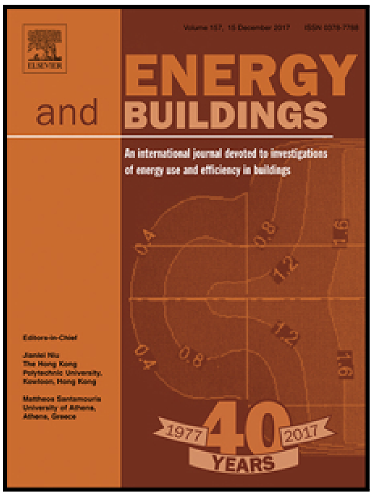

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Life Cycle Assessment of an Ambitious Renovation of a Norwegian Apartment Building to nZEB Standard

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Declaration of interest

Declaration of interest: None

Abstract

The upgrading of building infrastructure to modern standards represents a key tool for reducing global energy demand and emissions from buildings. In Norway, building upgrades have been prioritized despite the relatively low carbon intensity of the Norwegian energy mix through various incentive programs and continual improvement in building standards. Prioritizing upgrades is important as up to 90% of the existing Norwegian building stock is expected to remain standing by the year 2050. The overall impact of upgrading buildings is expected to be a net benefit to the environment but this is primarily in operation, and many studies on energy do not include the materials and resources required for upgrading. The ambitious building upgrade in the Stjernehus apartment block in Kristiansand, Norway represented an opportunity to analyse the emissions and cumulative energy demand of renovation strategies in a real-world case study. The Stjernehus apartment block, once declared the coldest apartment block in Norway, was renovated from 1960s standards to nearly passive house standard, leading to considerable improvements in operational energy demand. The renovation was evaluated in this study with respect to energy demand and overall lifetime environmental emissions using life cycle analysis over a 30-year period, and with three different scenarios for the energy supply. The results of this study show that despite the low carbon intensity of the Norwegian energy mix, there was a considerable environmental benefit to renovation. It is recommended that renovation of existing buildings continue as part of a successful climate mitigation strategy in Norway.

Keywords: Life cycle assessment, apartment building, low-carbon buildings, building energy efficiency, renovation, upgrading

1.1 Introduction

On 22 April 2016, more than 174 countries and the European Union (EU) signed the Paris Agreement, which was the major outcome of the December 2015 United Nations Climate Change Conference (COP21). The agreement entered into effect on 4 November 2016, 30 days after it had exceeded the thresholds of being ratified by more than 55 countries and including more than 55 % of global greenhouse gas emissions. Living up to the expectations of the agreement is a challenging task that requires commitment globally and from all industrial sectors.

The environmental impact of the building sector is significant, both in a Norwegian and a global context. Globally, the building sector consumes 40 % of energy produced, 40 % of materials and 25 % of water (UNEP-SBCI 2016) which must all be reduced to meet sustainability targets. European efforts to address this sector includes the European Energy Performance of Buildings Directive (EPBD) (EU 2010) and the European Energy Efficiency Directive (EED) (EU 2012). The EPBD requirement is that all new buildings shall be nearly zero-energy buildings (nZEB) after 2020 and increased renovation to nZEB level for buildings undergoing upgrading (termed *major refurbishment* in the EPBD).

The expectation is that 80-90 % of today's buildings will still be in use in 2050 (Analyse & Strategy and Multiconsult 2011; Prognosesenteret AS 2012; Skaar, Elvebakk et al. 2017), thus it is evident that upgrading will play an important role in reducing the total environmental impact of the building sector. This requires an ambitious strategy for the upgrading of existing buildings. In Norway, the dominant building types are single dwellings and apartment buildings, which account for 49 % and 23 % of the 2.4 million dwellings in Norway respectively (SSB 2015). Figure 1 shows that the majority of the apartment buildings were constructed before 1980 (Sandberg, Sartori et al. 2017). Knowing that the majority of these have not been upgraded (Prognosesenteret AS 2012), there is a large influx of apartment buildings with renovation needs expected in the years to come.

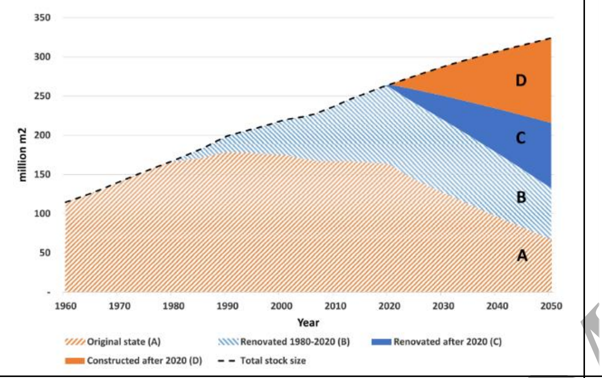


Figure 1. Evolution of Norwegian dwelling stock from 1960 to 2050 from Sandberg et al. (2017) [reprinted with permission from Elsevier, doi: 10.1016/j.enbuild.2017.04.016, license: https://creativecommons.org/licenses/by-nc-nd/4.0/]

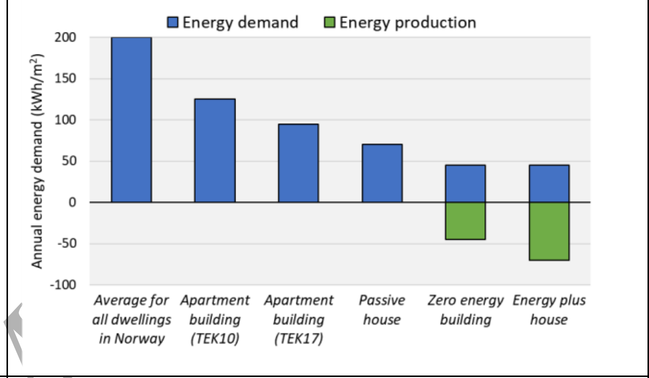


Figure 2. Average energy use for Norwegian buildings, modified from Figure 12 in 473.003 in Byggforskserien (2016)

The average energy use (kWh/m^2 per year) of Norwegian dwellings has been estimated to be around 200 kWh/m2 per year. Upgrading a dwelling in an apartment building from an average energy use to today's standard – using Norwegian building code TEK17 (KMD 2017) – will more than halve the energy use, as shown in Figure 2. Additional improvements to attain passive house (Standard Norge 2013), nZEB (EU 2010), or even plus house or powerhouse standard (Powerhouse 2016) will further reduce the energy demand of a building.

Recent efforts to upgrade older buildings have been to increase quality and decrease energy use (Kjølle, Denizou et al. 2013). The potential for reducing national GHG emissions by upgrading old buildings is great with up to a 20% reduction in total energy use possible in Norway (Thunes 2016). The highest potential for energy reduction through renovation lies in apartment buildings and single-family homes (Prognosesenteret AS 2012). With a life cycle perspective, the benefits of upgrading or providing improved maintenance are several, as long as basic construction work is done according to modern building standards.

The life cycle environmental impacts of buildings can be evaluated using life cycle assessment (LCA) techniques. LCA is useful as a tool for environmental comparison between alternative systems which can help to aid decision making. Various studies have focused on materials used (Stephan, Crawford et al. 2012; Dodoo and Gustavsson 2013; Kildsgaard, Jarnehammar et al. 2013; Azari 2014; Bansal, Singh et al. 2014), energy demand in operation (Cellura, Guarino et al. 2014; Sandberg, Sartori et al. 2017), or a combination of these criteria over the lifetime of a building (Dahlstrom, Sornes et al. 2012; Brattebø, O'Born et al. 2016; Moschetti and Brattebø 2016). Most studies, however, have focused on new construction and not renovation of existing buildings. The few studies that have focused on renovation have found that there is a positive lifetime environmental benefit from renovating an existing building instead of constructing a new one (Juan, Gao et al. 2010; Cellura, Di Gangi et al. 2013; Cetiner and Edis 2014; Tettey, Dodoo et al. 2014; Brattebø, O'Born et al. 2016; Vilches, Garcia-Martinez et al. 2017). The extent to which this is true in the Norwegian context is of interest, especially given the low carbon emissions energy profile of the country and need for infrastructure improvement in the coming years (Prognosesenteret AS 2012).

The goal of this study is to analyse the environmental impact of an ambitious upgrading of an apartment building in order evaluate the environmental impact and to identify key parameters for the environmental performance. The results of this study show the main life cycle environmental impacts from a renovation of an apartment building located in southern Norway. Additional goals of the study were to determine how different energy sources for heating the building impact results and how these analyses can provide decision making support for planners and designers for future building upgrades.

1.2 Methods

Life Cycle Assessment (LCA) is used to provide objective and science based information on the environmental impact of a system providing a specified function (e.g. a product or a service) (Curran 2008; Skaar and Fet 2012). Here the system of interest is the apartment building, providing the function of housing. There are four stages in an LCA: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. These four stages describe the LCA process in general, but multiple iterations between the stages are typically required.

The first stage defines the goal and scope of the LCA, which includes identifying the purpose for conducting the study and to whom the results will be communicated (ISO 2006). This helps define the scope of the study, identify the function, determine the functional unit, select impact categories and define system boundaries.

In the second stage the life cycle inventory (LCI) is created. This is a quantification of the energy and material flows of the system, related to the functional unit. The data gathering in this case has been based on combining data from previous studies of Stjernehus (Husbanken 2013; Holen 2014) with specific data gathered from the entrepreneur (Wrålsen 2016). The project manager of the renovation of Stjernehus provided lists of procurements, locations of the suppliers and documentation on the transportation of the materials to the construction site. Energy characteristics have been gathered from (Hasenmüller 2017) and the energy mix for the district heating in Kristiansand has been based on public data from Norsk Fjernvarme (Norsk Fjernvarme 2018). These data have been the basis for the case study described in Section 1.4. The system boundaries of the life cycle inventory are modelled in accordance with European standards for assessing sustainability of construction works (CEN 2011) and construction works (CEN 2013).

The third stage is the life cycle impact assessment (LCIA), where the environmental impact of the system is quantified and assessed. The purpose is to identify significant impact categories and determine the sources of the contributing emissions.

The fourth stage is interpretation of the results. As LCA is an iterative process, interpretation is done at every stage. The results may lead to revision of earlier stages of the LCA. This purpose of this stage is also to provide information on conclusions, limitations and recommendations of the study.

To perform the analysis we have used SimaPro version 8.3 (PRé 2018) and ecoinvent 3.1 (ecoinvent 2018) as the background database, with system model *allocation default (APOS)*. Data for the renovation activities in the foreground system have been collected specifically for Stjernehus. The impact assessment has been performed with LCIA method ReCiPe (Huijbregts, Steinmann et al. 2016).

1.3 Case study

1.3.1 Functional unit, system and system boundaries

The functional unit in the case study is the upgrading of one apartment building built in 1965 to a low energy class 1 in energy use. The total useable floor area (UFA) in the building 3750 m^2 of with a time perspective over 30 years. The location and details of the apartment building in the case study are described below. Processes that are included in the system are processes related to the upgrading of the apartment building, the energy consumption in the use phase, and the end-of-life of the materials that enter the system during the upgrading (e.g. the new windows and doors, insulation, etc.).

Table 1. System boundaries according to EN15804 and EN15978.

System boundaries (X=modules included in the study) according to EN15804 and EN15978																		
A1–A3 Product stage			A4–A5 Construction stage		B1–B7 Use stage							C1–C4 End-of-life				D1–D4 Benefits and loads beyond the system boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw material extraction	Transport	Manufacturing	Transport	Construction and installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling	Exported energy /potential
X	X	X	X	X	x					X			X	X	X				x

The system boundaries correspond to the life cycle modules A1-B1, B6, C2-C4 and D4 of the EN15804 and EN15978 standards, as shown in Table 1 (CEN 2011; CEN 2013). The apartment building itself enters the system burden-free and ready for upgrading, which means that the environmental impacts of removal and end-of-life of materials from the existing building (e.g. asbestos facade, old windows and doors) are considered to belong to the previous life cycle of the building. After 30 years the apartment building also leaves the system burden-free for future use, but the end-of-life of all materials introduced in the upgrading are included in the system.

The system boundaries to nature are defined by the choice of background database and life cycle impact assessment method, which in this case is the Ecoinvent 3.1 (allocation default) database and the ReCiPe Europe 2008 life cycle impact assessment method as calculated in SimaPro v.8.3.

1.3.2 Stjernehus apartment building

This study analyses the upgrading of the apartment building called *Stjernehus*, which is in the city of Kristiansand on the south coast of Norway. The building underwent an upgrading in 2013-2015 as part of the research projects BESLUTT (Hauge, Amundsen et al. 2011) and BEVISST (Löfström, Hauge et al. 2015), and was a pilot building in *Buildings of the Future* (Hasenmüller 2017). The upgrade was a cooperation between SINTEF Building and Infrastructure, NBBL, BOB in Bergen and Sørlandet Boligbyggelag. The life cycle assessment is based on data from the upgrading of Stjernehus.

Stjernehus is a concrete apartment building constructed in 1960. It consists of 60 units, where 30 are 2-bedroom units of 42 m^2 and 30 are 3-bedroom units of 80 m^2 (Husbanken 2013). The building was colloquially known as Southern Norway's coldest apartment building (Lavenergiprogrammet 2015) and it underwent an upgrading in the period 2013-2015. Key reasons for the upgrade were increasing the comfort level for occupants and energy efficiency, as well as reducing the carbon footprint of the apartment building (Hasenmüller 2017).

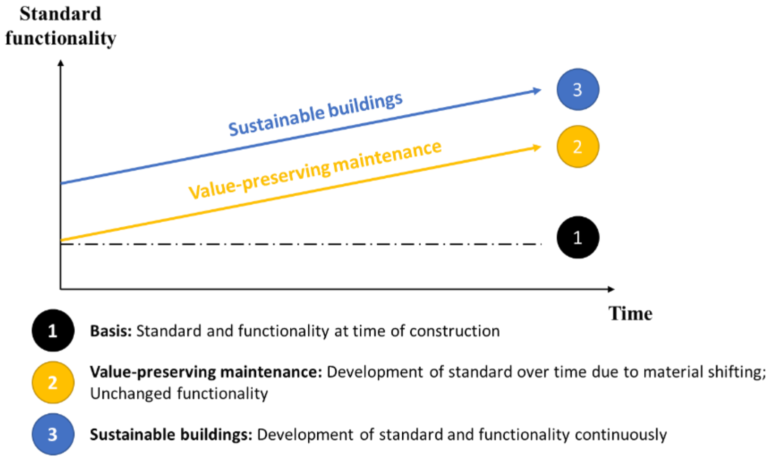
		3700 m^2 Usablel Floor Area Original net energy demand: 297 kWh/m^2 per year Upgraded building net energy demand: 88 kWh/m^2 per year
3a) Original building [photo: Lars Ørjan Vegusdal]	3b) Upgraded building [photo: Odd Helge Moen]	Key figures

Figure 3. Stjernehus, pre- and post-renovation

Prior to the upgrade, a scoping study was performed to help define the ambition levels for energy and carbon footprint. The energy ambition was to reach energy grade B and the carbon footprint ambition was to reduce the carbon footprint by 69 % compared to the original building. The energy grade is a measure of the maximum allowed annual delivered energy (kWh/m^2 per year) and is based on two factors: a fixed factor for each energy grade + a correction factor for dwelling size (Energimerking.no 2009). The energy grade B requirements for this type of apartment building is a maximum annual delivered energy of $120 + {}^{1600}/_{area}$ kWh/m^2. This corresponds to annual delivered energy of maximum $120 + {}^{1600}/_{42} = 158$ kWh/m^2 for the smaller apartments and $120 + {}^{1600}/_{80} = 140$ kWh/m^2 for the larger apartments.

The carbon footprint requirement in the upgrading project was based on using the online calculation tool Klimagassregnskap.no (Hasenmüller 2017). However, it should be noted that the results from Klimagassregnskap.no are not comparable with the LCA-results presented here as the system boundaries in this study differ. Building components that were not included in the carbon footprint calculated by Klimagassregnskap.no are included here (Wrålsen 2016).

Key issues identified prior to the upgrade were significant thermal bridges in the concrete construction, high heating demand and a general need for maintenance. As there was a need for maintenance, a window of opportunity opened for upgrading to a higher quality level instead of renovating to the original level (Berg, Denizou et al. 2013; Skaar, Elvebakk et al. 2017). This is illustrated in Figure 4.



1 **Basis:** Standard and functionality at time of construction

2 **Value-preserving maintenance:** Development of standard over time due to material shifting; Unchanged functionality

3 **Sustainable buildings:** Development of standard and functionality continuously

Figure 4. Quality of building construction over time **(**adapted from Bjørberg 2010 in Evjenth (2011))

There were significant issues with the building before the renovation related to high heating demands in winter, significant energy losses due to poor thermal bridging and a general maintenance backlog. The renovations on the Stjernehus building were focused on reducing energy losses through the walls, roof, windows and doors while modernising the heating system and improving the aesthetics of the building.

The renovation measures that were taken were adding insulation to the building envelope, removal of thermal bridges, replacement of facades, replacement of doors and windows, new balconies (glassed) and new heating and ventilation systems. The ventilation system was upgraded to a balanced ventilation system with heat recovery and adapted to accommodate direct connection to the district heating system in Kristiansand, which uses waste heat from incineration of municipal waste. The new heating system replaced the existing central oil boiler heating system. It is assumed that there is no replacement of the ventilation system during the 30 year study period. The expected service life of the main components in the ventilation system is 25-30 years. The exterior walls received new and modern insulation and the existing asbestos façade was replaced with concrete tiles. Modern energy saving doors and windows (triple glazing) were installed while a new roof was added while glass-concrete balconies were also added for the occupants. The average U-value for doors and windows after the renovation was 0.86. Improving the thermal insulation capacity of the building gave significant energy savings in the use phase of the apartment building.

1.4 Results and discussion

1.4.1 Life cycle inventory results

The model uses a 30-year life time for materials to meet the demands until a future renovation is expected. The overall material consumption and direct energy used in the rehabilitation process is shown in Table 2 below.

Table 2. Life cycle inventory for the renovation of Stjernehus

Component	Material	Quantity	Unit
Balcony	Bitumen (seal)	273	kg
	Window frame, PVC (U =1,6 W/m2k)	18.0	m2
	Concrete	17.0	m3
	Flat glass	4.70	tons
	Rockwool insulation	702	kg
	Aluminium	3.09	tons
	Steel	2.58	tons
	Wooden materials	1.00	m3
Exterior wall	Bitumen (seal)	1.54	tons

	Chemicals	176	kg
	Gypsum	2 534	kg
	Fibre cement tile, facade	47.6	tons
	Extruded polystyrene insulation	1 136	kg
	Rockwool insulation	13.9	tons
	Plastics, ventilation	1.32	tons
	Reinforcing steel	300	kg
	Wooden materials, wall	102	m3
Doors and windows	Door, inner, glass-wood	129	m2
	Door, outer, wood-aluminium	10.0	m2
	Door, inner, wood	112	m2
	Window frame, PVC (U =1,6 W/m2k)	760	m2
	Flat glass	9 500	kg
Roof	Bitumen (seal)	2.34	tons
	Rockwool insulation	2.96	tons
	Aluminium ducts	139	kg
	Wooden materials	2.00	m3
Ventilation	Control units	95.0	kg
	Rockwool insulation	2.06	tons
	Metals (aluminium and steel ducts)	1.73	tons
	Plastics (polycarbonates)	303	kg
Energy used in construction	Diesel, used in machines	48.8	GJ
	Electricity, site heating and ventilation	163	GJ

The embodied cumulative energy demand of the materials and the consumed energy from building operation for Stjernehus are shown in Figure 5 below.

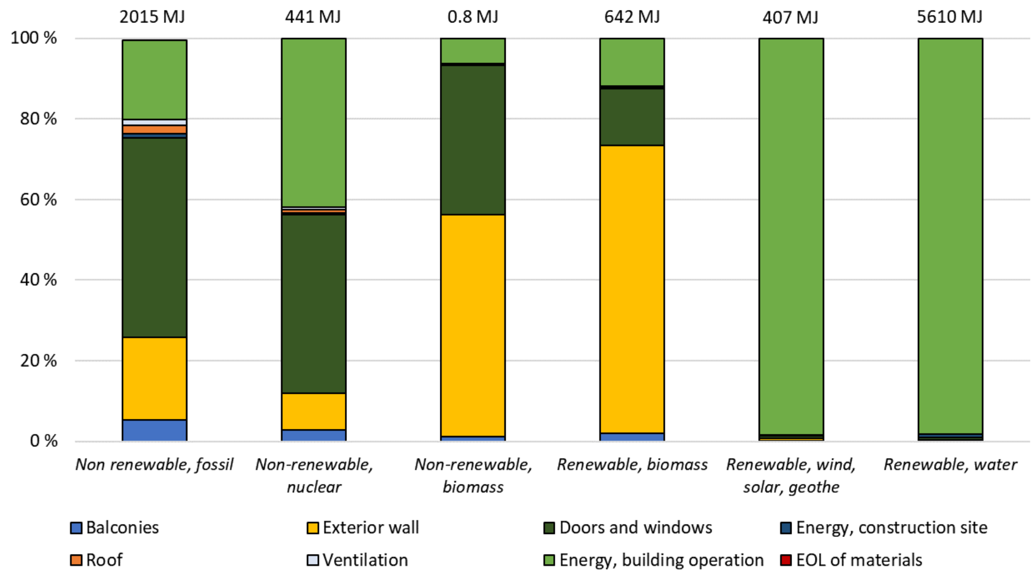


Figure 5. Cumulative energy demand for the Stjernehus renovation, by energy source in MJ

The overall lifetime cumulative energy demanded for the entire renovation and operation of the building is 9116 MJ per m^2. The dominant source of energy demand comes from the lifetime heating and cooling and electricity demand of the building, which represents 72% of the total cumulative energy demand. The energy used in the building comprises of space heating (191.9 MJ per m^2 per year), warm water heating (40.7 MJ per m^2 per year), and electricity (136.1 MJ per m^2 per year). Most of the electricity demand comes from renewable energy in the form of Norwegian hydroelectricity while the space heating comes from the district heating system that has so far shown to be able to meet heating demand.

1.4.2 Life cycle impact assessment results

This study utilizes four cases including a reference scenario that focus on the type of renovation and space heating methods. The following table shows the absolute and relative values of the midpoint impacts for the reference system (S0) and three scenarios on a per meter squared basis. The S0 scenario refers to the Stjernehus apartment block prior to renovation, S1 assumes that the boiler heating system is replaced by Norwegian electricity with no other upgrades, S2 is the actual renovation of the Stjernehus apartment, while S3 is the assumes a renovation while meeting all energy requirements with Norwegian electricity instead of district heating. These scenarios were chosen to illustrate the theoretical effects of utilizing low-emission Norwegian energy compared to other renovation strategies. The characterized results for each building are shown in Figure 6.

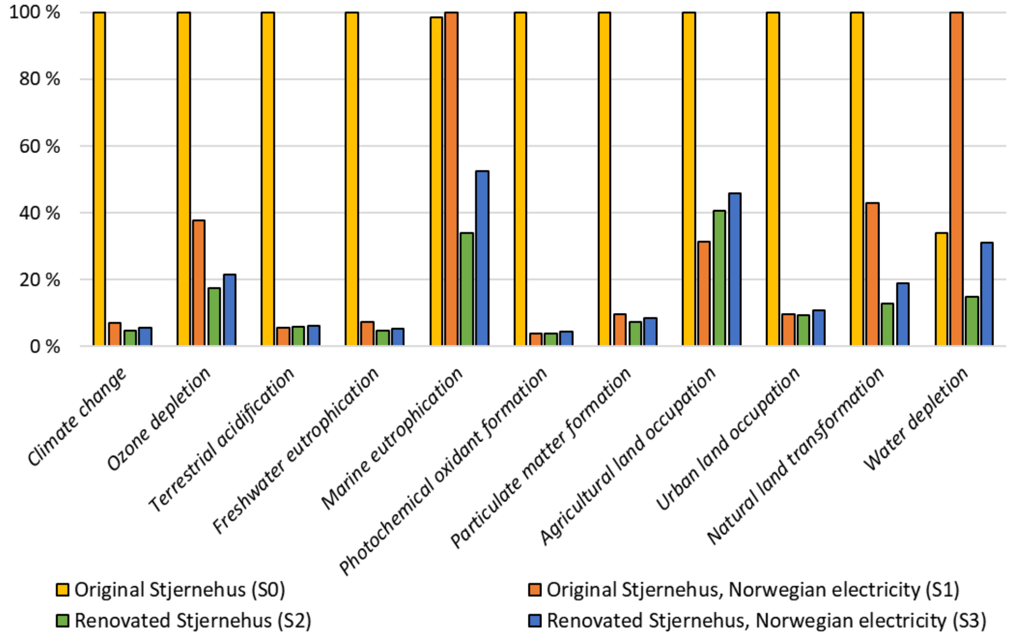


Figure 6. Relative total characterised emissions for each Stjernehus scenario

The reference scenario is shown to perform worse in all impact categories except marine eutrophication and water depletion, where S1 performs worse. S2 and S3, which utilise actual renovation parameters, perform better than either of the scenarios that do not have building renovation included. The actual renovated Stjernehus shows the lowest emissions of all scenarios except with respect to agricultural land occupation compared with S1, which is due to timber materials used in the renovation. Total emissions per m^2 building relative to the original Stjernehus reference scenario are summarized in Table 3 below.

Table 3. Relative characterized impacts for Stjernehus renovation and space heating scenarios

		Reference value/m^2	Relative to reference value		
Midpoint impact category	Unit	S0	S1	S2	S3
Climate change	kg CO_2 eq	3 263	0.07	0.05	0.06
Ozone depletion	kg CFC-11 eq	7.54E-05	0.38	0.17	0.22
Terrestrial acidification	kg SO_2 eq	14.3	0.06	0.06	0.06
Freshwater eutrophication	kg P eq	1.10	0.07	0.05	0.05
Marine eutrophication	kg N eq	1.07	1.02	0.34	0.53
Human toxicity	kg 1,4-DB eq	910	0.16	0.10	0.10
Photochemical oxidant formation	kg NMVOC	14.9	0.04	0.04	0.04

Particulate matter formation	kg PM_{10} eq	4.42	0.10	0.07	0.09
Terrestrial ecotoxicity	kg 1,4-DB eq	0.11	0.24	0.21	0.21
Freshwater ecotoxicity	kg 1,4-DB eq	31.2	1.20	0.38	0.44
Marine ecotoxicity	kg 1,4-DB eq	29.0	1.12	0.36	0.42
Ionising radiation	kBq U235 eq	87.2	1.57	0.34	0.59
Agricultural land occupation	m^2a	242	0.31	0.41	0.46
Urban land occupation	m^2a	27.5	0.10	0.09	0.11
Natural land transformation	m^2	0.32	0.43	0.13	0.19
Water depletion	m^3	101	2.95	0.44	0.92

The reference scenario, S0, has the highest emissions in all impact categories except marine eutrophication, water depletion and ecotoxicity impact categories. The use of oil boilers for heating depends on heating oil, which is often lower quality and energy density, leads to high combustion emissions and is the main contributor for the reference case in all impact categories. Scenario S1 has high water depletion relative to the base scenario due to increased use of grid electricity, primarily composed of Norwegian hydroelectricity. Material demand for the renovation are the primary emissions for scenarios S2 and S3. Both Figure 6 and Table 3 show that renovating the building was more beneficial to overall lifetime environmental impacts than only changing the heating system. The actual renovation, S2, also shows that the most environmental gains can be made by combining renovation strategies with modernized space heating technologies.

Figure 7 shows the total midpoint environmental impacts for the actual Stjernehus renovation in the form of a contribution analysis. The main components are the same as the life cycle inventory components in Table 3 with impacts from energy demand for the operation of the building added.

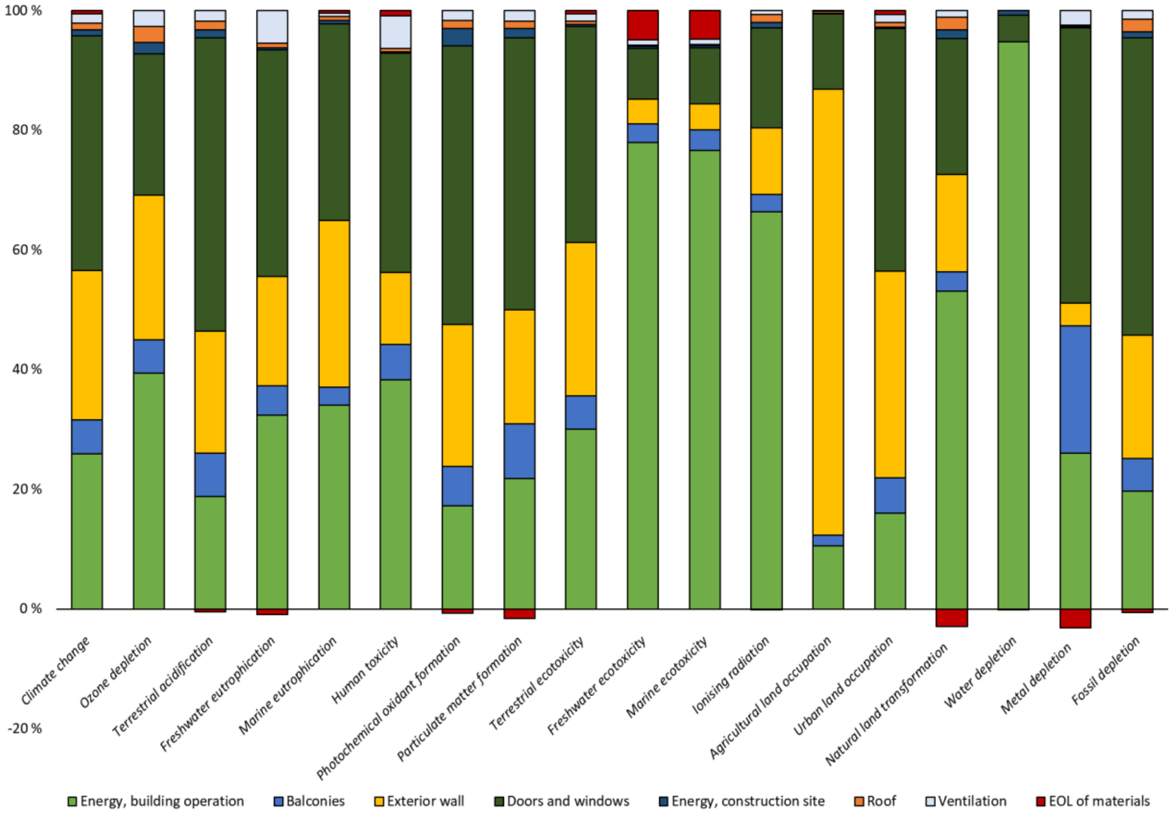


Figure 7. Contribution analysis of building components for the actual Stjernehus renovation (S2)

Energy demand from operating the building, production of doors and windows, and construction of the exterior walls are the three most significant processes. Summed up, these three processes contribute 78-99 % across all impact categories. Energy from building operation is the dominant process in ozone depletion (39%), marine eutrophication (34%), human toxicity (38%), freshwater and marine ecotoxicity (78% and 77%), ionizing radiation (66%), natural land transformation (53%) and water depletion (95%) impacts. The production of doors and windows is the dominant impact in climate change (39%), terrestrial acidification (49%), freshwater eutrophication (38%), photochemical oxidant formation (47%), particulate matter formation (45%), terrestrial ecotoxicity (36%), urban land occupation (41%) and fossil and metal depletion (46% and 50%) impacts. The exterior wall is the dominant process in agricultural land occupation (75%). The end of life treatment of materials has some positive marginal impacts in seven impact categories due to recycled materials, these are shown as negative values in Figure 7. The positive impacts from recycling are shown separately, as these occur beyond the system boundaries. This corresponds to module D in EN 15978. Balconies have significant impacts in metal depletion due to the large amount of steel and aluminium used. A full overview of the emissions according to impact categories and components can be found in *Appendix A: Life Cycle Impact Assessment results (LCIA results)*.

1.4.3 *Carbon footprint*

The total calculated lifetime climate change impact was 593.4 tons CO_2 equivalents for the renovated Stjernehus. The climate change impact was of particular interest for the Stjernehus project developers and was one of the main motivating factor for an ambitious renovation. An additional analysis of the materials that contributed most to the climate change impacts is shown in Figure 8.

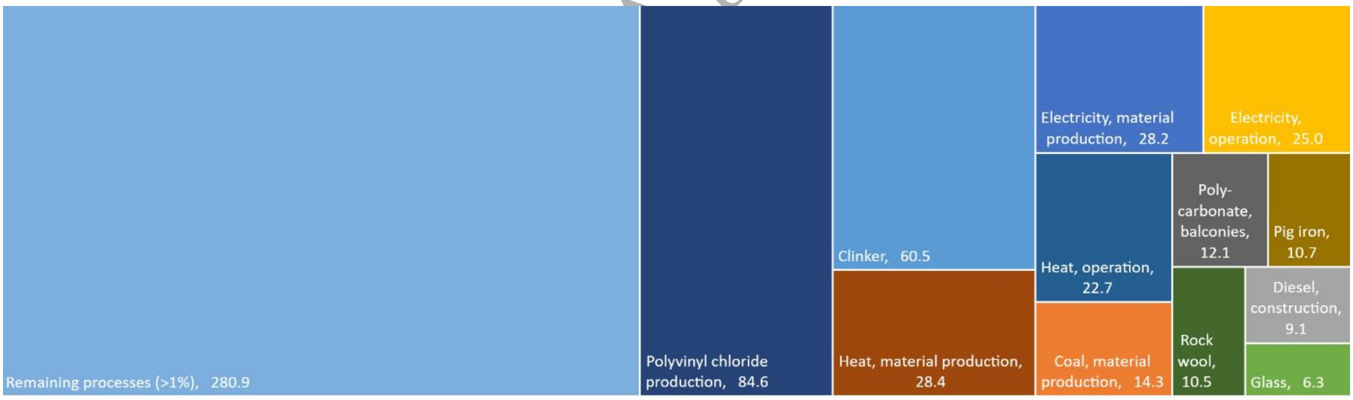


Figure 8. Climate change contribution for the renovated Stjernehus, by material type, in tons CO_2-equivalents

The main climate change impacts come from the production of polyvinyl chloride (PVC) used in the window and door frames, which represents 13.8% of the total lifetime climate change impacts. Clinker, primarily used in concrete for exterior walls, was the next highest contributor of climate change emissions at 10.2%. Electricity (4.2%) and heat (3.8%) used in operation are together 8% of the total climate change impacts, which is quite low due to the energy demand savings from the renovation. Climate change impacts from energy used in material production were higher than the lifetime operation emissions, as heat (4.8%) and electricity (4.8%) were 9.6% of the total. The processes that had a less than 1% impact made up 47.3% of the total emissions, which makes it difficult to make decisions that focus on these more diffuse impacts. The overall climate change impacts could be further reduced with switching materials, primarily PVC and clinker, to other less climate intense alternatives.

1.4.4 Discussion

The renovation of Stjernehus has both positive and negative consequences for the carbon footprint of the building. In the renovation process, the carbon footprint will increase due to the construction materials used and the emissions from the construction processes (e.g. due to diesel or electricity consumption). After the renovation is completed, there are two factors that contribute to a reduced carbon footprint. The first is the reduced energy consumption in the use phase, due to reduced heat loss. The second is the replacement of the original boiler heating system, which leads to reduced carbon footprint per kWh. In total, these lead to an annual decrease in the carbon footprint relative to the original building.

To evaluate if the renovation leads to a total reduction of the carbon footprint in a life cycle perspective, the increase in emissions from the renovation process must be compared with the decrease in the use phase. This can be achieved by calculating the carbon footprint payback period, which is the time it takes for the accumulated decrease in use emissions to be larger than the carbon footprint of the renovation itself, also called the carbon footprint break-even. The renovation is a carbon footprint reduction measure if the break-even occurs before the next significant renovation, which is typically 20-40 years after a major renovation. For Stjernehus, the carbon footprint payback period was 1.09 years, and can therefore be classified as an effective carbon footprint reduction measure. The main cause of the very short payback period is not actually the renovation of the building itself, but the replacement of the boiler heating system with a combination of district heating and electricity. This means that changing the energy supply is the most significant action taken to reduce the carbon footprint. The renovation itself does lead to reduced carbon footprint due to reduced energy consumption, but it could also be argued that these are mainly increasing the comfort level for the occupants.

The main factor that influences the payback period in the modelling is the carbon footprint per kWh energy delivered. The Norwegian consumption mix has been used in this study, which includes the effects of imports/exports and domestic production. For electricity, there is no scientific consensus on which electricity mix to use which makes In a Norwegian context, this is a value choice that has a significant impact on the end results when energy reduction is calculated. The Norwegian electricity mix is approximately 25 g CO_2/kWh and the Nordic electricity mix is approximately 130 g CO2/kWh (Skeie, Lien et al. 2018). The choice of Norwegian electricity mix is both in line with common approaches in the building industry (e.g. the Norwegian EPD system) and is a conservative choice. If a European energy mix was chosen, the payback period will be significantly shorter.

It is also possible to calculate the energy payback period which requires accumulative energy demand (CED) calculation. The CED breakeven in this study was found to be 2.11 years which was slightly longer than the carbon footprint payback period. This is not influenced by the choice of electricity mix, but the conclusion is similar. The renovation is both a carbon reduction measure and an energy reduction measure when evaluating in a life cycle perspective. These results are based on assumption of the user behaviour. In practice, differences in user expectations and user behaviour can lead to large differences in energy consumption (Sunikka-Blank and Galvin 2012; Thomsen and Hauge 2016). This varies from user to user and from building type to building type. It is for example easier to accept lower indoor temperatures in an old house with poor insulation than in a new house.

The discussion above evaluates the sensitivity of the carbon footprint to the choice of electricity mix. Skaar et al. (2017) have shown that there is a significant variation in the carbon footprint between similar materials, based on existing EPDs. This means that it is necessary to not only specify which materials to use, but also to follow up when choosing specific suppliers. The effect of requiring low carbon products has not been investigated here.

1.4.5 *Comparison to other research results*

Comparing the LCA results of this study to those of other renovation and upgrading projects is not straightforward. The initial state of the building and the ambition level of the refurbishment project will vary from case to case. In addition, the system boundaries and time perspective can also vary from case to case. To paraphrase Tolstoy: well-functioning buildings are all alike; every decayed building needs refurbishment in its own way. Vilches et al. (2017) performed a literature review of LCA of building refurbishment. To compare the results on a general level (apples and pears), the payback periods identified in the literature review can be compared. For multi-family buildings, the payback period for all impact categories were found to be within a time span of 2 to 7.5 years. For carbon footprint, the result of this study was 1.09 years and for cumulative energy demand (CED) it was 2.11 years. Although the findings of this study were lower than the literature review, they are in the same order of magnitude and confirm that upgrading can be an environmentally beneficial choice.

1.5 Conclusions

The results for the actual upgrading of Stjernehus in a 30-year perspective (scenario S2) show a reduction in all environmental impact categories, with a 56-96 % reduction compared to the original building (S0). Payback periods are 1.09 years for carbon footprint and 2.11 years for cumulative energy demand (CED). These results show that the actual upgrading (scenario S2) lead to significant reductions in the environmental footprint of the apartment building in a 30-year time perspective.

Furthermore, all upgrading scenarios (S1-S3) show significant reduction of the carbon footprint, but not with a corresponding reduction in all impact categories. For freshwater ecotoxicity, marine ecotoxicity, ionising radiation and water depletion the upgrading will lead to higher impacts. This indicates that using carbon footprint as the only indicator leads to a risk of problem shifting. The most significant factor influencing these results in the case study is the choice of energy system.

Recommendations to LCA practitioners are to not focus exclusively on carbon footprint, as this may lead to problem shifting; this is especially relevant when selecting energy systems. Recommendations to inhabitants and decision makers in the building industry is to approach each case individually, using a life cycle perspective from the onset of the renovation. Significant building components in the Stjernehus renovation were found to be exterior walls, doors and windows, and balconies. Here further optimisation is possible, for example by selecting low-carbon products when choosing suppliers.

The results show that an ambitious upgrading leads to a significantly lower environmental impact for the apartment building case study. However, most apartment buildings renovations do not have high environmental ambitions. Further research is needed for reducing the cost of upgrading and streamlining the upgrading solutions. This can contribute to a higher number of renovations in general and an increased ambition level in individual renovation projects.

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1.7 References

Analyse & Strategy and Multiconsult (2011). Konsekvensanalyse av å innføre nye forskriftskrav til energieffektivisering av bygg, Multiconsult.

Azari, R. (2014). "Integrated energy and environmental life cycle assessment of office building envelopes." Energy and Buildings **82**: 156-162.

Bansal, D., R. Singh and R. L. Sawhney (2014). "Effect of construction materials on embodied energy and cost of buildings—A case study of residential houses in India up to 60m2 of plinth area." Energy and Buildings **69**: 260-266.

Berg, B., K. Denizou, T. Wigenstad, K. Buvik, Å. L. Hauge, D. Kittang, E. Magnus, K. Thorshaug, C. F. Øyen and W. Knudsen (2013). Kunnskapsstatus i REBO : Bærekraftig oppgradering av boligblokker – med fokus på miljøvennlig energibruk og universell utforming.

Brattebø, H., R. J. O'Born, N. H. Sandberg, M. I. Vestrum and I. Sartori (2016). Fremtidig utvikling i energiforbruk og CO2-utslipp for Norges boligmasse. Trondheim, NTNU and SINTEF.

Byggforskserien (2016). 473.101 Energikrav til bygninger, SINTEF.

Cellura, M., A. Di Gangi, S. Longo and A. Orioli (2013). "An Italian input–output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings." Energy and Buildings **62**: 97-106.

Cellura, M., F. Guarino, S. Longo and M. Mistretta (2014). "Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study." Energy and Buildings **72**: 371-381.

CEN (2011). NS-EN 15978: Bærekraftige byggverk : vurdering av bygningers miljøpåvirkning : beregningsmetode = sustainability of construction works : assessment of environmental performance of buildings : calculation method. Oslo, Standard Norge.

CEN (2013). EN 15804:2012+A1:2013: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

Cetiner, I. and E. Edis (2014). "An environmental and economic sustainability assessment method for the retrofitting of residential buildings." Energy and Buildings **74**: 132-140.

Curran, M. A. (2008). Life-Cycle Assessment. Encyclopedia of Ecology. S. E. a. F. Jorgensen, B. Amsterdam, Elsevier**:** 2168-2174.

Dahlstrom, O., K. Sornes, S. T. Eriksen and E. G. Hertwich (2012). "Life cycle assessment of a single-family residence built to either conventional- or passive house standard." Energy and Buildings **54**: 470-479.

Dodoo, A. and L. Gustavsson (2013). "Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply." Applied Energy **112**: 834-842.

ecoinvent. (2018). "ecoinvent." from http://www.ecoinvent.org.

Energimerking.no. (2009). "Karakterskalaen." Retrieved 2016-12-21, 2016, from https://www.energimerking.no/no/energimerking-bygg/om-energimerkesystemet-og-regelverket/karakterskalaen/.

EU (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

EU (2012). "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency."

Evjenth, A., P. Sandvik, A.-J. Almås and S. Bjørverg (2011). Grunnlag for, og krav om, utbedring av eksisterende bygninger, KRD Kommunal- og Regionaldepartementet.

Hasenmüller, B. (2017). "Oppgradering av eksisterende boligblokk." Retrieved 2018-01-24, 2018, from http://www.arkitektur.no/stjernehus-borettslag-oppgradering.

Hauge, Å. L., K. H. Amundsen and S. E. Mellegård (2011). Beslutningsprosesser i borettslag og sameiere. Hva fører til bærekraftige oppgraderingsprosjekter?

Holen, J. (2014). Case study of a retrofitting project: GHG calculation & study of decision making processes, Aalborg University.

Huijbregts, M. A. J., Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander and R. van Zelm (2016). "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level." The International Journal of Life Cycle Assessment **22**(2): 138-147.

Husbanken. (2013). "Stjernehus Borettslag - oppgradering." Retrieved 2016-12-21, 2016, from http://www.husbanken.no/forbildeprosjekter/prosjekt/?id=257483.
ISO (2006). Miljøstyring, livsløpsvurdering, prinsipper og rammeverk (ISO 14040:2006) = Environmental management, life cycle assessment, principles and framework (ISO 14040:2006). Lysaker, Standard Norge.
Juan, Y.-K., P. Gao and J. Wang (2010). "A hybrid decision support system for sustainable office building renovation and energy performance improvement." Energy and Buildings **42**(3): 290-297.
Kildsgaard, I., A. Jarnehammar, A. Widheden and M. Wall (2013). "Energy and Environmental Performance of Multi-Story Apartment Buildings Built in Timber Construction Using Passive House Principles." Buildings **3**(1): 258-277.
Kjølle, K., K. Denizou, A. G. Lien, E. Magnus, K. Buvik, Å. L. Hauge, M. Klinski, E. Löfström, T. Wigenstad and C. F. Øyen (2013). Flerfaglig analyse av casestudier i REBO. Bærekraftig oppgradering av boligblokker ; Flerfaglig analyse av casestudier – med vekt på ambisjonsnivå for universell utforming og energistandard. Bærekraftig oppgradering av boligblokker, SINTEF akademisk forlag.
KMD (2017). Byggteknisk forskrift (TEK17). K.-o. moderniseringsdepartementet.
Lavenergiprogrammet. (2015). "Framtidens bygg avsluttes. Hva nå?" Retrieved 2016-12-21, 2016, from http://lavenergiprogrammet.no/aktuelt/framtidens-bygg-avsluttes-hva-na/.
Löfström, E., Å. L. Hauge, S. Mellegård, E. Fredriksen and M. Klinski (2015). Bevisste strategier for oppgradering av boligselskaper, SINTEF Byggforsk.
Moschetti, R. and H. Brattebø (2016). "Sustainable Business Models for Deep Energy Retrofitting of Buildings: State-of-the-art and Methodological Approach." Energy Procedia **96**: 435-445.
Norsk Fjernvarme. (2018). "Fjernkontrollen." Retrieved 2018-01-24, 2018, from http://www.fjernkontrollen.no.
Powerhouse. (2016). "The Powerhouse definition." from http://www.powerhouse.no/content/uploads/2014/02/2016.06.14_Powerhouse-definition_til-publisering.pdf.
PRé. (2018). "SimaPro." from http://www.pre.nl.
Prognosesenteret AS (2012). Potensial- og barrierestudie: Energieffektivisering av norske boliger, Enova.
Sandberg, N. H., I. Sartori, M. I. Vestrum and H. Brattebo (2017). "Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016-2050." Energy and Buildings **146**: 220-232.
Skaar, C., K. Elvebakk and K. S. Skeie (2017). Klimafotspor fra byggematerialer ved ambisiøs oppgradering av boligblokker, SINTEF Building and Infrastructure.
Skaar, C. and A. M. Fet (2012). "Accountability in the Value Chain: From Environmental Product Declaration (EPD) to CSR Product Declaration." Corporate Social Responsibility and Environmental Management **19**(4): 228-239.
Skaar, C., B. Solem and P. Rüther (2017). Composite floors in urban buildings: Options for a low carbon building design. 6th Forum Wood Building Nordic. Trondheim.
Skeie, K. S., A. G. Lien, C. Skaar, E. Olsen, R. Skipervik, B. I. Iversen and P.-K. Westermann (2018). Rehabilitering av borettslag til nesten nullenerginivå. Trondheim, SINTEF Byggforsk.
SSB. (2015). "Boliger, 1. januar 2014." Retrieved 2016-12-21, 2016, from https://www.ssb.no/bygg-bolig-og-eiendom/statistikker/boligstat/aar/2015-04-22.
Standard Norge (2013). NS 3700:2013 Kriterier for passivhus og lavenergibygninger - Boligbygninger, Standard Norge.
Stephan, A., R. H. Crawford and K. de Myttenaere (2012). "Towards a comprehensive life cycle energy analysis framework for residential buildings." Energy and Buildings **55**: 592-600.
Sunikka-Blank, M. and R. Galvin (2012). "Introducing the prebound effect: the gap between performance and actual energy consumption." Building Research & Information **40**(3): 260-273.
Tettey, U. Y. A., A. Dodoo and L. Gustavsson (2014). "Effects of different insulation materials on primary energy and CO2 emission of a multi-storey residential building." Energy and Buildings **82**: 369-377.

Thomsen, J. and Å. L. Hauge (2016). Beboeropplevelse og inneklima i norske passivhus. Foreløpige resultater fra forskningsprosjektet EBLE – evaluering av boliger med lavt energibehov. STI fagdag. Trondheim, Oslo.

Thunes, J.-V. (2016). "- Ved å rehabilitere gamle bygg kan vi halvere energibruken." Retrieved 2018-01-24, from https://www.vvsforum.no/2016/ved-a-rehabilitere-gamle-bygg-kan-vi-halvere-energibruken/.

UNEP-SBCI. (2016). "UNEP Sustainable Buildings and Climate Initative: Why Buildings." Retrieved 2016-11-18, 2016, from http://www.unep.org/sbci/AboutSBCI/Background.asp.

Vilches, A., A. Garcia-Martinez and B. Sanchez-Montañes (2017). "Life cycle assessment (LCA) of building refurbishment: A literature review." Energy and Buildings **135**: 286-301.

Wrålsen, B. (2016). Life Cycle Assessment of an Ambitious Upgrading of an Apartment Building ; An Environmental Approach on Upgrading Projects. MSc, Norwegian University of Science and Technology (NTNU).

Appendix A: Life Cycle Impact Assessment results (LCIA results)

Impact category	Unit	Total	Energy, building operation	Balconies	Exterior wall	Doors and windows	Energy, construction site	Roof	Ventilation	EOL of materials
Climate change	kg CO2 eq	5.93E+05	1.54E+05	3.37E+04	1.48E+05	2.33E+05	5.63E+03	6.97E+03	9.01E+03	3.33E+03
Ozone depletion	kg CFC-11 eq	4.94E-02	1.95E-02	2.72E-03	1.19E-02	1.17E-02	9.54E-04	1.31E-03	1.29E-03	2.49E-05
Terrestrial acidification	kg SO2 eq	3.07E+03	5.79E+02	2.25E+02	6.31E+02	1.52E+03	4.01E+01	4.56E+01	5.45E+01	-1.65E+01
Freshwater eutrophication	kg P eq	1.97E+02	6.45E+01	9.69E+00	3.64E+01	7.57E+01	5.33E-01	1.58E+00	1.09E+01	-1.88E+00
Marine eutrophication	kg N eq	1.38E+03	4.69E+02	4.10E+01	3.83E+02	4.54E+02	7.38E+00	9.09E+00	8.65E+00	5.49E+00
Human toxicity	kg 1,4-DB eq	3.28E+05	1.25E+05	1.94E+04	3.93E+04	1.20E+05	8.87E+02	1.88E+03	1.76E+04	3.04E+03
Photochemical oxidant formation	kg NMVOC	2.17E+03	3.76E+02	1.44E+02	5.19E+02	1.02E+03	6.48E+01	2.93E+01	3.55E+01	-1.61E+01
Particulate matter formation	kg PM10 eq	1.23E+03	2.73E+02	1.15E+02	2.39E+02	5.70E+02	2.04E+01	1.53E+01	2.22E+01	-1.99E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	8.39E+01	2.52E+01	4.73E+00	2.14E+01	3.03E+01	2.77E-01	5.13E-01	1.02E+00	4.39E-01
Freshwater ecotoxicity	kg 1,4-DB eq	4.48E+04	3.49E+04	1.36E+03	1.87E+03	3.78E+03	1.74E+02	7.15E+01	4.02E+02	2.21E+03
Marine ecotoxicity	kg 1,4-DB eq	3.96E+04	3.04E+04	1.38E+03	1.71E+03	3.69E+03	1.52E+02	6.58E+01	3.80E+02	1.89E+03
Ionising radiation	kBq U235 eq	1.13E+05	7.48E+04	3.33E+03	1.26E+04	1.89E+04	9.44E+02	1.47E+03	7.89E+02	-3.18E+00
Agricultural land occupation	m2a	3.68E+05	3.88E+04	6.41E+03	2.75E+05	4.62E+04	3.55E+02	1.42E+03	3.77E+02	5.88E+00
Urban land occupation	m2a	9.70E+03	1.55E+03	5.70E+02	3.36E+03	3.93E+03	2.17E+01	7.86E+01	1.29E+02	6.09E+01
Natural land transformation	m2	1.54E+02	8.41E+01	5.08E+00	2.58E+01	3.61E+01	2.24E+00	3.37E+00	1.73E+00	-4.53E+00
Water depletion	m3	1.67E+05	1.58E+05	-9.92E+01	7.97E+01	7.39E+03	1.34E+03	5.55E+01	-9.00E+00	1.34E+01
Metal depletion	kg Fe eq	1.73E+05	4.65E+04	3.80E+04	6.79E+03	8.21E+04	4.24E+02	3.92E+02	4.33E+03	-5.50E+03
Fossil depletion	kg oil eq	1.68E+05	3.34E+04	9.14E+03	3.49E+04	8.40E+04	1.78E+03	3.61E+03	2.36E+03	-9.54E+02