillesand	1944	30	PVC windows	Lorry	Web page
	Grimstad	Sørlandslisten	Hommedalskogen 73, 4886 Grimstad	0	48.8	Moldings	Lorry	SBBL
	Oslo	Norlock	Skippergata 93, 4614 Kristiansand S	300	2.7	Doors	Lorry	Kruse Smith
			Sum	5691	504			
			Total km		6195			
			Average km per supplier		688.33			
			Total tons of materials to transport		176			

Table 39: Values for calculation of transportation of EOL from construction site.

From	**Destination**	**Distance**	**Mode**
Stjernehus	Avfall Sør	7.7 km	Lorry

Total tons of materials to transport	160	ton
Ton per lorry	58	tkm

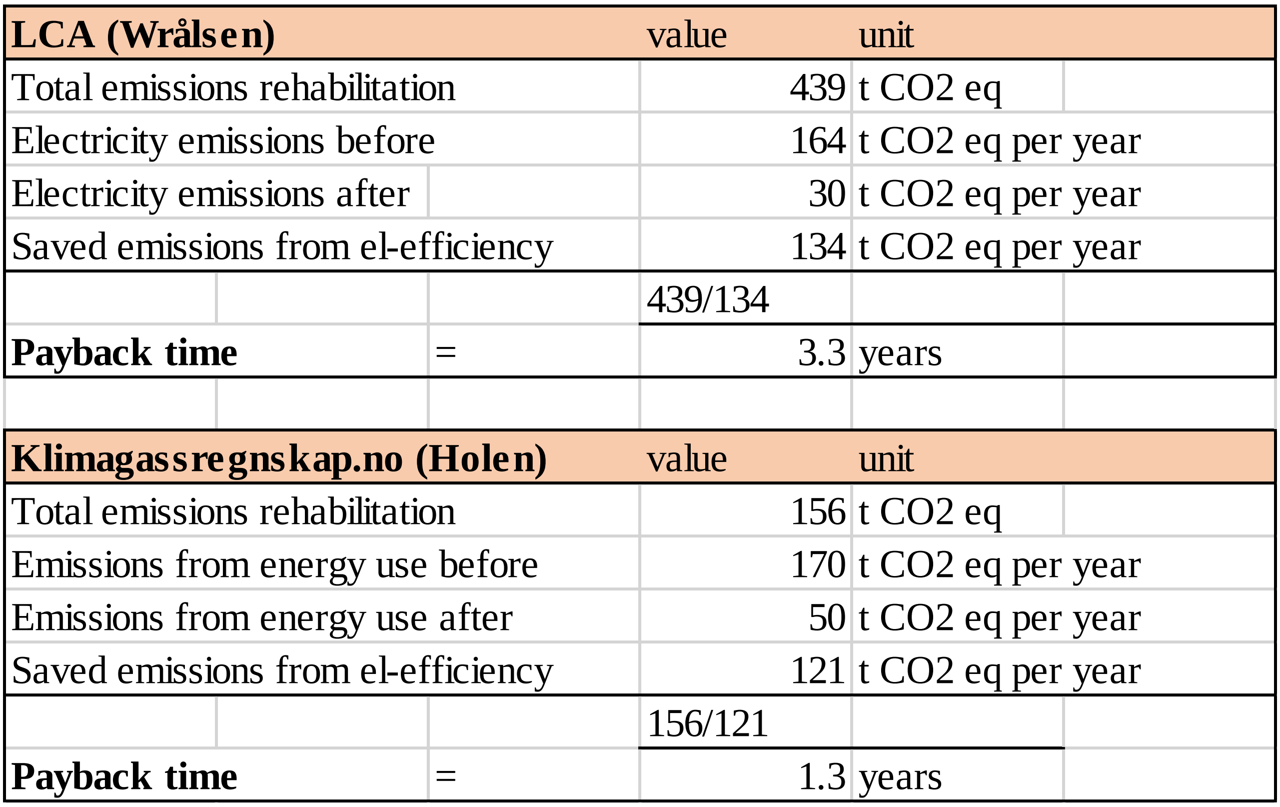
C. Environmental impact assessment

Table 40: Values for the environmental impact assessment, in chapter 4.2.3.

	Exterior walls	Roof	Balconies	Ventilation	Transportation	EOL materials	Doors & windows
Climate change, kg CO2 eq	1.14E+05	4.80E+03	4.11E+04	1.02E+04	3.38E+04	2.60E+04	9.87E+04
Fossil depletion, kg oil eq	3.06E+04	3.95E+03	1.07E+04	3.04E+03	1.18E+04	2.51E+03	4.01E+04
Freshwater ecotoxicity, kg 1,4-DB eq	9.19E+02	3.16E+01	4.32E+02	3.47E+02	8.52E+01	9.08E+03	1.29E+03
Freshwater eutrophication, kg P eq	2.89E+01	1.34E+00	1.57E+01	1.04E+01	2.70E+00	1.15E+00	3.60E+01
Human toxicity, kg 1,4-DB eq	3.64E+04	1.30E+03	1.77E+04	1.50E+04	3.68E+03	1.69E+04	4.83E+04
Ionising radiation, kg U235 eq	2.77E+04	1.05E+03	9.47E+03	2.69E+03	3.37E+03	1.31E+03	1.63E+04
Marine ecotoxicity, kg 1,4-DB eq	9.02E+02	2.94E+01	4.42E+02	3.43E+02	9.39E+01	7.88E+03	1.32E+03
Marine eutrophication, kg N eq	1.98E+01	9.95E-01	7.44E+00	2.71E+00	1.22E+01	3.26E+01	2.81E+01
Metal depletion, kg Fe eq	8.65E+03	2.01E+02	4.00E+03	4.95E+03	1.28E+03	4.20E+02	3.98E+04
Natural land transformation, m2	7.93E+01	2.57E+00	8.57E+00	2.24E+00	1.24E+01	-1.33E+00	1.71E+01
Ozone depletion, kg CFC-11 eq	2.15E-01	1.88E-03	2.79E-03	1.38E-03	5.36E-03	1.10E-03	4.65E-03
Particulate matter formation, kg PM10 eq	2.41E+02	2.50E+01	8.51E+01	3.18E+01	9.01E+01	2.04E+02	2.17E+02
Photochemical oxidant formation, kg NMV	3.55E+02	2.40E+01	1.25E+02	3.15E+01	3.51E+02	1.40E+02	4.12E+02
Terrestrial acidification, kg SO2 eq	4.88E+02	2.81E+01	1.92E+02	5.07E+01	2.00E+02	9.35E+02	5.73E+02
Terrestrial ecotoxicity, kg 1,4-DB eq	1.71E+01	5.08E-01	6.15E+00	1.33E+00	4.69E+00	1.43E+00	1.60E+01
Urban land occupation, m2a	9.49E+03	4.81E+01	3.38E+02	1.49E+02	4.59E+02	3.59E+02	1.51E+03
Water depletion, m3	4.11E+05	1.33E+04	7.28E+05	3.92E+04	4.16E+04	1.60E+04	4.40E+05

D. Calculations for Payback Time of Emissions

Table 41: Calculation of payback time of emissions for the LCA and Klimagassregnskap.no.

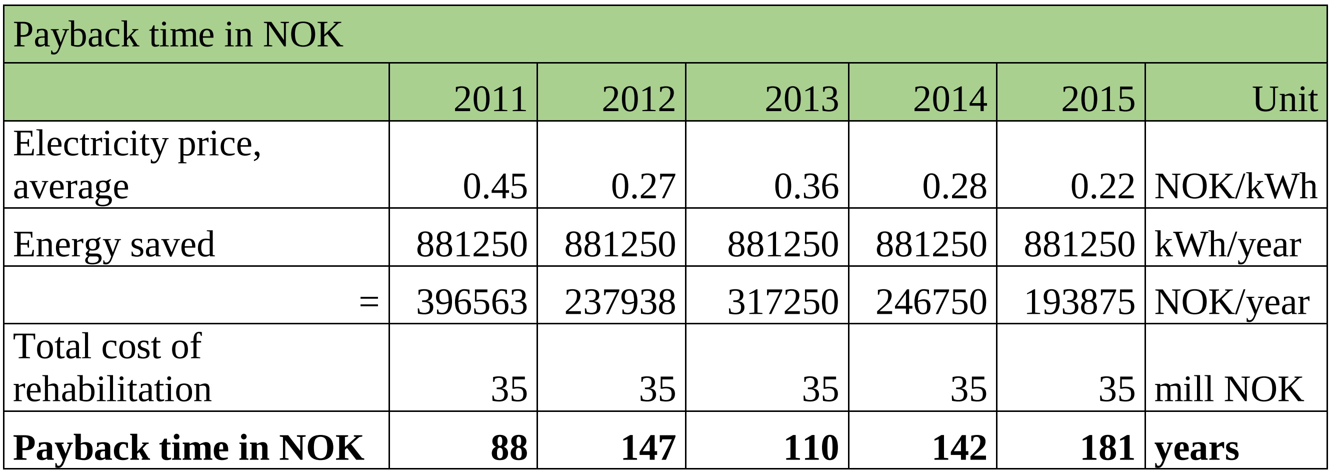


LCA (Wrålsen)		value	unit
Total emissions rehabilitation		439	t CO2 eq
Electricity emissions before		164	t CO2 eq per year
Electricity emissions after		30	t CO2 eq per year
Saved emissions from el-efficiency		134	t CO2 eq per year
		439/134	
Payback time	=	3.3	years

Klimagassregnskap.no (Holen)		value	unit
Total emissions rehabilitation		156	t CO2 eq
Emissions from energy use before		170	t CO2 eq per year
Emissions from energy use after		50	t CO2 eq per year
Saved emissions from el-efficiency		121	t CO2 eq per year
		156/121	
Payback time	=	1.3	years

E. Economic payback time

Table 42: Economic payback time in NOK for the upgrading, illustrated with different electricity prices over 5 years.



Payback time in NOK						
	2011	2012	2013	2014	2015	Unit
Electricity price, average	0.45	0.27	0.36	0.28	0.22	NOK/kWh
Energy saved	881250	881250	881250	881250	881250	kWh/year
=	396563	237938	317250	246750	193875	NOK/year
Total cost of rehabilitation	35	35	35	35	35	mill NOK
Payback time in NOK	**88**	**147**	**110**	**142**	**181**	**years**

F. Advanced contribution analysis

Table 43: Advanced contribution analysis for different impact categories.

Climate Change (GWP)		
Activity		*Contribution*
Polyvinylchloride (PVC), suspension polymerised		14 %
Disposal, PVC, to municipal incineration		12 %
Clinker, at plant		8 %
Transportation of materials		5 %
Natural gas, burned in industrial furnace		3 %
Pig iron, at plant		3 %
PVC, emulsion polymerised, at plant		3 %
Lignite, burned in power plant		2 %
Stressor	*To compartment*	*Relative impact*
Carbone dioxide, fossil	Air	91 %
Methane, fossil	Air	6 %
Human Toxicity		
Activity		*Contribution*
Disposal, sulfidic tailings		20 %
Disposal, steel, to municipal incineration		18 %
Disposal, spoil from lignite mining, in surface landfill		16 %
Disposal, spoil from coal mining, in surface landfill		8 %
Steel, electric, un- and low-alloyed		5 %
Disposal, PVC, to municipal incineration		4 %
Zinc, primary, at regional storage		3 %
PVC, suspension polymerised, at plant		3 %
Stressor	*To compartment*	*Relative impact*
Manganese (mn)	Water	55 %
Arsenic, ion	Water	9 %
Mercury	Air	10 %

Particulate Matter Formation		
Activity		*Contribution*
disposal, gypsum, 19.4% water, to sanitary landfill/ CH/ kg		15 %
basalt, at mine/ RER/ kg		9 %
zinc coating, coils/ RER/ m2		8 %
iron ore, 46% Fe, at mine/ GLO/ kg		6 %
operation, lorry 3.5-20t, fleet average/ CH/ vkm		6 %
polyvinylchloride, suspension polymerised, at plant/ RER/ kg		6 %
Stressor	*To compartment*	*Relative impact*
Particulates (PM), > 2.5 um	Air	37 %
sulfur dioxide	Air	26 %
nox to air	Air	24 %

Terrestrial Acidification		
Activity		*Contribution*
Disposal, gypsum, to sanitary landfill		28 %
Zinc coating, coils		14 %
Polyvinylchloride (PVC), suspension polymerised		6 %
Transportation construction materials		5 %
Nickel, 99.5%, at plant		4 %
Rock wool, at plant		4 %
Stressor	*To compartment*	*Relative impact*
Sulfur dioxide	Air	48 %
Nox to air	Air	22 %
Ammonia	Air	15 %

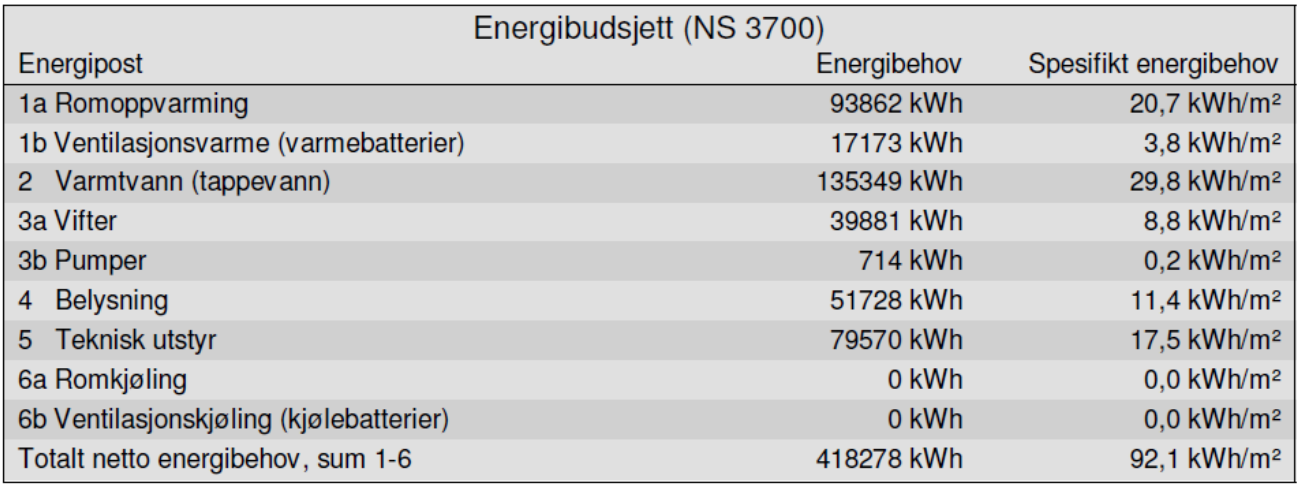
Freshwater Eutrophication		
Activity		*Contribution*
disposal, spoil from lignite mining, in surface landfill		49 %
disposal, spoil from coal mining, in surface landfill		23 %
disposal, sulfidic tailings, off-site		20 %
Stressor	*To compartment*	*Relative impact*
phosphate, water, ground-, long-term, kg	Water, ground	83 %
phosphate, water, ground-, kg	Water, ground	16 %

Metal Depletion		
Activity		*Contribution*
manganese concentrate, at beneficiation		26 %
iron ore, 46% Fe, at mine		24 %
ferronickel, 25% Ni, at plant		17 %
chromite, ore concentrate, at beneficiation		15 %
Stressor	*To compartment*	*Relative impact*
manganese, mn, resource, in ground, kg	Resource, ground	26 %
fe, resource, in ground, kg	Resource, ground	24 %
nickel, resource, in ground, kg	Resource, ground	17 %
chromium, resource, in ground, kg	Resource, ground	15 %

G. SIMIEN

In the table below, relevant data is presented from the energy report conducted for the ambitious upgrading of Stjernehus (Skogheim, 2014).

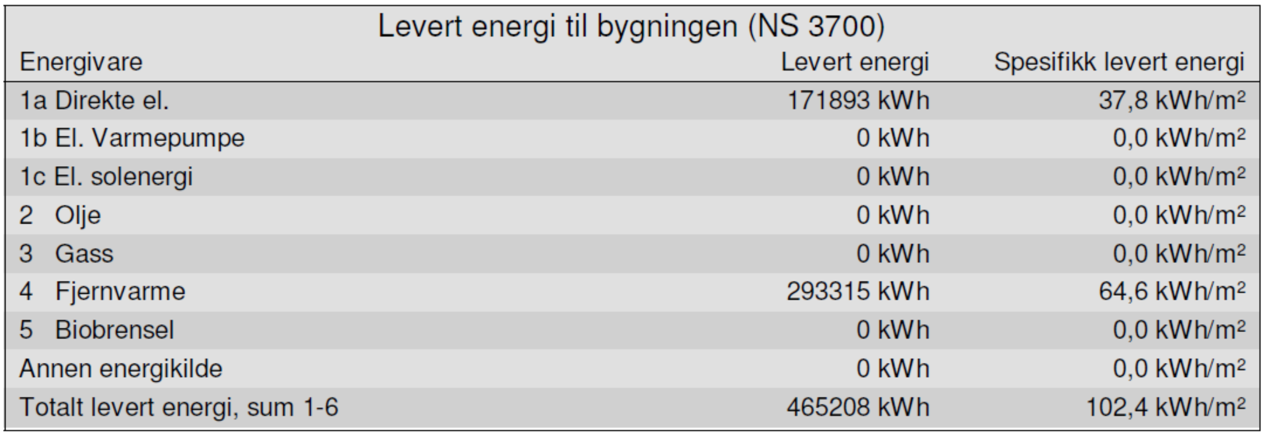
Table 44: Energy budget for NS 3700, from the energy report performed by Sweco (Skogheim, 2014).



Energibudsjett (NS 3700)

Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	93862 kWh	20,7 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	17173 kWh	3,8 kWh/m²
2 Varmtvann (tappevann)	135349 kWh	29,8 kWh/m²
3a Vifter	39881 kWh	8,8 kWh/m²
3b Pumper	714 kWh	0,2 kWh/m²
4 Belysning	51728 kWh	11,4 kWh/m²
5 Teknisk utstyr	79570 kWh	17,5 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	0 kWh	0,0 kWh/m²
Totalt netto energibehov, sum 1-6	418278 kWh	92,1 kWh/m²

Table 45: Delivered energy requirements for NS 3700, from the energy report performed by Sweco (Skogheim, 2014).



Levert energi til bygningen (NS 3700)

Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	171893 kWh	37,8 kWh/m²
1b El. Varmepumpe	0 kWh	0,0 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	293315 kWh	64,6 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	465208 kWh	102,4 kWh/m²