Master's thesis

NTNU
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Life cycle emissions- and cost analysis of residential building scenarios in a zero emission neighborhood, Ydalir

Master's thesis in Industrial Ecology
Supervisor: Juudit Ottelin
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Abstract

Today's society is facing significant challenges related to climate and energy, with substantial costs associated with the green transition. The building sector contributes significantly to greenhouse gas emissions and energy consumption. Despite the increasing population and the need for new housing, luxurious habits continue to intensify the impact of buildings on the environment. In response, various measures have been implemented to reduce the sector's environmental impact, such as the FME ZEN (Zero Emission Neighborhoods) research center, which aims to reduce emissions through real-life testing in living laboratories.

This study focuses on the residential development of FME ZEN in Ydalir, which commits to a 50% reduction in emissions compared to industry standards. The objective is to analyze three building scenarios' performance from environmental and economic perspectives per net floor area. The scenarios include a development according to current building regulations (TEK17), an energy-efficient building according to passive house standards (PH), and an intermediate scenario representing the effects of minor changes (IM). The results, based on the ZEB-COM ambition level (production, construction, replacement, and energy in operations), show that the PH scenario has the lowest emissions at 207 kgCO2eq/$m^{2\ BRA}$, while the IM and TEK17 scenarios have emissions of 229 and 245 kgCO2eq/$m^{2\ BRA}$, respectively. The order changes when considering life cycle costs, with passive houses being the most expensive solution with a net present value of 34,545 NOK/$m^{2\ BRA}$, while the IM and TEK17 scenarios cost 34,233 and 33,883 NOK/$m^{2\ BRA}$, respectively.

These results are challenging to verify through existing studies due to individual parameters that make it difficult to generalize buildings. However, the study shows the coinciding effects of choosing climate-friendly materials such as wood, the impact of local power production, and the increased upfront emissions and costs associated with selecting energy-efficient buildings, largely offset during the operational phase.

In summary, the results demonstrate that all the building scenarios provide a strong starting point from both an economic and environmental perspective, meeting local emission reduction requirements. Passive houses stand out as the scenario with the best environmental performance with only a slight price difference (+2% more than TEK17) that could be mitigated by future increases in energy prices, growing interest from potential buyers, or potential emission taxation. This provides future developers and decision-makers with three scenarios that can promote green development and reduce emissions from the sector in an economically sustainable manner. It also highlights the potential for additional energy and emission reductions through a slight percentage increase in investment and the effect of local energy production.

Sammendrag

Dagens samfunn står ovenfor store utfordringer knyttet til klima, energi, samt store kostnader knyttet til en grønn omstilling. Bygninger er en av driverne til store andeler av klimagassutslipp og energiforbruk i dagens samfunn, og til tross for stadig befolkningsvekst og behov for nye boliger, er luksuriøse vaner med på å intensivere påvirkningen av bygninger. Med bakgrunn i dette er det iverksatt flere tiltak for å redusere miljøpåvirkningen knyttet fra sektorer, et eksempel er FME ZEN, forskningssenter for nullutslipps nabolag, som jobber mot å redusere utslipp ved hjelp av levende laboratorier, hvor løsninger utvikles og testes i praksis.

Dette studiet tar utgangspunkt i FME ZEN sin bolig utbygging i Ydalir, som forplikter seg til en utslippsreduksjon 50% av bransjestandard, for å analysere ytelsen av tre bygningsscenario fra et miljø og økonomisk perspektiv per netto gulvareal (BRA). De respektive scenarioene er en utbygging i henhold til dagens byggetekniske standard (TEK17), et energieffektivt bygg i henhold til passiv hus standard (PH), og et scenario som representerer effekten av mindre endringer (IM). Resultatene som fremkommer, gitt ZEB-COM omfang (produksjon, konstruksjon, utskiftning, og energibruk i drift), viser minst utslipp fra PH scenario med 207 $kgCO_2eq/m^{2\ BRA}$, mens IM og TEK17 har utslipp på 229 og 245 $kgCO_2eq/m^{2\ BRA}$. Rekkefølgen endrer seg når man ser på livsløps kostnadene, hvor nå passivhus er den dyreste løsningen på 34,545 $NOK/m^{2\ BRA}$, mens IM og TEK17 ligger på 34,233 og 33,883 $NOK/m^{2\ BRA}$.

Resultatene er vanskelig å verifisere gjennom eksisterende studier ettersom individuelle parameter gjør det vanskelig å generaliser bygg. På tross av dette kan man se sammenfallende effekt ved valg av klimavennlige materialer som tre, effekt av lokal kraft produksjon og økte tidligfase utslipp og kostnader knyttet til valg av energi effektive bygg som i stor grad blir innhentet i driftsfasen.

Oppsummert, viser resultatene at bygningsscenarioene alle er et sterkt utgangspunkt fra både et økonomisk og miljømessig perspektiv, hvor alle faller innenfor de lokale kravene til utslippskutt. Vider ser man at passivhus er scenarioet med best miljømessig ytelse med bare et lite tillegg i prisen (+2% sammenlignet med TEK17), en differanse som kan utlignes av fremtidig økning i energipriser, økt interesse i kjøpegruppen, eller potensiell utslippsbeskatting. Dette presenter fremtidige utbyggere og beslutningstakere med tre scenario som vil kunne fremme den grønne utviklingen og kutte utslipp fra sektoren på en økonomisk bærekraftig måte. Det viser også effekten av lokal energiproduksjon, og mulighet for ytterligere energi- og utslippskutt gitt en liten prosentmessig tilleggsinvestering.

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Finally, I must thank my family, friends, and classmates for supporting me throughout the thesis and studies in general. They have been vital in making the student period a wonderful chapter in my life.

Content

Abbreviations:

LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCCA	Life cycle cost analysis
PH	Passive house scenario
IM	Intermediate scenario
EPD	Environmental product declaration
BTA	Total building area, including walls(Gross floor area)
BRA	Total building area, excluding walls (Net floor area)
GWP	Global warming potential expressed as CO_2-eq
GHG	Greenhouse gas, often related to GHG emissions
TEK	Norwegian building code, technical building regulations
TEK17	TEK17 scenario, most recent building Norwegian building code
FME-ZEN	Research center for environmentally friendly energy - Zero emission neighborhoods in smart cities
FME-ZEB	Research center for environmentally friendly energy - Zero Emission Buildings
RQ	Research question
U-value	Heat transfer coefficient
GHG-investment	Increased initial emissions to achieve reduced operational emissions and life cycle emissions.
PV	Photovoltaic (solar panels)
DH	Domestic heating

List of figures:

List of tables:

Equations:

1 Introduction

The building sector plays a significant role in modern society, providing shelter and comfort, and is considered a basic human need. However, with population growth and the pursuit of luxurious living, the sector is a driver of challenges such as biodiversity loss, resource depletion, and climate change (Ellis, 2015). According to the Intergovernmental Panel on Climate Change (IPCC), buildings account for 6% of global greenhouse gas emissions (GHG), 32% of global energy use, and 19% of all energy-related emissions (IPCC, 2022c), where further growth is expected (Ürge-Vorsatz et al., 2014). In order to achieve the goals set by the Paris Agreement, which aims to limit global warming to 2 degrees above pre-industrial levels, there is a need for innovation and change in the building sector to reduce emissions and energy consumption (UNFCCC, n.d.). Emission reduction is also crucial to reach the Norwegian governments goal of 55% emission reduction by 2030 compared to 1990 levels (Regjeringen.no, 2022).

Mitigation measures in the building sector also address the United Nations (UN) Sustainable Development Goals (SDGs) 13, Climate Action. However, there is a wide consensus supporting actions to reach far beyond climate action and contribute to meeting fifteen other SDGs, like bringing health gains through improved indoor air quality and thermal comfort and reducing financial stresses in all world regions. Overall decarbonized building stock contributes to well-being and has significant macro- and micro-economic effects, such as increased productivity of labor, job creation, reduced poverty, especially energy poverty, and improved energy security that ultimately reduces net costs of mitigation measures in buildings (Ürge-Vorsatz et al., 2014). This underlines the importance of mitigation action and well-design solutions in the sector.

One of the initiatives towards this goal is the Norwegian research center for zero emission neighborhoods (FME ZEN), which aims to develop and demonstrate new zero-emission building solutions for the residential and commercial sectors and serve as innovation hubs. The center is a collaboration between research institutions, industry, and public authorities and aims to develop new building solutions that can be scaled up and replicated in other regions. The project focuses on developing integrated building systems that can achieve zero-emission performance through the use of renewable energy sources, energy-efficient technologies, and smart control systems. This is achieved through nine pilot projects (living labs) spread throughout Norway, which is expected to demonstrate that it is possible to achieve zero-emission buildings that are both cost-effective and comfortable to live in (Wiik et al., 2021).

One of these pilot projects is Ydalir, located northeast of Elverum. Ydalir contains a new school, kindergarten, and potentially 100.000m^2 housing units in the development phase, as well as local solar energy production, district heating, and a reduction of private cars (Lien et al., 2021; Yttersian et al., 2019). The initial guideline for Ydalir, *Masterplan*, presented a demand for passive house standards and a 50% reduction in GHG emissions per gross floor area (BTA) (Elverum Vekst, 2019). However, a revised edition was presented due to new research and a balance between social considerations, environment, and economy. The revised edition removes the demand for passive house standards and replaces the 50% emissions reduction with an upper greenhouse gas (GHG) emissions limit, allowing for more scenarios to be considered and a more comprehensive and optimized solution. The emission limits are presented in Table 1.

Table 1: Emission limits Ydalir (Elverum Vekst, 2019)

	Life cycle emissions per gross floor area [kgCO$_2$eq/BTA]	**Annual emissions per gross floor area [kgCO$_2$eq/BTA]**
Apartment building	390	6.5
Low-rise apartment building	473	7.9
Detached house	433	7.2

The zero-emissions neighborhoods (ZEN) focus on limiting GHG emissions within the Norwegian government's technical building regulations. However, to do so, one must uncover where actions have the highest effect. In a building's life cycle, the product stage and use stage are often the primary sources of emissions (Wiik, Fufa, Kristjansdottir, et al., 2018), where the two are reliant on each other and product selection and decisions in early stages often set the basis for use stage emissions. Additionally, a long-term solution must be profitable for the contractor and affordable for the buyer to be sustainable, as the building's prices are identified as one of the main factors for choosing an environmentally friendly solution (Værp, 2020).

Therefore, this master's thesis aims to uncover where emission reduction presents the highest effect, how the balance between embodied emissions and energy use in operation affects the overall life cycle emissions and the trade-offs with economic objectives given different scenarios. By doing so, the study provides an image of whether the construction scenarios comply with the requirements set by the local authorities and the costs associated with the project, weighed against the projected income from energy export, sale, and rent. This is valuable information for the developer but also transferable to other cases, a valuable addition to existing literature, and something that could be used for decision-making in future developments or studies.

Based on this, the research questions of this paper are as follows:

- **RQ1**: What are the embodied and operational emissions from different construction scenarios of housing area B4 Ydalir, a zero-emission neighborhood in Eastern Norway, and do they comply with the local emission limits?

- **RQ2:** Do low-emission buildings correlate with increased costs from a life cycle perspective?

The methods used to approach these questions are life cycle analysis (LCA), energy calculations using SIMIEN (Simien, 2020), and life cycle cost analysis (LCCA). The LCA utilized Norwegian environmental product declarations (EPDs) to assess the environmental impact of the building, while the LCCA analysis considered market prices from the Norwegian market to assess the life cycle costs for three scenarios: Passivehouse (PH), Intermediate (IM), and TEK17. The scenarios differ primarily in terms of insulation thickness, windows, and ventilation systems, allowing for an examination of how minor differences could impact the overall results. The Passivehouse scenario presents a low-energy building according to NS3700 (Standard Norge, 2013b), the TEK17 scenario is a building according to current Norwegian building regulations TEK17 (Direktoratet for byggkvalitet, 2017), while the Intermediate scenario is in between the two and is included to present how only some changes affect the result.

2 Literature Review

A review of existing solutions and studies was conducted to gather knowledge on the subject, find general trends, and uncover the research gap. This section discusses the two main emitting life cycle phases of a building, embodied and operational emissions, and costs. The embodied emissions section includes results presented in the preliminary report to this master thesis, *A LCA of embodied emissions in Norwegian passive house, Ydalir* (Siglevik, 2022), and supporting literature. In some cases, these sources also discuss operational emissions, which is presented in the following subsection, supplemented with additional research. The last section presents a general overview of where the most significant share of expenses is placed in the building life cycle and the magnitude of these, according to existing studies.

The literature review on embodied emissions and costs contains input from multiple studies. Some are case studies, often with multiple scenarios, whereas others present average results from comprehensive literature reviews. The data were collected using ZEN Publications and known search engines for scientific literature, such as Google Scholar, Science Direct, Web of Science, and Oria. As a background for the study, a range of similar case studies has been gathered as a measure to gather knowledge about how the results are affected by construction design.

2.1 Embodied Emissions of Material Use

A comprehensive literature review, consisting of a systematic analysis of 650+ building LCA cases located worldwide, is presented by Röck et al. (2020). The study discusses findings regarding operational energy use, embodied emissions, and how recent development effect the trends. The study groups the LCA cases after *Existing Standard, New Standard*, and *New Advanced*, with reduced total life cycle emissions accordingly due to energy efficient improvements. However, the trends shift for embodied emissions, where the average findings show the lowest emission for the standard scenario with 253 $kgCO_2eq/m^{2BTA}$, while the advanced is 377 $kgCO_2eq/m^{2BTA}$. The findings for the advanced scenarios vary from 103–423 $kgCO_2eq/m^{2BTA}$ and surpass 1250 $kgCO_2eq/m^{2BTA}$ in extreme cases presenting high variations in the results. The study also finds that all embodied GHG scenarios are able to reach life cycle emission benchmarks, presenting the discussion of 'GHG-investments' effectiveness, especially regarding carbon-spike and expected energy sector decarbonization. The analysis also presents a need to improve the transparency and comparability of LCA studies (Röck et al., 2020).

High variations in building LCA results are also discussed in a literature review conducted by International Energy Agency Energy in Buildings and Communities Programme (IEA EBC), where cradle-to-gate embodied GHG emissions results from around 80 case studies are presented. The variations are partly attributed to differences in methodological choices and system configurations, like the goal, scope, level of detail, and method. Another aspect is accounting for carbon storage in wood, effectively offsetting GHG emissions from building components. An additional aspect to consider is that some case study calculations are based on BTA, while others are based on BRA, which is shown to result in a difference of at least 10% in the evaluated area. The study thereby concludes that generalization is insufficient to address building GHG emissions. However, inspecting existing studies could uncover trends and the effect of changes. A common emission source in the analyzed buildings is concrete and metals, where one of the reasons presented is that concrete is often used in large amounts in foundations. Furthermore, cases comparing timber with concrete or steel demonstrate that timber is a less emission-intensive solution. The study also finds that low-energy buildings typically present higher early-stage emissions but overall reduction if including operations. Furthermore, the study discusses how the results from building LCA could easily be misinterpreted due to significant variations but also states the importance of transparency, consistency, updated and improved background data, and analysis following international standards and scope definitions (IEA, 2016).

Improvement of life cycle assessments in the building sector is also discussed by Säynäjoki et al. (2017), which presents results from reviewed studies varying from 0.03 and 2.00 tons of GHG emissions per gross area. The methodology is identified as one of the weaknesses, regarding the variation in results, as the lower end of results mainly were found in process LCA studies and the higher end by Input Output LCA studies, while hybrid LCAs being placed in-between. Furthermore, the paper discusses the importance of including all phases in the analysis, as pre-use phase emissions are tied to the use phase. Making decisions based on an individual life cycle stage without considering the others leads, can lead to incorrect decisions. Furthermore, the study emphasis the importance of transparency and a standardized approach to make the results comparable and readable for decisions-makers with general knowledge of LCA (Säynäjoki et al., 2017). This is supported by Schneider-Marin et al. (2022), which present both LCA and LCCA as having great potential in answering a multitude of questions related to building performance. However, there is a need to align the setup and principles of LCA and LCCA with each other and other LCAs and LCCAs to get a fair comparison (Schneider-Marin et al., 2022).

The reviewed papers show high deviations and impacts linked to the study's timing, scope, and location, underlining the need for a local, transparent, consistent, and standardized approach. Thus, this review's focus is shifted to case studies from Norway and other Nordic countries, as these are the most relevant for this master’s thesis. However, the methodological differences could also be seen in Norway, where there are many approaches to doing an LCA, and a broad range of LCA tools, something, as discussed in the literature, could influence the results (IEA, 2016; Röck et al., 2020; Säynäjoki et al., 2017). Examples of this in Norway are certification methods like BREEAM-NOR and FutureBuilt, advisory documents like ZEN and Byggforsk, and tools like ByggLCA and OneClick, which all present emission limits for achieving emission reduction in the building sector. These approaches are based on the same standard but often with different grouping, scope, approach, and ambition levels, producing different results. Common for all methods is that they include production stage emissions (A1-3) and emissions linked to replacements in operation (B4), while the other phases vary. However, due to the methodological differences, there is a difference in the GHG limits for phases A1-3 and B4-5 ranging from 4,3-8kgCO_2eq/$m^{2\ BRA}$ yr (Wiik et al., 2022). Also, a recent addition to the Norwegian building regulation TEK17 sets requirements for life cycle analysis with a scope of its own (Direktoratet for Byggkvalitet, 2017, 2022).

A study by Wiik et al. (2018), "*Lessons learned from embodied GHG emission calculations in zero emission buildings (ZEB)",* present a comprehensive review of the calculation methodologies and embodied GHG emission results from ZEB (Zero Emission Buildings) case studies in Norway. The study highlights the shift in emissions from operational energy use to materials due to energy-saving measures. The study compares seven different case studies for the life cycle stages: production, energy in operation, and maintenance. Emissions from production present, on average, 48% of the emissions over the building's life cycle, whereas the basic structural building elements, on average, present 83% of the emissions, including the solar panels. However, many of the studies compared in this paper are not residential buildings, leaving three comparable buildings, the *Single Family House concept* (SFH)*, Multi comfort house,* and *Living Laboratory*. The SFH and Multi comfort house present emissions appearing from material production of 260 and 315 $kgCO_2eq/m^{2BRA}$, while the Living Laboratory has significantly higher emissions from this phase with 727 $kgCO_2eq/m^{2\ BRA}$ (Wiik et al., 2018). The original paper for the Living Laboratory by Wiik & Wiberg (2017) states that the higher emissions could be linked to a more detailed inventory and comprehensive system boundary, presenting the effect of extending the scope of the analysis. Additionally, the Living Lab has a lower floor area, presenting higher material concentration and emissions per net floor area (BRA). However, the most significant difference is presented by the photovoltaic (PV) system (Wiik & Wiberg, 2017).

A Norwegian research project for Enova by Fuglseth et al. (2020) discusses how material choices affect the overall life cycle emissions of various building types, building scenarios, and barriers to implementing new materials. A detached house and an apartment building were presented, something close to the focus of this thesis. They were presented for a reference scenario according to TEK17 standard, and an alternative focusing on low-emission materials, both with minimalistic building construction. The findings were that the detached houses present 144 and 88 kgCO2e/m^{2BTA} for the TEK17 and low emissions scenario, respectively, and 323 and 156 kgCO2e/m^{2BTA} for the apartment building. The measures to reach such a reduction were to change materials in the load-bearing system with more climate-friendly products within those same material categories, for instance, selecting steel with higher scrap steel content and selecting low-carbon concrete instead of regular. In addition, less emission-intensive materials were selected for building elements in cases where it does not affect other building components (such as replacing ceramic tiles with vinyl). The transport distance of the materials is also identified as an essential factor in the production stage emissions. The study also shows scenarios with renovation, which present significantly less emissions. The main barriers to achieving the low emission transition are identified as prices due to low supply and demand and lack of supporting regulations and incentives. Also, availability, innovation, and knowledge linked to reuse and low-emission materials is presented as an essential factor for the transition (Fuglseth et al., 2020)

Another study comparing passive housing and a base case following technical building regulations was conducted in Norway by Dahlstrøm et al. (2012), comparing a single-family resident built according to passive house standard NS3700 (Standard Norge, 2013b) and TEK10 (Direktoratet for byggkvalitet, 2010). The paper presents the highest production stage emissions from the passive house due to a heavier and material-intensive construction with ca. 210 kg $CO_{2q}eq/m^{2\ BRA}$, while the TEK10 scenario is ca. 175 $kgCO_2eq/m^{2\ BRA}$. The most significant single contributor in both scenarios is transport, followed by mineral wool (Dahlstrøm et al., 2012).

This difference is also supported in a recent study by Wiik et al. (2022). The study discusses similar topics as this master's thesis in a different Ydalir area for another building type. The study analyzes two apartment buildings, comparing a TEK17 and a passive house scenario. Through an LCA, the study presents that operational emissions are the highest, followed by embodied emissions. The production stage emissions are 98 and 110 kg CO_2eq/m^{2BTA} for building 7, while it is increased to 141 and 155 kg CO_2eq/m^{2BTA} for building 8, given TEK17 and Passive house scenario, respectively. The main difference between the two buildings is that building 8 has a PV system, which presents the highest single-element emissions, followed by outer walls and foundations (Wiik et al., 2022).

A case study on Zero Village Bergen, by Lausselet et al. (2019), analyses where in a development's life cycle the highest share of emissions occur and identifies buildings as the highest emitting element over a lifetime of 60 years. Buildings are found to account for 52% of the emissions, while mobility makes out 40% and open spaces 2.3%. Furthermore, the study presents that over the building's life cycle, 29% of the emissions appear from the production stage (A1-3), equal to 192 kgCO_2eq/m^{2BRA}, while operational energy (B6) and replacements (B4) make out 59% and 12%, respectively. The emission intensity of domestic heating is presented as an important factor, and not allocating the incineration of waste to heat production could potentially decrease the operational energy emissions by 25%, making the production phase (embodied emissions) the most significant contributor (Lausselet et al., 2019).

Three master theses have previously been conducted on FME ZEN Ydalir by Lund (2019), Nielsen et al. (2019), and Yttersian (2019). Lund (2019) conducted a scenario analysis using LCA. The analysis covered various elements, including buildings, mobility, infrastructure, networks, and on-site energy infrastructure. The objective was to identify the most significant contributors to GHG emissions throughout the life cycle of the neighborhood. The study found that 18% (ca. 245 kgCO_2eq/m$^{2\ BTA}$) of the emissions occur from A1-3 (Lund, 2019). Nielsen et al. (2019) present a different scope, with a cradle-to-gate LCA on Ydalir school, and is included as the study presents how accounting for carbon storage in wood potentially could present negative results (Nilsen et al., 2019). Finally, Yttersian (2019) compares LCA tools for Ydalir with a similar scope as Lund. (2019). The emissions from building in phase A1-A3 present emissions ranging from 240-310 kgCO_2eq/m$^{2\ BRA,}$ underlining the difference presented by using different LCA tools (Yttersian, 2019). Although Yttersian (2019) and Lund (2019) discuss different topics, the analysis result is quite close, where the difference could be explained by differentiating between BTA and BRA. Nilsen presents the effect of extending the scope, which could be one reason for the varying results found by (Röck et al., 2020).

Furthermore, some studies conducted outside of Norway are included to highlight how building design and supporting foundation of the building might influence the results. A Danish study by Kanafani & Birgisdottir (2021) presents how construction choices affect life cycle emissions by comparing emissions linked to three different non-ZEN housing units, a standard house, a modern architectural building with a flat roof and plastered walls, and a house with wooden frame walls. The study is based on a comprehensive literature review and is therefore presenting a general average. Wood-based constructions are presented with significantly fewer emissions than others, with 1.7 kgCO_2eq/m^{2BRA}yr, around 50% less than modern architectural houses and 58% less than the industry standard (Kanafani & Birgisdottir, 2021).

Another study discussing the effect of wood construction is *Wood innovation in the residential construction sector: opportunities and constraints* by Goverse et al. (2001), which evaluated the material-related emissions from buildings in the Netherlands. The study investigated the potential for reducing emissions by increasing the use of wood in residential housing. The study showed that transitioning to more wood-intensive structures could reduce material-related emissions by up to 50%. The study presented data on the share of different building materials and their respective contributions to emissions. The results also indicated that a more wood-intensive solution could reduce building weight as it has a lower mass density than concrete. Additionally, it discusses how a lighter wooden structure requires less supporting foundation. The study indicated that, despite accounting for only 5-8% of the material mass, cement contributes 36-54% of the emissions (Goverse et al., 2001).

A Finnish study by A Säynäjoki et al. (2012) discusses emissions linked to different residential areas scenarios for further development with a hybrid LCA approach based on Input-Output analysis and LCA. The study presents construction scenarios for low-energy buildings, passive houses, and a base case. The study presents that from the base case, 55,055 ton CO_2eq derives from the construction of the buildings, where the low energy scenario presents a 1.5% increase and passive house 5.0%, a difference supported by Dahlstrøm et al. (2012), but slightly lower than the other Norwegian case studies (Säynäjoki et al., 2012).

The collected data from existing literature provide varying results, underlining the issues stated by Röck et al. (2020), IEA (2016), and Säynäjoki et al. (2017). The embodied emissions range from -90 to 726 $kgCO_2eq/m^2$ with an average of 220 $kgCO_2eq/m^2$. However, it also presents an issue regarding the comparison of LCA results, the difference between the functional units (FU) used, per gross area (BTA) or net area (BRA), where average calculations presenting BTA are shown to have 35% fewer emissions, possibly since its divided over a larger area. Due to the wide variation in the scopes of the studies, the findings should not be used to generalize embodied emissions in buildings but rather provide a vital understanding of how different parameters and methodological choices affect the results. This underlines the importance of transparency in reporting, a standardized approach, and the need for more studies on the matter. Furthermore, it presents the need for emission calculations in individual developments, as they might deviate significantly from each other. Figure 1 presents an overview of the findings in the literature, where only average values are used for the more comprehensive literature reviews.

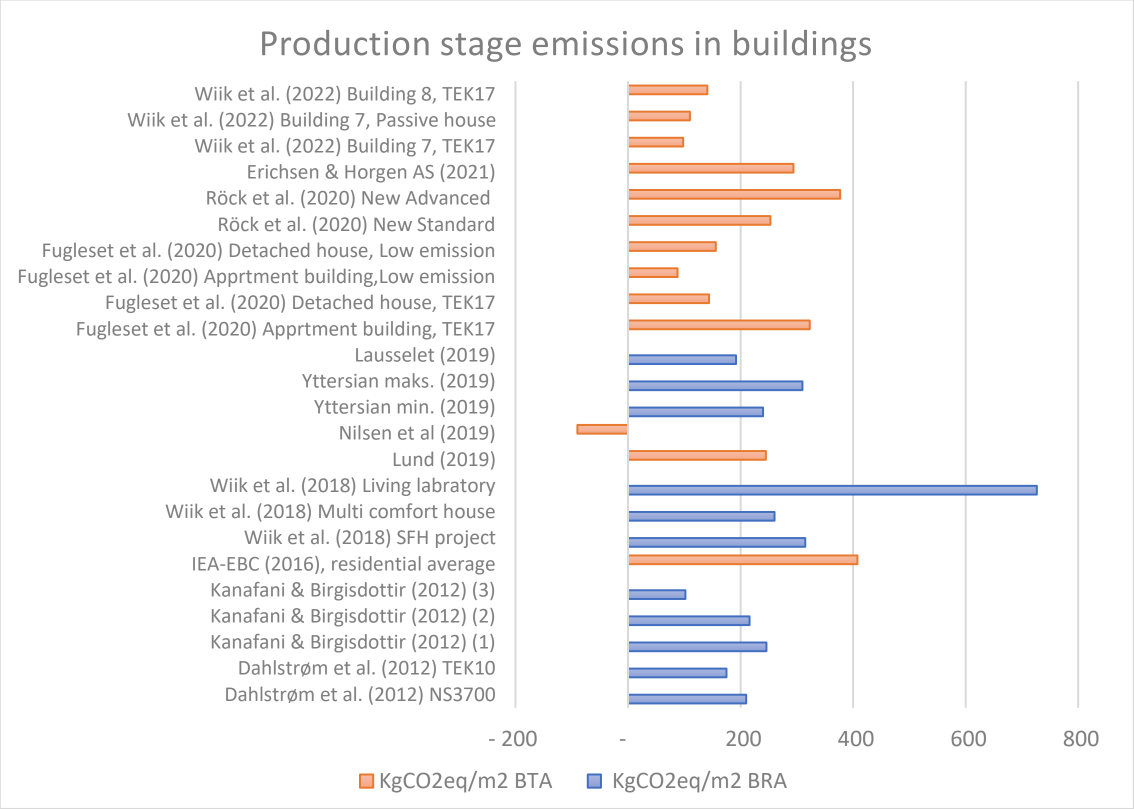


Figure 1: Overview of findings on production stage emissions in building from existing studies, reported per net (BRA) and gross (BTA) floor area

In conclusion, the material choice and scope of the analysis play a critical role in determining the results and should be reported according to standards to ensure transparency. It is evident that building materials play a significant role in life cycle emissions from buildings, and choosing a wood-intensive structure is a preferable option. Additionally, the weight of the building can also impact the results, as a lighter structure requires less supporting foundation. Many reports also indicate that, although passive houses often have lower operational emissions than a base case, they often have higher production stage emissions due to the heavier structure and increased insulation and material thickness. The review addresses the need for further research on life cycle emissions from buildings, both for individual cases as an industry average might deviate, but also to provide more case studies that could further advise methodological strengths and weaknesses, as well as provide decision-makers with more building scenarios to add to the general understanding regarding embodied emissions from buildings.

2.2 Operational Energy Use

To be able to get a complete overview of the emissions linked to a building throughout its lifetime, it is essential to cover energy-related emissions and energy use in buildings. Most of the previous section's sources presented this as a significant share of the overall life cycle emissions.

The previously presented foreign case studies by Säynäjoki et al. (2012) and Kanafani & Birgisdottir (2020) also present operational emissions for building scenarios. Säynäjoki et al. (2012) address that constructing energy-efficient buildings causes more GHG emissions in the production stage than conventional buildings and issues linked to the carbon spike (high GHG emissions in a short time associated with the construction phase). The base case, an average construction in Finland, presents the highest operational emissions of the three construction scenarios with 884 tCO_2 e/yr generated over a 50-year lifetime, originating from heating, cooling, and use of communal building electricity. The passive and low-energy scenarios present 320 and 552 tCO2 e/yr operational life cycle emissions, respectively. The study also presents a renovation and no-action scenario, where renovation presents significantly fewer emissions linked to construction and operational emissions on the same level as low-energy houses. According to this study, keeping the buildings as it is today with no action results in equivalent emissions as the passive house due to significant operational emissions. Conclusively, the study presents the passive house as the best new construction scenario, although there is discussion around the early carbon spike in construction (Säynäjoki et al., 2012).

The Danish study by Kanafani and Birgisdottir (2021) assumes a constant operational emission of around 1,7kgCO_2e./m^{2BRA}yr linked to energy use in operations for the building scenarios presented (Kanafani & Birgisdottir, 2021). However, Zimmerman et al. (2020) show an in-depth analysis of 60 buildings to create a reference scenario showcasing that more energy-efficient buildings present a slight increase in material-linked emissions but a significant reduction in operational emissions. The rapport also addresses the effect of solar panels, where the benefit in operation is shown to outweigh the additional production stage emissions, presenting a net positive effect, but this is presented as uncertain in the future due to more power production by renewables and lower emission intensive energy sources (Zimmermann et al., 2020).

Furthermore, Röck et al. (2020) also cover the aspect of operational energy-related emissions (B6) and find that new, especially advanced, buildings reduce the emission from energy use significantly at the cost of a higher initial GHG investment. However, the magnitude of operational energy emission reduction is sufficient to reduce the total life cycle emissions. The operational emissions for the three scenarios presented in the study, *Exiting Standard, New Standard,* and *New Advanced,* are 28, 24, and 14 kgCO_2eq/m^{2BTA}yr, respectively. The findings are based on the mean of the 650+ building LCA cases analyzed, however, with widely varying results. The findings are not comparable with other case studies presented in this section, as the operational energy use emissions factors are based on global studies, where emissions factors used for Norwegian studies often are significantly less due to a higher share of renewables. However, the change in results could be transferable to this study as the scenarios are of similar nature, where one sees a reduction of 14% from the *Existing Standard* to the *New Standard*, and a 41% reduction from the *New Standard* to the *New Advanced* for operational energy use, while the total life cycle emissions are reduced 11% and 17% accordingly. The study also shows how the contribution of operational emissions to the total is reduced for the different scenarios, where the two standard scenarios present about 80%, while *New Advanced* is close to 50%, however, the emission intensity of energy is highly influencing this (Röck et al., 2020)

In order to get comparable studies with this thesis's scope, Norwegian studies are also gathered for operational emissions to get a fair comparison with cases using a similar energy mix as the development in this thesis. The study by Wiik et al. (2018) presents that most emissions occur in the operational phase due to operational energy use or replacements. The distribution of these emissions differs for the different building types and scopes. However, for the *SFH concept* and *Multi comfort building*, above 40% occur from energy use in operation, making this a significant source of emissions, similar to material production (Wiik, Fufa, Kristjansdottir, et al., 2018). The third residential building from the study, *Living Laboratory,* does not present emissions from this phase as it is outside the scope of the study, but presents significant emissions linked to replacements, about five times higher than the other two, mainly due to solar panels (Wiik & Wiberg, 2017).

A detailed analysis of the *SFH concept* is obtained by *A zero-emission concept analysis of a single-family house* (SFH) by Dokka et al. (2013), which shows that operational emissions present 41% of the overall life cycle emissions. The appliances, heat pump system, and lighting are identified as the primary source of these emissions. Appliances, heat pump system, and lighting present 2392, 2107, and 1215 kWh/yr, respectively, resulting in gross emissions of 1.9, 1.7, and 1 kgCO_2e/m^{2BRA}yr. The paper also discusses power production by solar panels, where the PV system is shown to cover the annual energy use in the building. However, due to periodic mismatches between PV production and energy demand, 38% of the operational energy use is imported from the grid. Allocating for PV power production reduces the overall life cycle emissions of the building by 75%, presenting a significant impact on the results. Even though solar panels are the most significant single contributor to embodied emissions (30-38%), it presents a net positive effect on the life cycle emissions (Dokka et al., 2013).

Furthermore, two of the master theses presented in the previous section analyze operational emissions. Lund (2019) presents emissions linked production and replacement of PV and domestic heating (DH) systems, which are the source of energy use in the building. The study shows the benefits of this in the operational phase and how it, compared to alternative heating and power supply, presents overall negative emissions. The rapport also discusses the importance of an alternative energy mix, as an increase in emission intensity in the energy mix causes a significant change in the results (Lund, 2019). Yttersian (2019) has a similar scope where operational emissions account for 7.7% of the overall life cycle emissions of the buildings, while this is reduced to 4.2% considering local power production. The study also presents a scenario with a European electricity mix, no local power production, and an electric E-boiler as heating instead of DH. In this case, operational energy use accounts for about 50% of the emissions from the building's life cycle (Yttersian, 2019). Both studies present significant emissions due to replacements during the operational phase, where this is the source of ⅓ of the material-specific emissions in Lund (2019) and around ½ in Yttersian (2019), presenting the importance of durable products (Lund, 2019; Yttersian, 2019)

The study by Dahlstrøm et al. (2012) also presents energy performance and operational emissions from buildings by comparing a TEK10 building (previous technical building regulation) and Passivehouse. The study finds an energy budget of 116kWh/$m^{2\ BRA}$ yr for the TEK10 building and 82kWh/$m^{2\ BRA}$ yr for the passive house scenario, a 30% reduction. The primary source of energy demand in the building is space heating, and it is therefore presented three different heating scenarios than exclusive electricity for heating: electricity and wood, electricity supplemented by a solar collector, and electricity and an air-water heat pump.

These scenarios are considered for both buildings and present different results. For the TEK10 scenario, *electricity and an air-water heat pump* show the highest effect (15% emission reduction from el.), while for Passivehouse, *electricity supplemented by a solar collector* is the best, with 9% reduced emissions compared to exclusively using electricity for heating. The paper also discusses the importance of energy mix by comparing Norwegian (Nordel) and European (UCTE) electricity production mix. The comparison shows similar life cycle emissions for Passivehouse and TEK10 buildings considering the Norwegian mix, within a range of ±6% considering all scenarios, as the difference in embodied emissions is outweighed by the operational energy use. However, this is not the case for a more emission-intensive UCTE, where electricity use in operations now presents the most significant share of life cycle emissions and thereby presents significantly less life cycle emissions for the more energy-efficient passive house (Dahlstrøm et al., 2012).

Another study with a similar but updated comparison is the ZEN study by Wiik et al. (2022), where two buildings built according to TEK17 and Passivehouse standard are compared, building 7 without a PV system and the slightly smaller building 8 with a PV system. The study shows similar results for the energy use in the building as Dahlstrøm et al. (2012), with a total net energy requirement of 120,5 and 125,5 kWh/$m^{2\ BRA}$yr for the TEK17 scenario and 92,3 and 95,1 kWh/$m^{2\ BRA}$ yr in the Passivehouse scenario, for building 7 and 8 respectively. For both TEK17 buildings, room heating is the primary energy consumption, presenting about 40% of the energy use in the building. However, for the passive house scenario, this is considerably reduced to 27%, and the primary energy use is for this scenario water heating. The emissions that derive from energy use in the buildings are 5,06 and 5,1 kgCO_2e/$m^{2\ BTA}$yr for the TEK17 scenarios and 4,06 and 4,04 kgCO_2e/$m^{2\ BTA}$yr for the Passivehouse for building 7 and 8, respectively. If the exported solar power were to be included in this, the results for building 8 would be further reduced (Wiik et al., 2022).

The existing studies show that buildings' operational emissions are a significant source of greenhouse gas emissions throughout the building's life cycle, accounting for over 80% in some cases. These emissions are primarily linked to energy use, with appliances, heat pumps, and lighting being the primary sources. However, the impact of operational emissions can be significantly reduced using renewable energy sources, such as solar panels, which are shown to cover up to 75% of the building's energy needs. Replacements during the operational phase are also a significant source of emissions, highlighting the importance of durable products. More energy-efficient buildings tend to have lower operational emissions, although they may have slightly higher material-linked emissions. Using alternative energy mixes and the carbon intensity of the electricity grid can also significantly impact operational emissions. Overall, reducing operational emissions is crucial to mitigate the environmental impact of buildings and achieve sustainability goals. Figure 2 presents an overview of the results for the most relevant case studies (Nordic) for this master's thesis, as location significantly influences operational emissions.

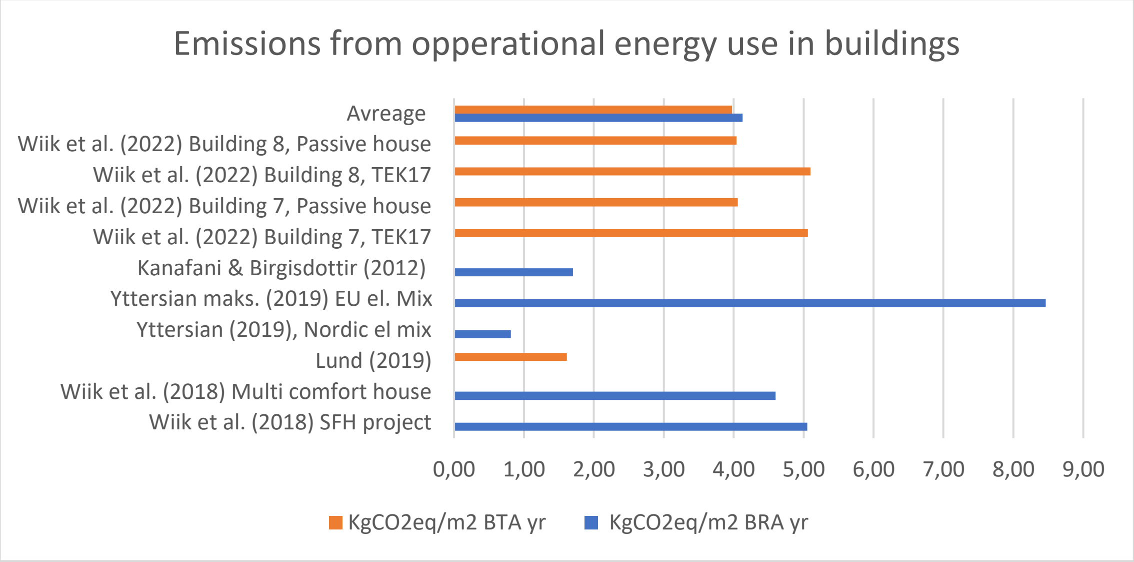


Figure 2: Overview of emissions from operational energy use in buildings presented by existing Nordic studies for gross (BTA) and net (BRA) floor area.

As for embodied emissions, these findings show how individual cases and studies vary significantly and should not be used to generalize emissions from operational energy use. However, operational emissions are presented to impact the overall life cycle emissions significantly. Furthermore, changes in the energy system in the buildings highly influence energy consumption, presenting a need for individual analysis for new developments. It also presents a need for more studies on the matter, conducted in a transparent and readable way according to standards in order to provide decision-makers with clear and comparable results, as well as add to existing LCA cases found in the literature to include more scenarios and add to background data to analyze general trends regarding the environmental impact by buildings.

2.3 The importance of costs

Addressing the GHG emissions that occur from buildings is essential from an environmental perspective. However, as stated by Værp (2020), one needs affordable buildings to make the contractor and customers choose a sustainable solution (Værp, 2020), which presents the importance of including the cost perspective in the analysis. Where most of the studies discussed in the previous section present operational and embodied emissions, only two include a cost analysis, the ZEN study by Wiik et al. (2022) and the study by Säynäjoki et al. (2012). This section expands the literature search to life cycle cost analyses.

Wiik et al. (2022) present cost calculations conducted in accordance with *NS 3454:2013 life cycle costs for buildings* and *NS 3453:2016 Specification of costs for construction projects* comparing two apartments built according to TEK17 and Passivehouse standards. The analysis shows that the total project costs of the Passivehouse scenario are 4,57 million NOK (45 700 NOK/m$^{2\ BTA}$), where the house itself costs 2,98 million NOK. The overall costs of the TEK17 scenario are 3-5% cheaper than the Passivehouse due to less materials, isolation, and layered glass, it is also slightly bigger, diving the square meter price further down to approximately 36 197 NOK/m$^{2\ BTA}$. For both buildings and scenarios, the building shell itself is the most significant expense ranging from 1,66 to 1,94 million NOK. The study concludes that even with an annual energy price 34 – 36 NOK/m$^{2\ BTA}$yr cheaper with the passive house scenario, the TEK17 building will present reduced costs of 3,1-5,2% over the life cycle of the building, making the Passivehouse non-profitable within the analysis period, something that correlates with reference values from *Norsk Prisbok* presented in the study. Regarding the distribution of costs, the study shows that for the passive house, approximately 12% of the costs are due to energy in operations and ~20% for TEK17 (Wiik et al., 2022).

The study by Säynäjoki et al. (2012) is based on a hybrid LCA combining input-output LCA and process LCA. The study shows the same as the ZEN study, lower energy use in the passive house compared to the base case and thereby lower energy-related costs, but higher construction costs. This study does not include the annual costs or costs linked to energy use in the buildings and does, therefore, not conclude which building is most profitable. The findings were 2% higher construction costs for the low energy scenario and 6% higher for the Passivehouse, compared to the baseline, which costs 2 163 €/m^{2BTA} (Säynäjoki et al., 2012), a difference close to what is presented by Wiik et al. (2022). This would translate to 23 796 NOK/m^{2BTA} considering an exchange rate of 11 (Norges Bank, 2023), but due to inflation and different price levels, these values are hard to convert to updated Norwegian prices. If linking the costs to emissions, the paper finds that with a 6% higher investment, one reduces the overall life cycle emissions by 23%. However, this is only considering construction costs (Säynäjoki et al., 2012).

Another factor discussed in the literature is the costs associated with choosing prefabricated structures and modular buildings instead of on-site constructed structures. This is identified as a cost-saving measure that improves the quality of the building. Some of the reasons for this are presented as due to streamlined processes, quality control, and reduced waste (Massiva Husfabrikk, n.d.; Skanska, n.d.). This is supported by a study conducted by Svindal & Habibi (2020), which finds that by moving the production of building modules to indoor factories, the work can be more easily standardized and streamlined. It is also noted that manufacturing modules in factories will reduce construction errors and increase the quality of the final product. The most significant advantages of prefabrication are presented as shorter construction time, better quality, and predictable economics in projects. However, it is also noted that the economic aspect varies from project to project, and external factors have a significant impact on prices, making it difficult to establish a general price (Svindland & Habibi, 2020).

A study by Nord et al. (2010) compares costs linked to two buildings, one according to TEK07 and one in Passivehouse standard. The prices are not directly comparable with the scope of this paper as both standards and prices have changed since then. The study discusses, amongst others, the aspect that location inside of Norway has to operational costs. The study shows that the location of the building has a higher effect on the square meter price of the two scenarios than the standard it is built in, where the highest to lowest price energy scenarios differ by 5%. In contrast, the two buildings' scenarios differ by 3,5%. Considering the total life cycle costs of the two, the passive house is 28% more expensive but also 27,5% bigger, presenting a quite similar square meter price (Nord et al., 2010).

Kale et al. (2016) presents a case study of the cost-benefit of transitioning to energy-efficient commercial buildings with local energy production by solar panels in India. The study shows the need for a significant increase in initial investment by an energy-efficient approach in the range of 1,3-16%, but also saving potential of 4,3% to 54,6% considering a minimum initial investment or proposed PV system, respectively, over the lifecycle of the building. This means that the increase in initial investment would be equalized by the use phase savings (Kale et al., 2016). However, as the case is located closer to the equator than Norway and therefore has more direct sunlight, the power production and operational saving potential might differ in more northern latitudes.

A study by Islam et al. (2015) presents a comprehensive literature review on life cycle costs in residential buildings. It discusses the contemporary issues and their relationship, the significance of system boundaries, assumptions, and reports on how it affects economic and environmental impacts. One of the measures was a literature review presenting the distribution of expenses according to life cycle phases, presented in Table 2, including results from the case study.

Table 2: Distribution of life cycle costs presented by Islam et al. (2015)

	Discount rate	Construction	Operation	Maintenance
Europe	4% 50 years	56 %	22 %	2 %
	2,5% 60 years	46 - 64%	23 - 34%	13 - 20%
	4% 50 years	65 %	25 %	10 %
North American	2, 4, 6, 8% 35 years	88 %	11 %	2 %
	4% 50 years	68 - 79%	3 - 9%	12 - 29%
Case study (Australia)	6% 50 years	61,7%	9,74%	25,9%
Average		**66,5%**	**17,0%**	**12,8%**

The study finds that the construction phase is the main expense from the building's life cycle with an average share of 66,5%, while operation and maintenance present varying results but with a generally higher share of costs linked to operations. It also discusses the LCCA model as sensitive to discount rates (Islam et al., 2015).

A Sintef study by Klinski et al. (2012) does, through a literature review, find that the cost of building a passive house varies depending on building size, compactness, window area, and ventilation system. It shows that the costs of building a passive house that uses renewable energy can be relatively moderate compared to a typical new house of the same size and comfort level. The additional costs of building passive houses in Austria were found to be 4-12% higher than those of building low-energy houses in 24 projects with 1,500 apartments, 9 of which met the passive house standard. Compact buildings were found to have lower costs per square meter, and documented zero-energy and plus-energy houses had higher costs per square meter than passive houses. One of the studies presented, which compared "passive solar houses" and "three-liter houses" found that they were 11,2% cheaper than passive houses, partially due to differences in project ambition levels (Klinski et al., 2012).

As the main focus of this paper is to compare an energy-efficient scenario with a base case, it is of interest to include a study by Hajare & Elwakil (2020) as it aims to study the economic payoff of making energy-efficient choices in a residential building over its life cycle. The study compares the energy system of a base case with improvements like:

- Case 1 – Azimuth angle, thermal insulation of exterior walls, and glazing
- Case 2 – Increased energy efficiency HVAC system, LED lightning, and PV system
- Case 3 – A combination of 1 and 2 with azimuth angle, thermal insulation of exterior walls, glazing, HVAC system efficiency, lighting fixture, and P.V. system

The study finds an initial investment of 4 875$ for the base case, where cases 1-3 present an increase of 30%, 216%, and 246%, respectively. However, due to cost savings due to less energy consumption in operations, the base case is found to be the one with the highest life cycle costs, where case 1-3 is 12%, 2%, and 13% cheaper, respectively. The study thereby shows how reduced energy-related costs in operation justify an increased initial investment for energy-related improvements (Hajare & Elwakil, 2020)

The material choice in the building is something shown to be essential for the environmental performance of the building but is also shown to affect the costs. A case study by Liang et al. (2021) compares life cycle emissions and cost for a high-rise timber and concrete building. The study shows that by an initial additional investment of 9,64% for the timber scenario, one reduces the life cycle emissions by -11,6% (Liang et al., 2021). Material choices are also discussed by Gonzalo & Bovea (2017) for isolation, where it is evident that insolation thickness and type highly influence both costs and emissions of the building. The thickness of isolation is only shown beneficial to a certain point, where excessive amounts lead to higher costs and production stage emissions without significant savings of operational energy cost or emissions (Braulio-Gonzalo & Bovea, 2017), presenting the importance of a thorough energy analysis.

Another aspect is which of the energy performance improvements is the best solution regarding both costs and emissions, where a study presented by Moran et al. (2017) presents a scenario analysis comparing super-insulated housing and the use of renewable technology for nearly zero energy building in a temperate oceanic climate. The study found that a building designed with gas as the primary heating source and a significant amount of renewable energy installations had the lowest life cycle cost. In terms of energy performance, a super-insulated building with gas as the primary heating source was found to be the most cost-effective solution. Although two other case studies had the most efficient heating systems, they were found to have high life cycle costs due to their use of expensive electricity for heat pumps. Despite the higher cost of gas compared to wood pellets, the greater efficiency of the gas boiler made it the most optimal solution overall. However, the results are heavily reliant on the electricity mix. The study also presents a sustainability index factor, aggregating energy, economic, and emissions results to an overall sustainability assessment, showing that the best option from an economic perspective drops to 5th best due to high global warming potential (GWP). The study presents the need for a well-weighted analysis of different options and impacts before deciding upon one solution (Moran et al., 2017).

A general factor regarding economic analysis compared to environmental is the regionality and volatile nature of economics, which also affect the findings in this literature review, where changes in the economy are fast and can make economic data obsolete with the same speed, as discussed by Schneider-Marin et al. (2022) Something which presents a need for updated and local data to read out general trends. Another possible source of off-put is if LCCA and LCA are conducted based on different datasets and software, where a fixed approach might improve the comparison (Schneider-Marin et al., 2022).

In summary, most of the existing studies addressed present the main expenses to occur in either the projecting and construction phase, energy use and running costs in operation, or maintenance and replacements throughout the lifespan of the buildings. However, the distribution of the expenses differs by scope, timing, parameters, location, and other factors making it hard to find a general cost for buildings as each project is individual, as presented in Figure 3. Therefore, the discussed studies are presented to indicate differences between building scenarios and distribution of the costs rather than generalize building costs. In the figure, all values have been converted to NOK. The energy price and consumption are identified as important factors to the life cycle cost and to weather an increased initial investment for energy saving measures and local energy production pays off. A typical observation in existing studies is higher initial investment costs for low-energy scenarios but reduced operational costs.

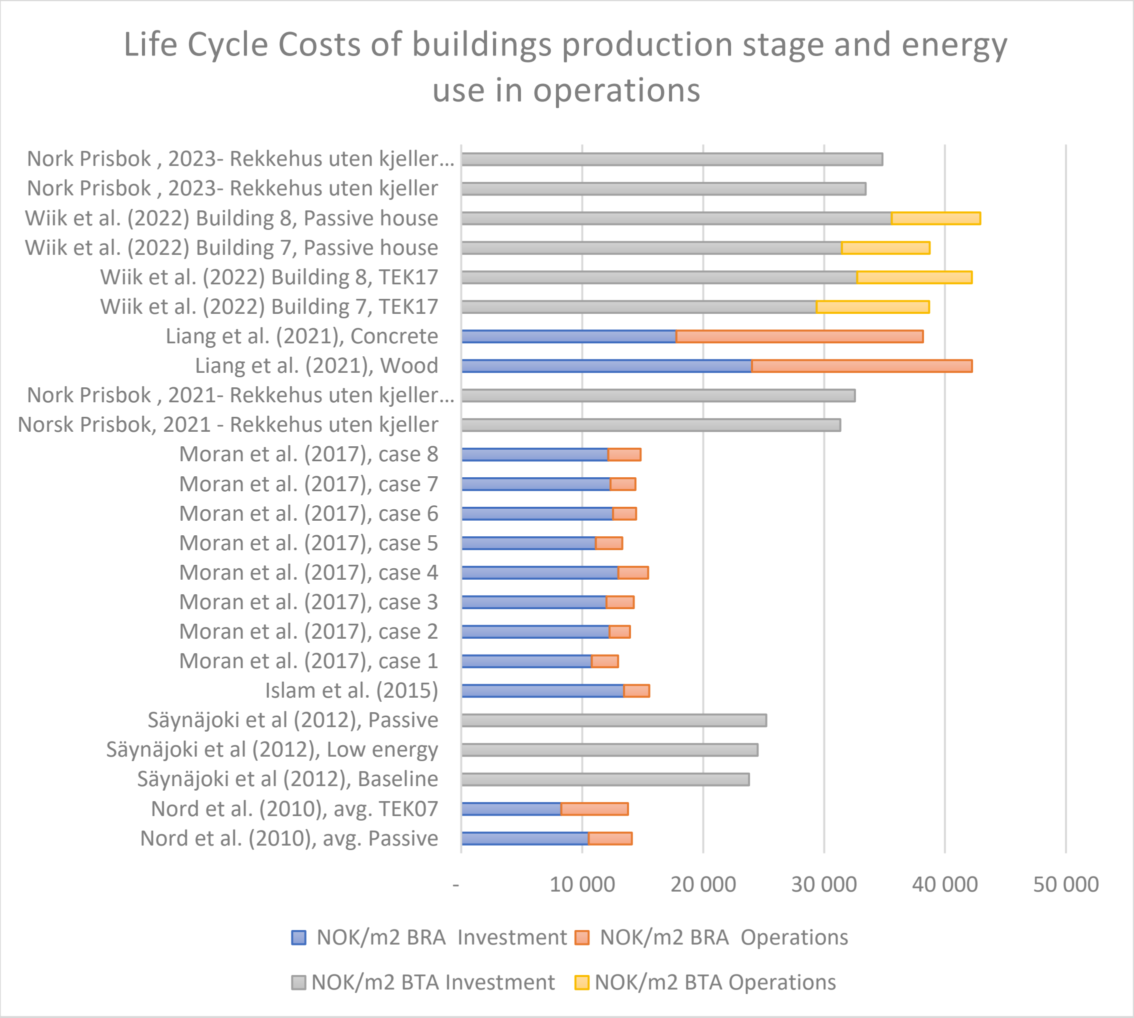


Figure 3: Overview of results found in existing studies on life cycle costs from investment and operations in buildings presented in NOK per gross (BTA) and net (BRA) floor area.

Existing studies present an average life cycle cost of 26,227 NOK/m^2 and 6,390 NOK/m^2 for investment and operations, respectively. However, as the distribution of results is highly affected by region, timing, and differences between the individual cases, a need for further research with updated data that represent the individual case is needed, both as a measure to guide the developer, but also supply decision-makers with updated research and a broader range of construction scenarios on the topic. This project presents a scenario analysis of a wooden modular building with solar panels, special loan terms based on a rental agreement, and connection to local district heating, subjects when discussed in cited literature deemed influential on both costs and emissions. Therefore, it is considered an important contribution to further work towards zero emissions neighborhoods.

3 Case area

This section presents the area of interest, current status, and general details for the development. The area analyzed in this study is Ydalir area B4 (gnr. 31 bnr. 1313), located in Elverum municipality, Norway. The planning area is a former quarry that is now roughly planned (Plan1 AS, 2019). Ydalir is, as mentioned, one of FME ZEN living labs and contains a school and kindergarten, while 100 000 m^2 of dwellings is either built, under construction, or planning. As well as a living area, it is an area for research and innovation.

Area B4 is planned for five two-story apartment blocks that, in total, present 50 apartments and around 3900 m^2 BRA in the west main field of Ydalir, as illustrated in Figure 4 (Elverum Vekst, 2019).

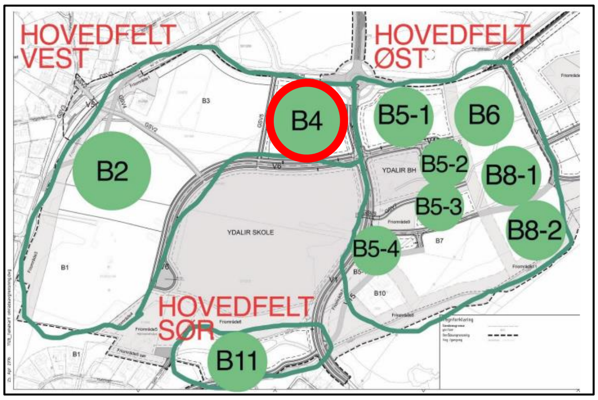


Figure 4: Illustration Ydalir (Elverum Vekst, 2019).

The progress in area B4 is still in the early stages, where the construction details and building specifics are still to be decided. However, the tender presented by Odin Prosjektering AS for the initiative holder Elverum Utleiebolig AS presents information, illustrations, and details of the plans in the area. Figure 5 presents the illustration of area B4 from the tender (Odin Prosjektering AS, 2021c).

Figure 5: Illustration Area B4 Ydalir (Odin Prosjektering AS, 2021c)

As Figure 5 presents, the five buildings are of the same nature and size and are assumed to be built on the same module. The analysis is therefore narrowed down to one building, Building A, south in the project area. The results could therefore be easily scaled up to address the whole area.

Building A is a two-story apartment building with 12 apartments, two 2-rooms, two 3-rooms, one 4-room, and one 5-room apartment on each floor, presenting a total net living area of 780m^2 (BRA) and gross floor area of 900m^2 (BTA). An illustration of the building is presented in Figure 6

Figure 6: Building A illustration (Odin Prosjektering AS, 2021a)

For the buildings in area B4, some buildings or units will be offered for sale and others for rent, creating options for both homebuyers and renters. The definite share of rental and sale is not finalized, but for the purpose of this study, it is assumed to be 50/50. The rental object is "tilvisningsleiligheter" (Shown apartment), an agreement between a landlord and the municipality to refer housing applicants to the landlord. The housing is meant for people who have difficulty finding a suitable home, especially those struggling financially. This agreement is meant to supplement the housing provided by the municipality. The agreement is standardized by the Housing Bank and used when applying for loans (Husbanken, 2023b). This means a loan with better terms than usual for the building owner and, therefore, a beneficial agreement for both parties.

4 Methodology

This section presents the methodologies used to answer the research questions where the goal is to uncover life cycle emissions linked to different construction scenarios, if these are within the stated emission limits, and how the costs of low-emissions constructions compare to standard technical building regulations. The methods used for this purpose are Life Cycle Cost Analysis (LCCA) and Life Cycle Analysis (LCA), where also energy calculations in buildings are performed to calculate operational costs and emissions. These methodologies are essential for evaluating the sustainability and economic viability of the project. As well as presenting the methods used for the analysis, this section presents data collection, categorization, standards, and assumptions/limitations. The calculations are presented per unit net floor area (per BRA), as this is constant for all scenarios, to make it scalable for the whole area or only the respective building, presenting functional units (FU) for costs, emissions, and energy as NOK/BRA, kgCO_2eq/BRA, and kWh/BRA (all net floor area assumed to be heated) respectively. The scope of the study is limited to the building itself for product stage, construction, replacements, and energy use in operations, something explainer in detail in the following subsections.

As highlighted in the literature review, this phase underscores the criticality of conducting consistent and transferrable analyses to ensure the clarity and comparability of the results. In line with this, the analysis is founded upon multiple standards outlined in Table 3**,** while also incorporating an examination based on a predefined scope of FME-ZEB, ZEB-COM.

Table 3: Standards used for conducting the analysis

Standard	Title
NS 3453: 2016 (Standard Norge, 2016)	Specification of costs in construction projects
NS 3451:2022 (Standard Norge, 2022)	Building component table and system code tables for buildings and associated outdoor areas
SN-NSPEK 3031:2020 (Standard Norge, 2021)	Building energy performance - Calculation of energy demand and energy supply
NS 3720:2018 (Standard Norge, 2018)	Method for calculating greenhouse gas emissions for buildings
NS 3700:2013 (Standard Norge, 2013b)	Criteria for passive houses and low-energy buildings - Residential buildings
NS 3454:2013 (Standard Norge, 2013a)	Life cycle costs for structures - Principles and classifications
NS-EN 14040:2006 (Standard Norge, 2006)	Environmental management, life cycle assessment, principles, and frameworks
NS-EN 15978:2011 (Standard Norge, 2011)	Sustainability of construction works, Assessment of environmental performance of buildings, Calculation method

4.1 Life cycle analysis

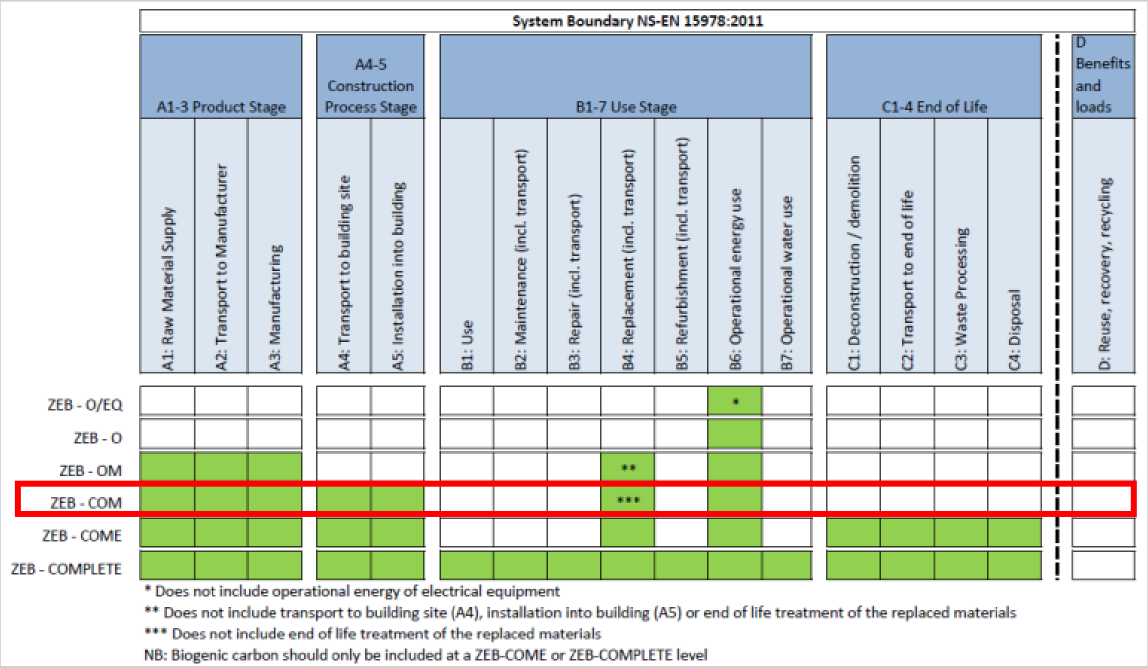
Life Cycle Analysis (LCA) is a widely recognized and internationally standardized methodology used to evaluate a product's or system's environmental impacts throughout its life cycle. The LCA process follows a rigorous and structured methodology, as outlined in ISO 14040:2006 (Standard Norge, 2006) and ISO 14044:2006 (ISO, 2006), which includes the following phases: goal and scope definition, life cycle inventory (LCI) assessment, and life cycle impact assessment (LCIA), and interpretation. The goal and scope definition phase establishes the objectives and boundaries of the study and establishes the assumptions made for the analysis. The LCI phase quantifies the inputs and outputs of the system being studied, including energy inputs, raw materials, ancillary inputs, products, co-products, and waste, as well as emissions to air, water, and soil. The LCIA phase converts the inventory data into impact categories that are comparable and understandable. Finally, the interpretation phase integrates the data from the previous phases to provide an overall assessment and recommendations for further research or improvements (ISO, 2006; Standard Norge, 2006). It is important to note that LCA results are not absolute values, but best estimates based on the specific assumptions and boundaries set in the study and, therefore, should be interpreted as potential impacts rather than definitive conclusions.

Due to the complexity of the background data in an LCA of a building, from raw materials to disposal, it often requires the use of specialized databases and software tools to perform the necessary calculations. According to Ydalir Masterplan, GHG calculations and reporting should be done according to NS 3720:2018 - *Method for greenhouse gas calculations for* buildings (Standard Norge, 2018), with OneClick LCA (One Click LCA LTD, n.d.) being the recommended software (Elverum Vekst, 2019). OneClick LCA is a software tool specifically designed to support the performance of LCAs. It contains a comprehensive database of environmental product declarations (EPDs), which are third-party verified documents that provide transparent and comparable information about the environmental performance of products over their entire life cycle (OneClick LCA, n.d.).

4.1.1 Goal and Scope

The goal of the LCA is to clearly present life cycle emissions from three wooden housing construction in the case area, with different energy performances. The scenarios are developed according to the TEK17 standard, Passivehouse standard (PH), and middle ground, Intermediate scenario (IM), to inspect the effect of minor changes. The functional unit is presented as emissions per unit net floor area [kgCO$_2$eq/BRA] to make the result comparable with existing literature and scalable for the whole area.

The analysis performed in this project was guided by the EN15978 standard from Standard Norge (2011), which provides a methodical framework for LCA studies of building products. This standard aims to assess the environmental performance of buildings and provides a grouping of the different life cycle phases (Standard Norge, 2011). The FME ZEB (Zero emission buildings) presents various scopes, adopted from EN15978, to define several definitions and ambition levels for the life cycle analysis of buildings. This is transferred to FME ZEN and also used to define the system boundaries of this thesis (Wiik, Fufa, Baer, et al., 2018). The ambition level chosen for this study is ZEB-COM, presenting a partial LCA where some parts are excluded, as illustrated by Figure 7. The study also includes phase D2-Exported energy derived from solar panels' local energy production.



System Boundary NS-EN 15978:2011

	A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life				D Benefits and loads
	A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D: Reuse, recovery, recycling
ZEB - O/EQ											🟩 *						
ZEB - O											🟩						
ZEB - OM	🟩	🟩	🟩						🟩 **		🟩						
ZEB - COM	🟩	🟩	🟩	🟩	🟩				🟩 ***		🟩						
ZEB - COME	🟩	🟩	🟩	🟩	🟩				🟩		🟩		🟩	🟩	🟩	🟩	
ZEB - COMPLETE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	

* Does not include operational energy of electrical equipment

** Does not include transport to building site (A4), installation into building (A5) or end of life treatment of the replaced materials

*** Does not include end of life treatment of the replaced materials

NB: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level

Figure 7: Description of ZEB ambition levels from the Norwegian ZEB definition guideline (Fufa et al., 2016), ZEB COM chosen for this study

Phase A1-A3 is based on the material inventory presented in Section 4.1.2 for the building shell, while inventory and surface treatment are excluded due to uncertainty and influence by personal preferences. Phase A4-5 is based on general average construction processes presented in OneClick, something considered sufficient as it presents little influence on the overall emissions. The operational energy use (B6) is based on energy performance stated for the modular building and energy calculations performed using the energy calculation tool SIMIEN, further discussed in Section 4.1.3. Phase B4 Replacements are limited to windows and solar panels as there is high uncertainty linked to the need for replacements, and other products like membranes present little influence on results. Windows is presented with an expected lifetime of 30 years in Norsk Prisbok, 40 years in OneClick LCA (EPD Norge), and 45 years by Budzinski et al. (2020), making it fair to assume one replacement for the lifetime of the building after 40 years. The solar panel system is presented with an expected lifetime of 20 years in OneClick, 25 years in Norsk Prisbok, and 30 years by Kristjansdottir et al. (2016). However, due to an expectation of improved quality and durability in future solar panels, this is also considered only to be replaced once.

The LCA also includes biogenic carbon storage, something outside of the scope, as additional information in the LCA. Carbon is stored in the building instead of being emitted over the lifetime of the building (60 years), presenting negative emissions. Parts of this is reemitted in the end-of-life phase of the building, depending on the waste treatment process, but this is something outside the scope of the paper and thereby concluded that 100% is reemitted after 60 years. However, there is also an effect of delaying the emissions, given new growth in the extraction area, where new biogenic growth would extract carbon from the atmosphere, thereby presenting negative emissions. ILCD Handbook presents a factor of -0.01 $kgCO_2eq/kg$ yr for this, but this is a rough estimate as elements like vegetation type, location, climate, and if new vegetation actually is established in the area would significantly affect the carbon capture (European Commission, Joint Research Centre, 2010).

4.1.2 LCI – Research Materials

The study references a project in the development phase, with limited data available. This means that a lot is based on assumptions and dialogue with involved actors, Sintef, Elverum Vekst, and Odin Prosjektering AS. Through dialogue with Odin, it becomes clear that no definitive solution for the building has been established yet, but Skanska being the most likely contractor.

Sintef presents a technical approval of Skanska Element- og Modulbygg (TG 2147) by Skanska Husfabrikken AS (Hrnjicevic, 2021), which is assumed to be used for the buildings in area B4. The certification presents a standard execution of the wooden structure sectional house system, including the wall, floor divider, roof constructions, and element joining, but not windows, internal surfaces, technical installations, or foundation (Hrnjicevic, 2021). This is considered a solid basis for reducing the environmental impact as using a wooden structure is considered less emission-intensive than many alternative materials (Fuglseth et al., 2020). The certification also provides product-specific information, including names and technical specifications such as carrying capacity and heat transfer coefficient (U-value).

The certification does not provide information on the quantities of construction elements or measurements. The measurements are therefore obtained from the tender by Odin Prosjektering AS, providing information on roof plans, windows, and doors. The roof plan and illustrations in the tender (Figure 8-10) are measured using AutoCAD (Autodesk Inc., 2023) to determine the correct quantity of building components.

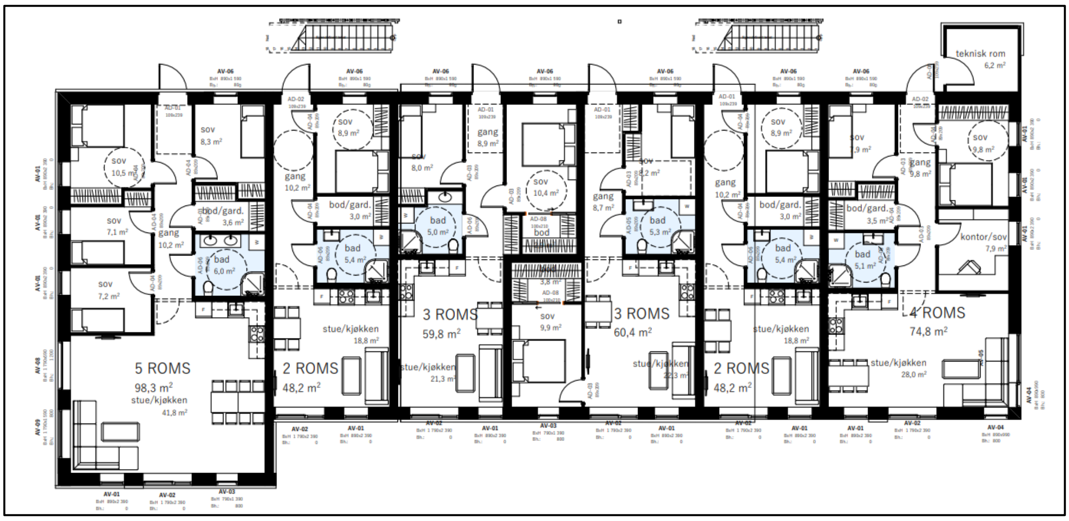


Figure 8: Floor plan (Odin Prosjektering AS, 2021b)

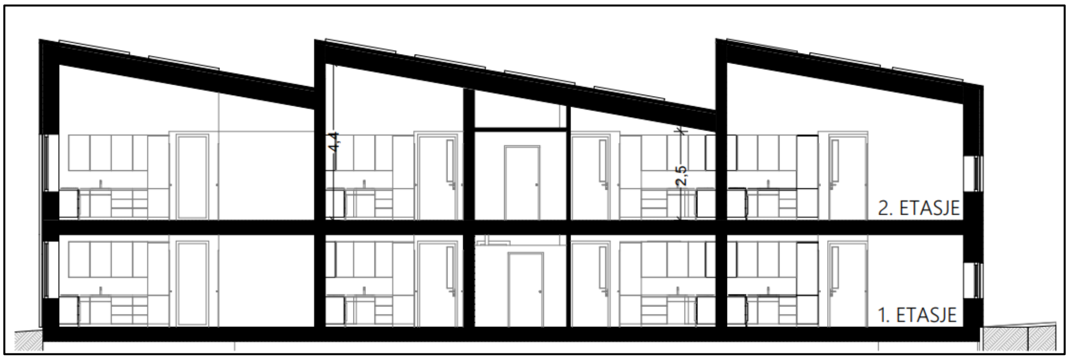


Figure 9: Design drawing presenting inside roof height (Odin Prosjektering AS, 2021d)

Figure 10: Outside height (Odin Prosjektering AS, 2021a)

The illustrations above create the basis for quantifying the different building elements by measuring the different surfaces. This information is further used with a material list to create the life cycle inventory. The appendix presents the complete material list (*Appendix 1 and 3*) and how the materials are constructed (*Appendix 2*). The list of building element quantities is calculated using the measurements from the roof plan and design drawings, presented in Table 4. These measurements are further used for developing the inventory for the analysis. To make the data more comparable to the industry standard for grouping building elements, the standardized *Table of building elements and table of codes for systems in buildings with associated outdoor areas NS 3451:2022,* is used to present the results (Standard Norge, 2022). It is essential to note that differences between the scenarios are limited to material quantities, where the products are constant, apart from windows.

Table 4: Building measurements

Nr.	**Element**		**Amount**	**Unit**
2	**Bygning**	**Building**	**779.4**	**m^2**
21	**Grunn og fundament**	**Foundation and footing**		
216	Direkte fundamentering	Direct foundation	449.9	m^2
23	**Yttervegg**	**Exterior wall**		
231	Bærende yttervegger	Load-bearing exterior walls	723.74	m^2
2341	Vindu	Window	136.16	m^2
2342	Dører	Doors	31.26	m^2
235	Utvendig kledning og overflate	Exterior cladding and finishes	556.32	m^2
24	**Innervegg**	**Interior wall**		
241	Bærende innervegger	Load-bearing interior walls	472.11	m^2
242	Ikke-bærende innervegger	Non-load-bearing interior walls	532.24	m^2
2442	Dører	Doors	93.96	m^2
25	**Dekker**	**Floor structures**		
251	Frittbærende dekker (Etasjeskiller)	Cantilevered floor structures	449.9	m^2
254	Systemgulv (Gulv mot grunndekke)	System floor	449.9	m^2
255	Gulv overflate (Dekke våtrom)	Floor surface	354	m^2
256	Faste himlinger og overflatebehandling	Fixed ceilings and surface treatments	449.9	m^2
26	**Yttertak**	**Roof**		
261	Primærkonstruksjon for yttertak	Primary structure for the roof	480.12	m^2
262	Taktekking	Roof covering	181.89	m^2
28	**Trapper, balkonger, m.m.**	**Stairs, balconies, etc.**	**160.4**	**m^2**
47	**Lokal elkraftproduksjon**	**Local power generation**		
471	Solceller	Solar panels	298.23	m^2

Measurements determine the surface area, while the contents inside the walls (such as beams and insulation) are determined through calculations. The number of beams was computed using a standard center distance of 600mm for the length of each floor, wall, or roof and adding one to account for the first beam, presented in Equation 1.

Equation 1 – Number of beams

$$Number\ of\ beams = \frac{length}{600mm} + 1$$

The calculated number of beams is rounded up to the nearest integer, as a beam gap of 600mm is considered the upper limit in most constructions. This is because insulation and plates are produced in this size, reducing work hours and waste, as well as it ensures an equal load-bearing capacity throughout the construction. The length of the beams is then determined using the width or height of the various elements, as presented by Equation 2.

Equation 2 – Length of beams

$$Length\ of\ beams = Number\ of\ beams * height/width\ of\ element$$

These calculations are not reliant on the circumference of the beams, as it is based on center distance. However, circumference is needed to calculate the total volume of material and isolation thickness, which significantly influences material quantities and the U-value in the building, thereby determining the different building scenarios. The beam thickness is further discussed in Section 4.1.3, as it needs to be within certain limits to present an acceptable U-value regarding national building regulations.

This information is sufficient for determining the quantities of materials needed. OneClick product-specific EPDs are utilized to build the inventory based on the products presented in the Skanska certification (Appendix 1). For unmatched products, similar products with the same properties are used. There is also some information not provided, where design suggestions from OneClick are selected. These are:

- Ground deck, approximately **73.33 kgCO_2eq m^2** (Rebar, EPS-isolation, Vapor barrier, Levelling mortar, Low carbon concrete class A)
- Stripe foundation, approximately **7.56 kgCO_2eq BRA** (Rebar, EPS-isolation, Low carbon concrete class A)
- Solar panel photovoltaic system, Finland average **141 kgCO_2eq m^2**
- Balconies **0.00875 kgCO_2eq m^2**

Ground deck and stripe foundation make out the foundation of the building, where factors such as soil type and condition, local building codes, the building's design, and the weight of the building play a role in determining the required foundation thickness and design. However, through research and dialogue with professors and building professionals on the subject, it has become clear that individual projects vary too much to give a rough estimate of how this varies, and a thorough analysis of individual projects would be needed to provide numbers on this. It is therefore assumed sufficient with a constant OneClick foundation suggestion for all building scenarios for this paper. The solar panel presents significant embodied emissions and is presented for a Finland average, however, the emission factor is in line with values presented in a Norwegian study by Kristjansdottir et al. (2016) comparing different solutions, and, based on this, deemed sufficient for this study (Kristjansdottir et al., 2016). The balconies present little effect on the result and are a simplified structure where the OneClick design suggestion is assumed to be adequate. Based on the inventory for the LCA, a similar data gathering where performed for material prices in Norsk Prisbok.

4.1.3 Energy calculations

An analysis of energy consumption is essential to include operational costs and emissions from the building. This also presents the main general differences between the different scenarios as a passive house focuses on reducing the energy need and heat leakage from the building compared to standard building regulations. The energy calculations have also been used to ensure that the building meets the NS3700 and TEK17 standards and further develop the building inventory regarding the thickness of walls, floor-to-ground, roof, and the technical capabilities of doors and windows.

The energy calculation tool, Simien (Simien, 2020), has been used to analyze the energy use in the building. Simien is a software program for conducting energy calculations in buildings. It helps to estimate the energy consumption and thermal performance of a building and determine the potential for energy savings. The tool is commonly used by architects, engineers, and building professionals to assess and optimize building design, construction materials, and HVAC systems. The tool is based on international energy efficiency standards and guidelines. It also considers regional climate data, building orientation, and other relevant factors. The simulation output provides valuable information for decision-making, including detailed reports and graphs, and can help identify areas for improvement in building energy efficiency (SIMIEN, n.d.).

The data input is adjusted to reach the minimum terms stated for the passive house standard by *NS3700:2013 Criteria for passive houses and low energy buildings* (Standard Norge, 2013b) and TEK17 standard presented by *SN-NSPEK3031:2021 Energy performance of building* (Standard Norge, 2021). These standards have served as advisory documents in combination with the technical specifications outlined in the technical approval for the modular building to devise a passive house and TEK17 scenario. An average computation of input data has been performed to determine an intermediate scenario, where the energy performance lies the basis for calculating wall, roof, and floor thickness, later used to create LCA and LCCA inventory. Table 5 presents the input data used for the calculation, where the dimensions of the different building elements are adjusted to accommodate the needed u-value. The red values in the table indicate constant values for all scenarios.

Table 5: Energy Scenarios

Energy performance	TEK17	Intermediate	Passivehouse	Unit
U-value outer wall	0.18	0.135	0.09	W/m2K
U-value roof	0.13	0.11	0.09	W/m2K
U-value floor	0.1	0.09	0.08	W/m2K
U-value window	0.8	0.75	0.7	W/m2K
U-value door	0.8	0.75	0.7	W/m2K
Normalized thermal bridge value	0.05	0.04	0.03	W/m2K
Air density, leakage number N50	0.6	0.6	0.6	1/h
Annual average efficiency temperature recycle	0.8	0.85	0.9	%
SFP-factor inside working hours	1.5	1.5	1.5	kW/(m3/s)
SFP-factor outside working hours	1	1	1	kW/(m3/s)
Sun-screen activated position	0.4	0.4	0.4	
Sun-screen not activated position	0.2	0.2	0.2	
Cooling battery	yes	yes	no	
Dimensions				
Outer wall	210.5	272.75	335	mm
Roof	325	375	425	mm
Floor to ground	310.5	323	335.5	mm
Carrying inner wall	250	250	250	mm
Non-carrying inner wall	125	125	125	mm
Floor divider	250	250	250	mm
Roof to cold loft	250	250	250	mm
Foundation	300	300	300	mm

Based on energy calculations, energy-related emissions are calculated by emission factors. The emissions intensities used to calculate the energy-related emissions are 0.13 kgCO_2eq/kWh for electricity consumption based on "*Electricity, EU28 + Norway, 60 years forecasted average (IEA/NS3720 energy mix, projection from 2015-2017 average)*" gathered from an LCA study for country specific electricity mixes based on NS 3720, IEA and Ecooinvent 3.3 in 2020 (ecoinvent, 2020). The heating source, district heating, is calculated by emission factor 0.0419 kgCO_2eq/kWh from "*District heat, Elverum, Norway*" based on data gathered from an LCA study for country-specific district heating based on Norsk Fjernvarme fuel distribution for Elverum in 2018 (ecoinvent, 2017). The energy-affiliated costs are presented in the next section.

4.2 Life Cycle Costs Analysis

LCCA adopts the life cycle approach from LCA and is a similar analysis. As LCA focuses on the environmental impacts, it also arises a need to analyze the sum of costs over a project's lifetime, which is the goal of the LCCA. The costs of the projects are something that's substantial for both the contractor and the customer. The approach follows the same system by developing an inventory of inputs and outputs for the different phases. However, economic factors are used instead of environmental impact factors, with the functional unit costs per unit floor area [NOK/$m^{2\ BRA}$] over the life cycle phases included in the scope.

As a measure to make the cost analysis comparable to the findings in the LCA, the same scope and life cycle phases are included. The LCCA, therefore, presents costs linked to the production and construction phase, as well as operational costs due to replacement and energy use. However, the categorizing and approach to obtain the results differ. The production and construction costs are grouped according to NS 3453:2016, as presented in Table 6 (Standard Norge, 2016).

Table 6: NS 3453:2016 cost grouping (Standard Norge, 2016)

Nr.	**Categories**
01	Common Costs
02	Building
03	HVAC installations
04	Electrical power installations
05	Telecom and automation
06	Other installations
	SUM 01-06 HOUSE COST
07	Outdoor
	SUM 01-07 CONTRACT COST
08	General costs
	SUM 01-08 CONSTRUCTION COST
09	Special costs
10	VAT
	SUM 01-10 BASE COST
11	Expected additions
	SUM 01-11 PROJECT COST
12	Uncertainty provision
	SUM 01-12 COST LIMIT

For this project phase, 2023 data from Norsk Prisbok is used (Norconsult Digital AS, 2023). Norsk Prisbok, or Norwegian Price Book, is a yearly updated price database that contains comprehensive and diverse price information regarding the costs of a construction project and elements. The content consists of more than 1900 pre-calculated elements, almost 5000 price lines, timings, and experience prices per square meter for several building types, structured according to NS 3457 (Norsk Prisbok, n.d.).

As a reference point for two of the scenarios in this thesis, TEK17 and Passivehouse, two of the building scenarios presented in Norsk Prisbok are used, *Rekkehus uten kjeller* and *Rekkehus uten kjeller – Passivhus*, as it is a similar construction of the same size (800m^2) as the development in this study, while the intermediate scenario is based on an average of the two. This is used both for comparison but also to fill in data gaps. The reference buildings present that 67% of the expenses occur due to housing costs, of whom 65% is due to the *02.Building*, while 19% is due to *10.VAT,* where VAT is 25% of construction costs (01-08). It also presents 4% higher costs linked to the Passivehouse than the TEK17 scenario, something that correlates with some of the findings from the literature review (Klinski et al., 2012; Nord et al., 2010; Säynäjoki et al., 2012).

As the project is in the development phase and no solution is yet decided upon, reference scenario prices are assumed for most of the categories, apart from *02.Building, 04.El power installations, and 10.VAT*. The reference scenario prices are presented in Norsk Prisbok as NOK/BTA. Therefore, these values are converted to NOK/BRA based on the difference in area between the two stated for the current development, where BRA=780m^2 and BTA=900m^2, making NOK/BRA prices approximately 15% higher. However, this calculation is constant for all scenarios and does not affect the main expenses of the building, *02.Building* and *10.VAT*, it is assumed to have little effect on the overall results.

The list of costs for *02.Building*, the largest cost item, is based on the material inventory developed in the LCI, where general product-specific prices, including work, are found in Norsk Prisbok. A detailed description of material costs is presented in Appendix 4. Category *04.El power installations* base most of the data on the reference calculation, but PV system is added, one of the most considerable single-element costs. The price of solar panels (system and installation) is also verified through a price estimate in contact with a solar panel developer. A factor not considered for this study is that major developments like this often get reduced prices compared to the marked standard, which could drive the investment costs down. The changes in *02.Building* and *04.El power installations* results in an updated *10.VAT*, 25% of construction costs.

In addition to initial expenses linked to the project's production and construction phase, there are costs linked to replacements, energy use, and loan interest. Another factor to consider is the annual price growth. The data collected on this phase is based on literature, published datasets on historical price development, and assumptions.

Based on information about building materials selected from Norsk Prisbok, OneClick LCA EPD's, and existing literature on the matter, most building materials last for the whole lifetime of the building, considering regular maintenance, apart from windows and solar panels. Regular maintenance and repairs are hard to determine and are assumed to present minor changes to the results. This is also not considered for the scope of the LCA and therefore left out of the scope of the LCCA. Replacement of windows and solar panels, on the other hand, presents a significant change to both the costs and emissions of the building and is therefore included with the assumption for one replacement in the lifetime of the building. Due to inflation and an increase in the consumer price index, an annual replacement cost of 2.85% increase is assumed based on documented average annual increase from 2000 to 2022 (SSB, 2023d). This rate is also used as *r = discount factor* in later calculations stating the net present value.

The cost linked to energy use is based on the calculation presented in the previous section and the average market prices presented by SSB. There is constant stress on the energy market, fluctuating prices, and a significant price increase over the last two years. The price increase is most extreme for electricity, where one sees a household net electricity prices increase from 2020 to 2022 of around 700%, something that in December 2021 resulted in the government introducing a temporary support scheme for households (IEA, 2022; SSB, 2023b). The increase is not as extreme for domestic heating, however, to provide consistency and credible values, an average from 2019 to 2022 is calculated for both domestic heating and electricity. This results in an average price of electricity in Norwegian households from 2019 to 2022 of 90.23 øre/kWh, while domestic heating is 79.85 øre/kWh (SSB, 2022b, 2023b). This is a simplified estimate, where a change in the energy prices could significantly impact the energy-related costs from the building and other building costs like material prices and transportation. However, as market fluctuations are hard to forecast, average values are deemed adequate. Furthermore, the study does not account for price growth for energy prices as the consumer price index presents a weaker annual development and high deviations for energy (SSB, 2023c), and the sum of energy import-export is assumed to have little effect on the total costs.

The development project will be funded through loans obtained from the Norwegian State Housing Bank due to the developer's provision of referral homes to the municipality. This financing arrangement offers more favorable loan conditions compared to standard loans. The interest rate utilized in this study is based on the average monthly interest rate recorded as 2.07%, based on historical interest from 2006 to 2023, for a downpayment time of 30 years (Husbanken, 2023a). However, due to the volatile nature of this rate, predicting future developments is complex, and an average rate is deemed adequate for this study. The share of investment financed through loans is assumed to be 85% of the initial investment cost.

Since the value of money is not constant in time, calculations are needed to present a net present value and annual costs considering today's market. This is calculated based on *NS 3454: 2013 Life cycle costs for construction works - Principles and classification,* which, amongst others, presents the NV (present value) formula, presented in Equation 3 (Standard Norge, 2013a). The NV formula is also used to calculate loan interest over the 30-year downpayment period.

Equation 3 – Present value

$$\boldsymbol{NV_T = \sum_{t=0}^{T} K_t * d_t}$$

- NVT present value of costs in the analysis period
- Kt is the cost in a given year t;
- T is the analysis period (number of years counted from the base year);
- t is a given year (number of years from the base year to t);
- dt is the discount factor for a given year t.

Equation 4 – Discount factor

$$\boldsymbol{d_t = (1 + r)^{-t}}$$

- dt is the discount factor for a given year t;
- r is the discount rate;
- t is a given year (number of years from the base year to t).

Based on the sum of the NV formula over the whole lifetime of the building, one could also calculate annual costs. To do so, the ÅK formula is used, presented in Equation 5.

Equation 5 – Annual costs

$$\text{Å}\boldsymbol{K = NV_T *}$$

Where *a* is the annuity factor and presented by:

Equation 6 – Annuity factor

$$\boldsymbol{a = \frac{r}{1 - (1 + r)^{(-T)}}}$$

As additional information, a theoretical overview of potential income is included related to sales and rent in the Ydalir area and expenses linked to income taxes from rent. Ydalir is an attractive area in growth, with recreational opportunities, schools, kindergartens, and workplaces in close proximity. There are also new buildings with a focus on energy efficiency. These factors can lead to a higher willingness to pay among buyers and are considered in the calculation. Statistics Norway (SSB) presents both prices for sales and rentals, which are respectively at 37,566 NOK/m2 (SSB, 2023a) and 1,550-2,120 NOK/m^2yr (SSB, 2022c). Furthermore, data on actual sales objects have been obtained through Finn.no, where eight sales objects are listed in the Ydalir area as of 15. March 2023, confirming the idea of a slightly higher sales price, with a mean square meter price of 46,698 NOK/m2, 20% above the SSB average (Finn.no, 2023). This provides a basis for pricing in this study, and an upward adjustment of rental and sales prices by 20% is included, as it is assumed that the willingness to rent corresponds to the sales valuation. Table 7 presents the complete valuation of the apartments.

Table 7: Potential income

	Apartment	Floor area [$m^{2\ BRA}$]	NOK/$m^{2\ BRA}$	NOK
Annual rent income	5 rooms	98.30	1,655.47	162,732.31
	2 rooms x 2	96.40	2,543.18	245,162.51
	3 rooms x 2	120.20	2,147.31	258,106.34
	4 rooms	74.80	1,859.40	139,083.13
	Whole floor	389.70	2,065.91	805,084.29
Sale Income	Whole floor	389.70	46,698.09	18,198,245.32

Based on annual price changes in the rental market from 2012 to today, its assumed an annual increase of 2.87% in the rental price over the lifetime of the building (SSB, 2022d). Since the loan interest is below both the average and rental price increases, it is assumed that the developer uses the entire downpayment period instead of big deposits as the income value would outgrow the interest, also leaving capital from sales open for new investments, making it a profitable agreement for the developer. Nevertheless, uncertainty is linked to future developments for all market prices.

5 Results

This section presents the results of the analysis relating to life cycle emissions and costs throughout the lifetime of the building to answer the research question. These findings also present the basis for further discussion in Section 6. First, results from the energy analysis conducted in SIMIEN are presented as this influences costs and emissions.

Based on Simien calculation, the energy analysis presents the total heat loss of the passive, intermediate, and TEK17 scenario as 0.42, 0.50, and 0.60. The analysis also presents the annual distribution of delivered energy to the building in Table 8. The table shows the lowest energy consumption by the Passivehouse, and if also accounting for energy export, a net negative consumption. As additional information, the source of consumption is included in the table as the annual energy budget, where the analysis finds that room heating, hot water, and technical equipment are the three primary sources of energy use for all scenarios. Technical equipment and hot water is fixed for all scenarios. However, the findings present a significant change in room heating, where the Passivehouse is 43% less than TEK17 based on less heat loss and, therefore, a reduced need for heating. A complete overview of the results from the energy analysis can be found in Appendix 6.

Table 8: Delivered energy to building and annual energy budget

Delivered energy to building [kWh / BRA yr]	**TEK17**	**Intermediate**	**Passivehouse**
01.Direct el.	27.5	27.5	27.5
02.El. To heat pump system	18.2	15.9	13.6
03.District heating	19.3	13.2	9.2
04.Solar power own use	-17.6	-17.1	-16.8
Total delivered energy [sum 01-04]	47.5	39.6	33.5
05. Solar power export	-37.1	-36.1	-37.9
Net delivered energy [sum 01-05]	10.3	3.5	-4.4
Annual energy budget [kWh / BRA yr]			
Rom heating	31.5	24.8	17.9
Ventilation heat	9.6	6.1	2.8
Hot water	26.3	26.3	26.3
Fans	6.2	6.2	6.2
Pumps	2.1	2.1	2.0
Lightning	7.6	7.6	7.6
Technical equipment	11.7	11.7	11.7
Ventilation cooling	3.6	0.0	0.0
Net energy demand	98.5	84.7	74.6

5.1 Emissions

Section 5.1 answers RQ1– *"What are the embodied and operational emissions from different construction scenarios of a house in area B4 Ydalir, a zero-emission neighborhood in Eastern Norway, and are they within the emission limits?"* where a comparison of a building built according to TEK17 and Passivhouse standard is conducted, as well as an intermediate scenario presenting the effect of only slight changes. The section also aims to uncover if the constructions comply with the maximum limit of 473 kgCO$_2$ eq/BRA considering phases A1-A3, B4, and B6 stated by the Ydalir Masterplan (Elverum Vekst, 2019).

First, the building scenarios' material-related emissions from phase A1-3 (production stage) are presented.

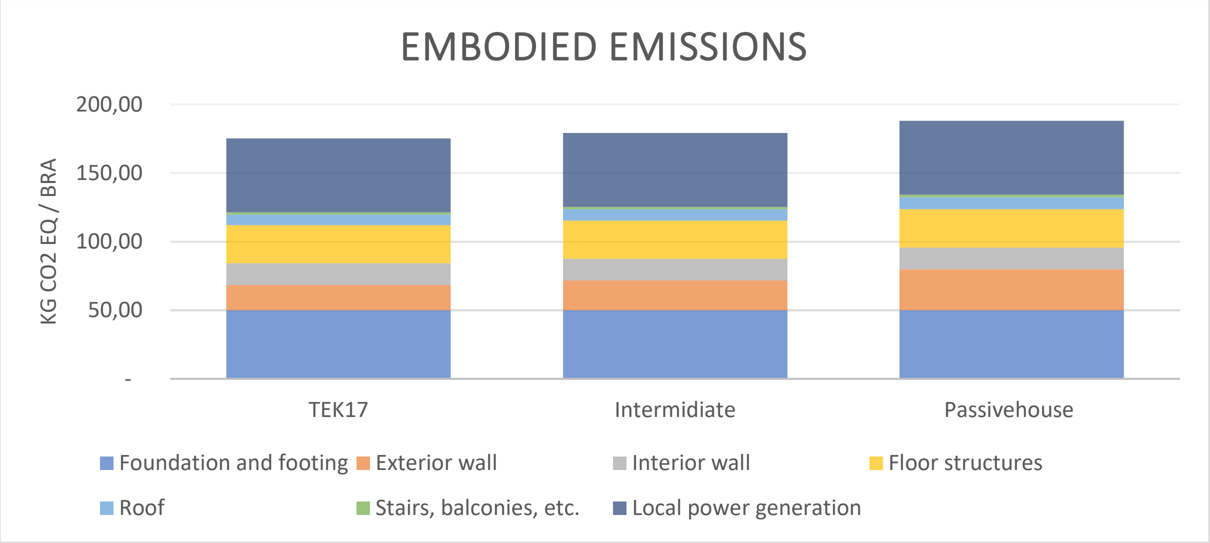


Figure 11: Emissions from phase A1-3 (kgCO$_2$eq/m$^{2\ BRA}$)

Figure 11 shows embodied emissions linked to the building structure grouped according to NS 3451:2022. The total embodied emissions show the highest impact by the Passivehouse scenario with 188 kgCO2eq/m$^{2\ BRA}$, where the Intermediate and TEK17 scenarios are 5% and 7% less, respectively. The most significant source of emissions is *Local power generation*, with 58.85 kgCO$_2$eq/m$^{2\ BRA}$, followed by *foundation and footing*, with 49.91 kgCO$_2$eq/m$^{2\ BRA}$, for all scenarios. The scenarios differ in emissions for the *Exterior wall, Floor structures*, and *Roof*, while the rest is constant for all scenarios. The Passivehouse scenario presents an increase in embodied emissions from TEK17 off 61%, 1%, and 15% for *Exterior walls, Floor structures*, and *Roof,* respectively.

Operational emissions are also highly influential to the total emissions from the building and a phase essential to address. The results are based on the energy analysis results and emission factors presented in Section 4.1.3 and Table 8.

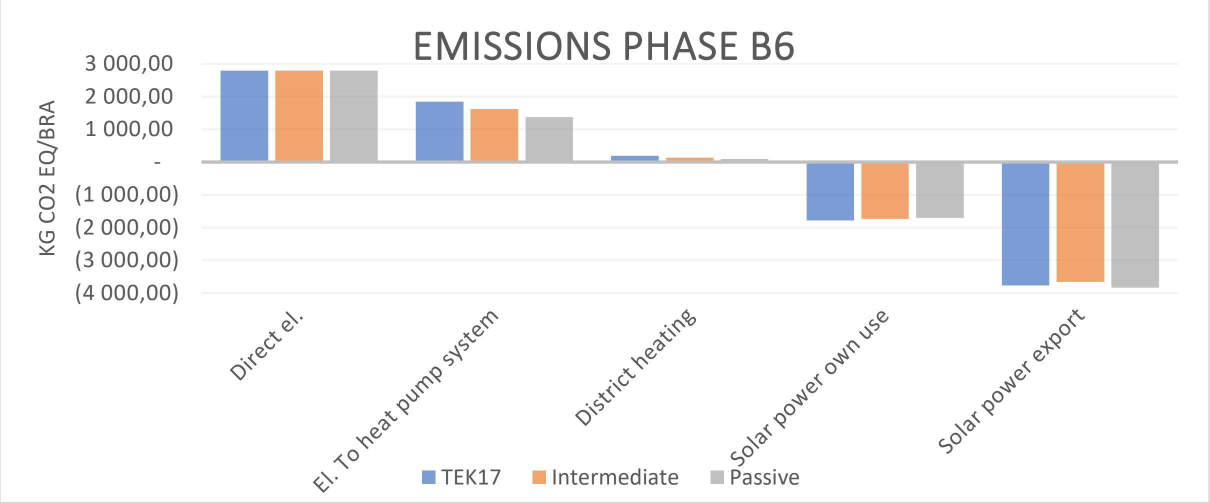


Figure 12: Emissions from energy use in operations phase B6 (kgCO$_2$eq/m$^{2\ BRA}$)

Figure 12 shows the distribution linked to the primary emission source of the building scenario, operational energy use (B6). The figure shows energy-related emissions occurring from direct electricity use, electricity used for heat pumps, and heating of the building by district heat. The analysis finds total annual emissions by energy consumption of 6.2, 5.8, and 5.5 kgCO$_2$eq/m$^{2\ BRA}$yr by TEK17, IM, and PH, respectively. However, around 40% of what is consumed is supplied by local power production, reducing the emissions to 3.9, 3.6, and 3.3 kgCO$_2$eq/m$^{2\ BRA}$yr. If also accounting for the exported energy, and thereby avoided energy production to the grid, one finds negative values for all scenarios and a net positive effect of phase B6.

Energy in operations and production stage emissions is presented as a significant share of total emissions in buildings. However, to present emissions according to ZEB-COM, one also needs to include A4 (Transport), A5 (Construction), and B4 (Replacement). Figure 13 presents the complete overview of life cycle emissions in accordance with ZEB-COM.

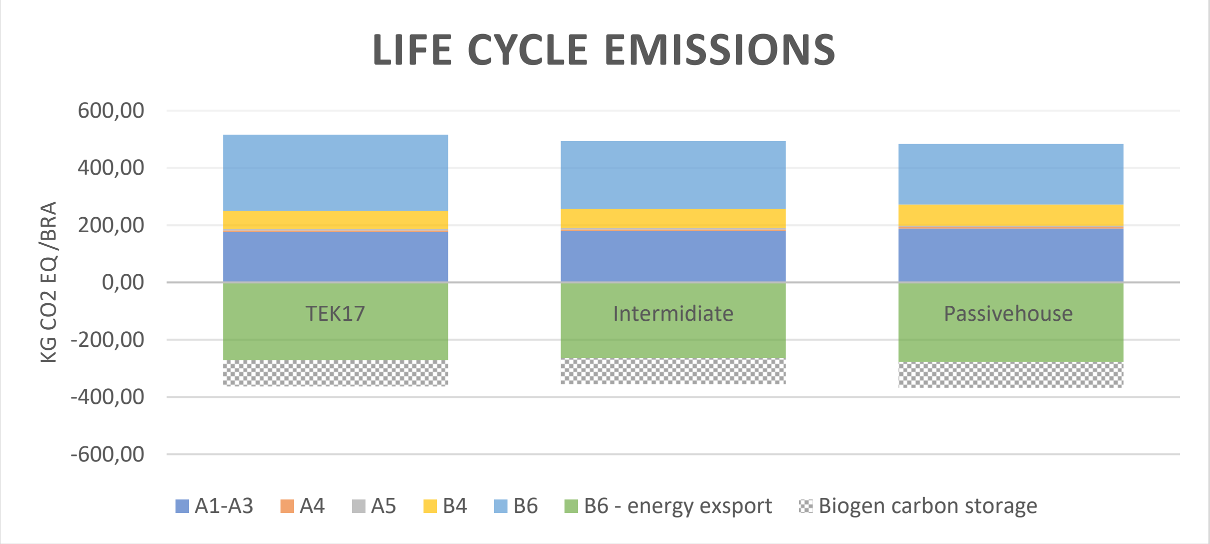


Figure 13: Life Cycle Emissions from phases A1-3, A4, A5, B4, and B6 for the three building scenarios TEK17, IM, and PH. Biogen carbon is included as additional information.

Figure X shows the emissions deriving from the building from the different life cycle phases. All scenarios show the highest emissions linked to B6 (52-44%), followed by A1-3 (34-39%) and B4 (12-15%). Phase A4 and A5 both present 1% each for all scenarios. Considering these phases, the TEK17, IM, and PH scenario presents 516.5, 493.2, and 484.1 kgCO_2eq/m^{2BRA}, respectively, presenting PH as the least emission-intensive scenario, resulting from fewer emissions linked to operational energy use. However, one also sees negative emissions linked to the building by exporting local power production and potential biogenic carbon storage. If this is included, the life cycle emissions are reduced to 153.8, 136.6, and 111.3 kgCO_2eq/m$^{2\ BRA}$ for TEK17, IM, and PH, respectively. Although the differences may seem small in **Figure X**, the Passivehouse has 24% lower emissions than TEK17 when the negative emissions are considered, which is a significant difference. Considering the scope presented by the masterplan, A1-A3, B4, B6, and energy export, the emissions are 234.9, 219.2, 197.2 kgCO_2eq/m$^{2\ BRA}$, showing that all construction scenarios are well within the stated terms of 473 GWP/BTA. If calculated per BTA, the results are also inside the terms without allocating for exported solar power with 439.1, 418.9, and 410.9 kgCO_2eq/m$^{2\ BTA}$ for TEK17, IM, and PH, respectively. A detailed overview is found in Table 9.

Table 9: Life Cycle Emissions

Life cycle emissions, kgCO_2eq/m$^{2\ BRA}$	TEK17	Intermediate	Passivehouse
A1-A3 – Production Stage	175.74	179.49	188.46
A4 - Transport	5.68	5.71	5.74
A5 - Construction	4.22	4.22	4.22
B1-B5 – Repairs and replacements	64.36	66.67	74.10
B6 – Energy use in operations	266.67	237.18	211.54
B6 - Energy export	- 271.79	- 264.10	- 276.92
Sum	**266.67**	**229.15**	**207,14**

As a measure to compare and verify the results, a simplified LCA calculation of reference buildings by OneClick LCA carbon designer was used. The calculations were performed for a Passivehouse, TEK17 building, Wood building, and Concrete building of the same nature and size as the building in this thesis and presented for ZEB-COM. It also includes a scenario with the building analyzed in this thesis without solar panels.

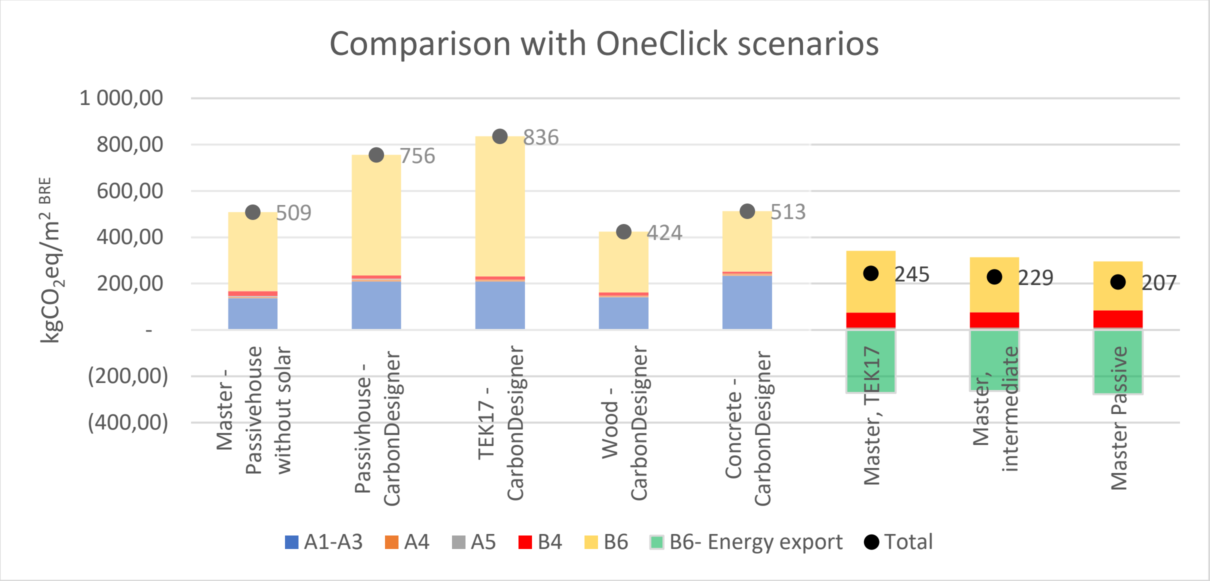


Figure 14: Comparison towards OneClick Carbon Designer design suggestions

Figure 14 shows higher emissions for all reference scenarios, mainly due to phase B6. The figure presents similar results for embodied emissions (A1-3) in the reference buildings as for the scenarios, where TEK17 and Passivehouse scenario presents 15% higher embodied emissions, Wood building 22% less, and Concrete 29% higher, compared to the average of scenarios analyzed in this thesis. The Passivehouse scenario without solar panels, replaced by standard wooden roofing, presents 24% reduced embodied emissions. The figure presents a smaller share of emissions due to replacements (B1-5), 70-90% less, mainly due to the lack of PV system, which brings us to phase B6. Due to the consumption of locally produced power, the emissions linked to operational energy use are higher for all reference scenarios. However, suppose one includes the negative emissions linked to energy export to the grid. In that case, the reference scenarios are, for most cases, more than doubled, presenting the significant effect of PV systems.

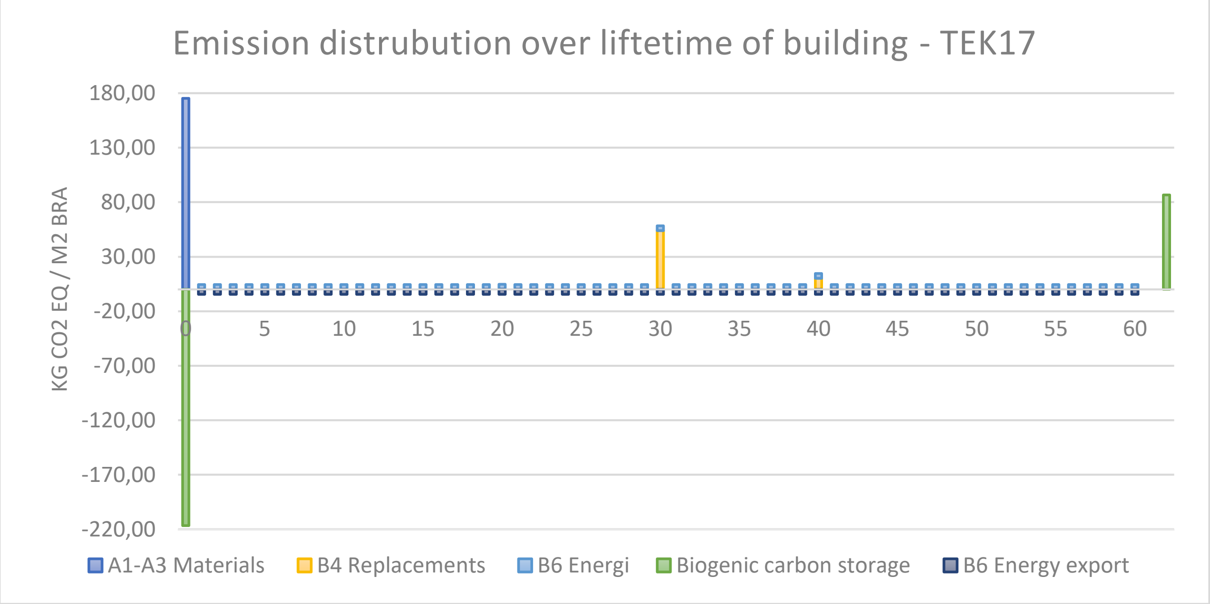


Figure 15: Timing of emissions TEK17 scenario

Figure 15 visualizes where in the lifetime of the building the emissions occur since timing might affect the impact. The analysis is only presented for TEK17, as the distribution is similar in all scenarios. The figure shows that there is an emission peak in the production stage of the project due to material production, while the following year's presents emissions are linked to energy consumption before a new peak year 30 due to the replacement of solar panels, and one after 40 years due to window replacements. The figure also presents annual negative emissions due to energy export, resulting in net negative emissions from phase B6 for all years. Furthermore, biogenic carbon storage is included, where emissions are stored in the building for the whole lifetime of the building, presenting negative emissions in the production stage before a part of it is re-emitted in the end-of-life phase.

To better understand where the emissions derive from in phases A1-3, an overview of material-specific emissions for 90% of the embodied emissions in the building is presented in Figure 16.

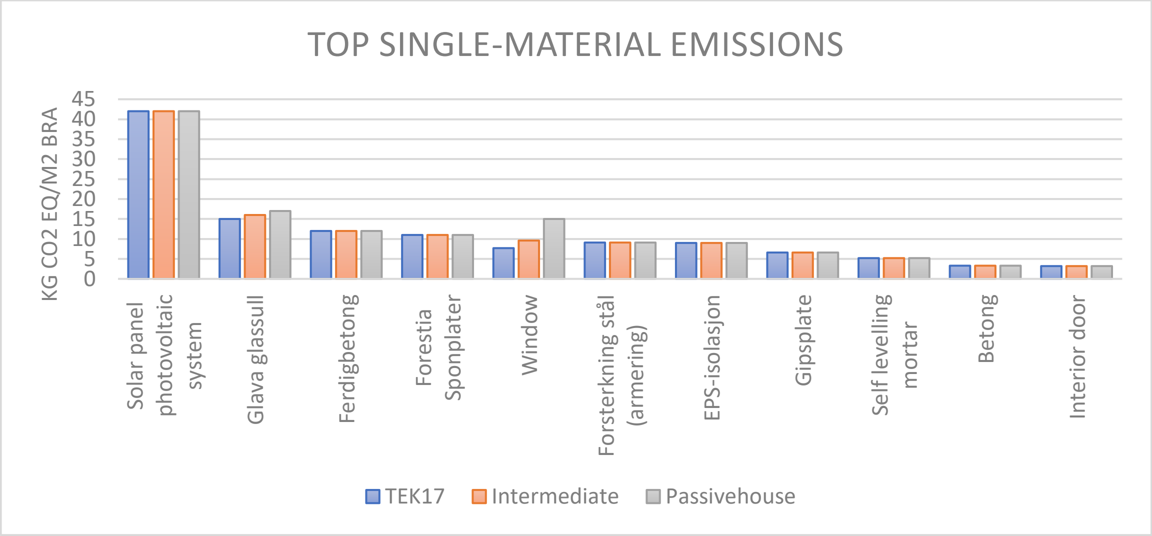


Figure 16: Top emitting materials

Considering 90% of the material-related emissions, one ends up with 11 materials, presented in Figure 16. The figure shows that most materials present the same value for all scenarios as the difference is mainly presented by wood beam thickness (not in top 11), isolation thickness, and window quality. PV system is the most prominent single contributing element, with around 30% of the embodied emissions in all scenarios. If also accounting for replacement, this value would be even higher. The second is glass wool (isolation), one of the materials of largest quantity in the building, contributing to about 10.7% (TEK17), 11.2% (IM), and 11.4% (PH) of the total emissions for the three scenarios. The biggest difference between the materials is found for windows, where the IM and PH scenario presents a 24.5% and 94.8% increase in emissions compared to TEK17.

Also, an overview of building element impact given change in impact factor is presented in Figure 17. This is only provided for materials as both the life cycle phase and scenario distribution is constant for the impact factors.

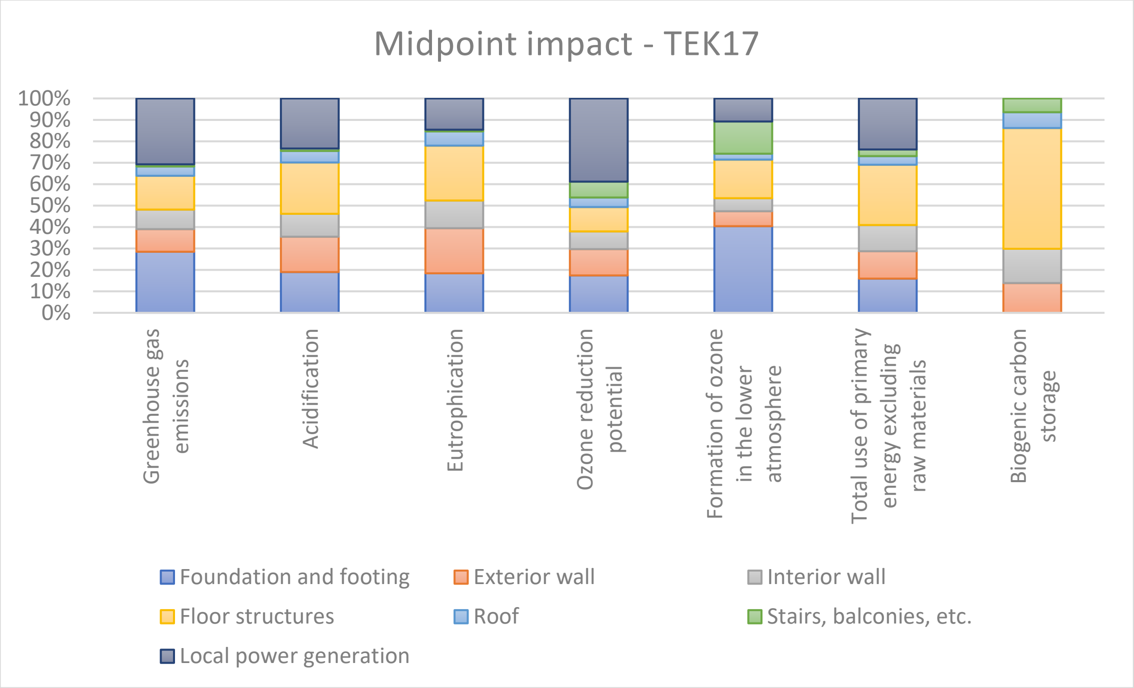


Figure 17: Normalized distribution of building element-specific impact given change in impact categories.

As the figure presents, the impact of the different elements varies significantly based on the environmental aspect one considers. For example, the foundation contributes to a large share of GHG emissions and shows an increased impact if considering ozone formation but is significantly reduced for the remaining factors. This aspect is further addressed in the discussion section of the thesis.

5.2 Costs

Section 5.3 presents the analysis of costs linked to the project to answer RQ2 – *"Do low-emission buildings correlate with increased costs from a life cycle perspective?".* The section presents an overview of initial investment costs, expenses linked to energy use, and costs deriving due to the operation of the building. Based on this, an overview of total and annual costs given a discounting factor of 2.85% is presented, as well as potential income. Also, the cost distribution and comparison of the environmental aspect are presented. The general findings are that the TEK17 is the cheapest while Passivehouse is the most expensive. However, with only a slight difference, something the following tables and graphs will present in detail.

The first table shows a cost distribution of initial costs, grouped according to NS 3453:2016, where data is gathered from Norsk Prisbok. The table shows that ~67% derive from *House cost*, where *2. Building* is responsible for ~58% of these costs and ~39% of the total. The second largest investment cost is due to *10.VAT* (19%), which is calculated based on *House cost,* meaning one could argue that the expense linked to house costs adds up to 86%. The sum of initial investments shows an increase of 1.6% for IM and 3.1% for PH compared to TEK17.

Table 10: Investment costs

Initial investment, NOK/BRA	**TEK17**	**Intermediate**	**Passive**
1. Common costs	2,541.00	2,595.50	2,650.00
2. Building	13,246.29	13,574.88	13,903.48
*3. HVAC installations**	3,716.00	3,691.00	3,666.00
4. Electrical installations	3,271.42	3,271.42	3,271.42
5. Telecom and automation	139.00	139.00	139.00
6. Other installations	0.00	0.00	0.00
SUM - House cost	22,913.71	23,271.81	23,629.90
7. Outdoor	0.00	0.00	0.00
SUM - Enterprise costs	22,913.71	23,271.81	23,629.90
8. General costs	3,014.00	3,055.00	3,096.00
SUM - Construction cost	25,927.71	26,326.81	26,725.90
9. Special costs	0.00	0.00	0.00
10. VAT	6,481.93	6,581.70	6,681.47
SUM - Basic cost	32,409.64	32,908.51	33,407.37
11. Expected additional cost	1,274.00	1,300.50	1,327.00
SUM 01-11 PROJECT COST	33,683.64	34,209.01	34,734.37
12. Provision for contingencies	318.00	325.00	332.00
SUM 01-12 COST FRAMEWORK	34,001.64	34,534.01	35,066.37

Table 10 presents the basis for investment costs linked to the project and used for calculating loans. In addition to loan downpayment and interests, there are operational costs linked to operational energy use and replacements. This is presented in Table 11, which presents the sum of operational costs over a 60-year lifetime. It presents that most expenses are linked to loan interest, while the other cost is in the range of ~2000NOK. However, energy export has negative values as it is exported and sold to the grid. The difference between the scenarios presents a slight difference considering loan and replacements with increased costs for IM and PH scenario accordingly, however, this is changed and amplified if considering energy-related costs, where TEK17 is the most expensive due to higher consumption and thereby less energy export income, resulting in overall higher operational costs by the TEK17 scenario.

Table 11: Operational costs

Total Operational Costs, NOK/BRA	**TEK17**	**Intermediate**	**Passivehouse**
Loan interest	10,175.35	10,334.67	10,493.99
Replacements	2,659.45	2,710.17	2,760.90
Energy consumption	2,337.62	1,965.69	1,670.92
Energy export	-2,006.87	-1,947.92	-2,046.31
Total	**13,165.54**	**13,062.61**	**12,879.50**

Based on both investment costs and operational costs, the total net value is presented in Table 12, backdated to today's market value. The table shows a total present value of the expenses smaller than the initial investments, even if including operational costs. This is a result of a loan interest less than price growth. The findings show 1% higher costs for the Intermediate scenario and 2% higher for the Passivehouse, compared to TEK17.

Table 12: Costs calculated for net present value

Total costs, NOK/BRA	**TEK17**	**Intermediate**	**Passivehouse**
Present value (NV)	33 883.07	34 233.58	34 545.37
Additional costs	0.00	350.50	662.30
Annual costs (ÅK)	1 184.05	1 196.29	1 207.19

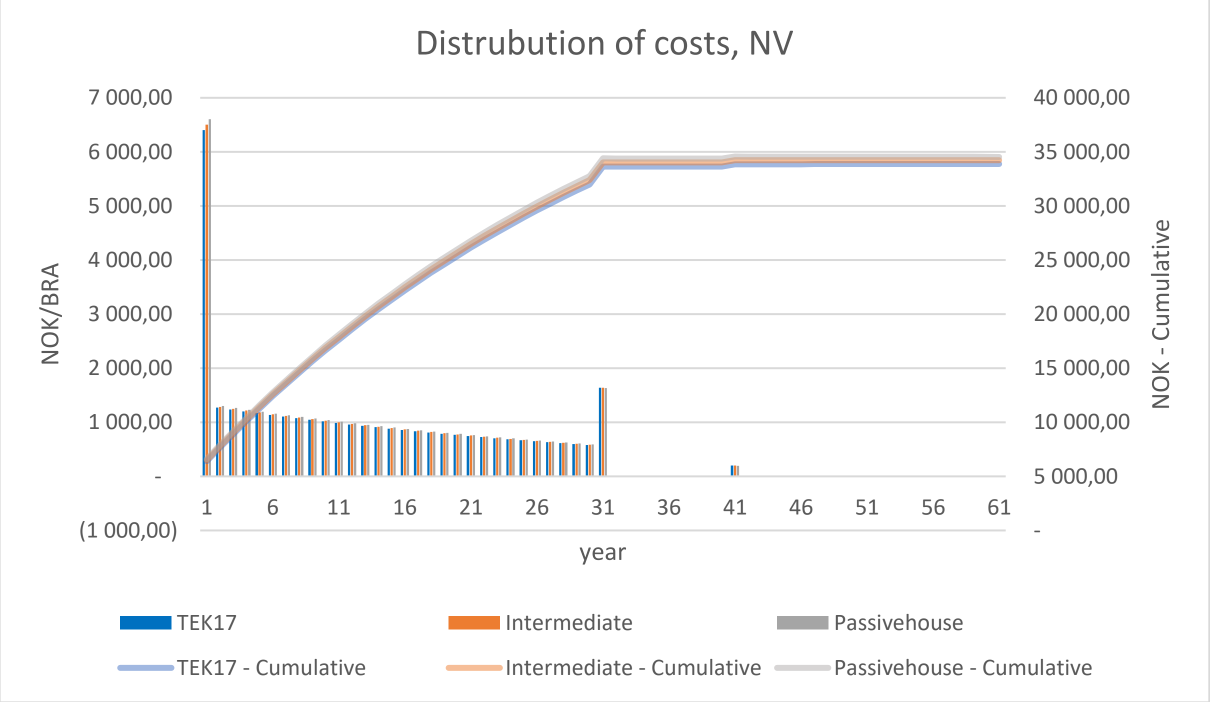


Figure 18: Distribution of costs over the lifetime of the building

Furthermore, an overview of where the cost occurs is presented in Figure 18 as present value (NV). The graph is similar to the one presented for the emissions distribution, which presents high costs linked to the initial investment and replacement. However, the cost occurring from the initial stage is distributed over the first 30 years due to downpayment and interest. The figure also presents expenses linked to loan downpayment and interest, which decrease over time due to price growth and thereby decrease the value of money. The costs linked to energy use are negligible compared to the other expenses since energy export covers most energy consumption costs.

As additional information, an overview of expected income is included in the analysis as this presents the economic sustainability of development of this nature, presented in Table 13. The table presents similar values to all scenarios as technical building regulation is assumed to have little effect on the results, however, there is a slight difference due to income taxes that also take expenses into account. The table shows a present value (NV) of more than twice the annual costs and an income from sale alone (50% of apartments) of 18 MNOK, which is almost enough to cover the initial investment.

Table 13: Theoretical income of rent and sale of apartments

Theoretical income, NOK/BRA	**TEK17**	**Intermediate**	**Passivehouse**
Present value (NV)	73,186.26	73,201.51	73,208.25
Additional costs	-	15.25	21.99
Annual costs (ÅK)	2,557.00	2,558.00	2,558.00

5.2.1 Comparison of costs and emissions

Furthermore the aspects of costs and emissions are compared for the different building scenarios to see life cycle costs and emissions change if considering more energy efficient scenarios.

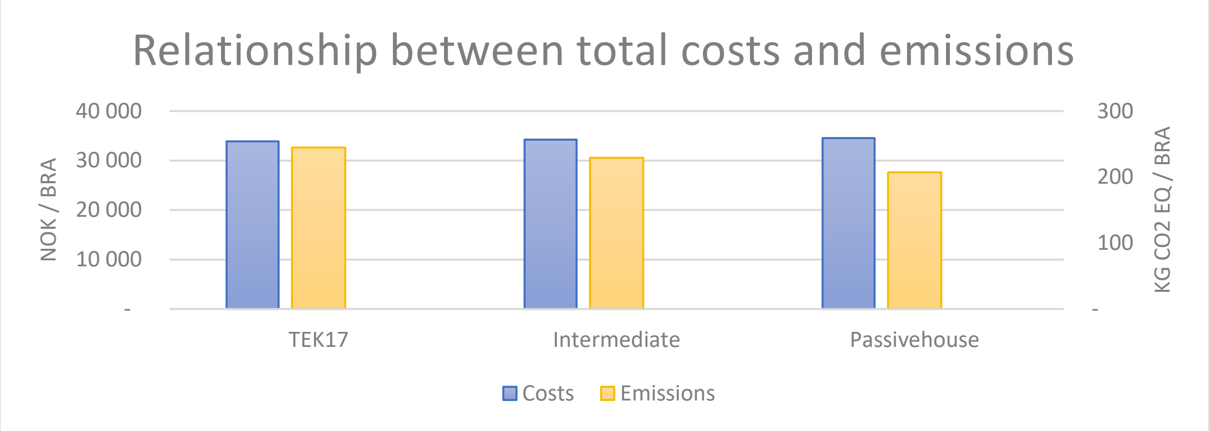


Figure 19: Comparison of life cycle costs and emissions

Considering the relationship between costs and emissions, presented in Figure 19, the TEK17 scenario is the cheapest but also most emission-intensive, while Passivehouse is on the other side of the scale. However, the rate of change is not the same between the scenarios. Compared to the TEK17 scenario, an Intermediate or Passivehouse construction would present 1.0% and 2.0% higher costs, respectively. In comparison, the emission reduction would be 6.4% and 15,4%, meaning an increase in investments would lead to a significantly higher share of emission reduction based on these results. However, if only considering costs linked to the building, the difference is +2.3% for Intermediate and +4.5% for Passivehouse, compared to TEK17, while the emissions are +2.2 and +7.3% accordingly due to higher material use in the more energy-efficient scenarios.

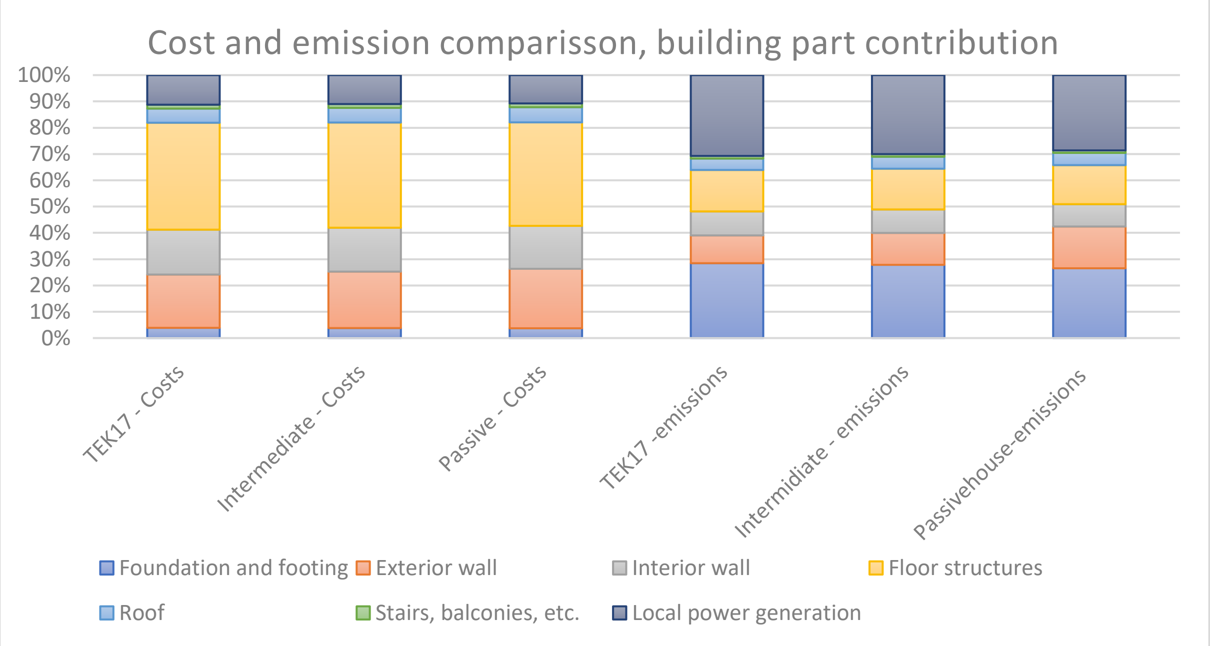


Figure 20: Normalized distribution of building element costs and emissions

Figure 20 compares the overall impact of materials on both the environment and costs. The NS 3451:2022 classification system was used to group emissions and costs, and the results showed a significant difference. Floor structures were the most expensive element, accounting for about 40% of costs but only contributing to the third largest source of emissions at around 15%. The most significant sources of emissions were from local power generation at about 30% and foundation at approximately 28%, which together made up nearly 60% of emissions. However, despite their high emission levels, foundation and local power generation were only the fourth and sixth highest expenses, representing just 4% and 11% of costs, respectively. The second and third highest costs were for exterior and interior walls, respectively, which were also ranked as the fourth and fifth largest sources of emissions.

6 Discussion

The discussion section interprets the results and connects the results to the research questions, addressing the life cycle emissions of different scenarios and the relationship between costs and emissions. It also compares the results to existing literature, highlighting this study's unique contribution and discussing how different parameters discussed in existing studies do or do not correlate with the results in this thesis. Furthermore, a critical evaluation of the findings from the results section is presented, analyzing the strengths and weaknesses of the choices made, background data, and methodologies used. The section also explores the impact of input changes, scope variations, and other factors on the results and suggests areas for further research to strengthen the analysis. Finally, recommendations are provided for specific development areas, along with general suggestions for future sector advancements. It is important to note that both LCA and LCCA offer estimates based on research, assumptions, and scope rather than absolute values.

6.1 Interpretation

This section provides an interpretation of the results presented in Section 5 and valuable insights into the life cycle emissions and costs associated with different construction scenarios of a house in the Ydalir zero-emission neighborhood in Eastern Norway. This is presented to answer the thesis research questions and offer a broader understanding of the implications of various construction approaches.

A short repetition is provided to revisit the scope of the study. The analysis compares the environmental and economic performance of buildings constructed according to current building regulations (TEK17), an energy-efficient building according to passive house standard (PH), and an intermediate scenario (IM) based on an average of the two to showcase the effect of more minor changes. Data is based on the technical plans provided by the project tender, Skanska modular building certification, and scope ZEB-COM. The analysis is only conducted for the building shell, while inventory and surface treatment are avoided. It is important to note that any changes to the inputs or assumptions may significantly impact the results, and therefore, the findings should be interpreted with caution.

6.1.1 Emission

The analysis shows that the highest source of emissions in the building scenarios is the embodied emissions occurring in phases A1-3, as the energy-related emissions are largely compensated through local production and export. The analysis shows that emissions from phase A1-3 increase by 2.2% and 7.2% for IM and PH scenarios, respectively, compared to the TEK17. Considering the total life cycle, the TEK17 is the highest emitting scenario. Variations in the energy performance of the buildings drive these changes. Thicker walls and windows with higher u-values increase emissions during production but reduce operational energy use for the lower energy scenarios. However, due to a less emission-intensive wooden structure than concrete, all scenarios have a solid foundation for low emission.

Moreover, discussing the most impactful materials and exploring less emission-intensive alternatives is essential. Figure X addresses this, presenting eleven materials resulting in 90% of the material-related emissions from phases A1-3. The PV system emerges as the primary contributor to material-related emissions during phases A1-A3 (30%) and B4. However, OneClick provides only one complete solution for a PV system, namely the *Solar Panel Photovoltaic system, Finland average* from 2013, internally verified. An updated third-party verified system or a detailed data gathering for the entire system would strengthen the study. However, as presented in LCI, the values correlate with other relevant studies on the subject and are therefore deemed adequate for this study.

The second-largest contributor in A1-3 is insulation (10.7-11.4%), which differs between the scenarios. PH, IM, and TEK17 have emissions of approximately 17, 16, and 15 tonCO2eq for the whole building, respectively, due to the use of Glava glass wool with a thermal conductivity of L=0.032 W/mK. The modular building certification prescribes insulation values ranging from 0.033 to 0,037 W/mK, suggesting that thinner walls could achieve the same u-value. However, considering the emission factors provided by the EPDs in OneClick for local general data, the emissions are 1.13, 1.07, and 1.59 kgCO2eq/m2 for insulation with thermal conductivities of 0.031, 0.032, and 0.034 W/mK respectively, favoring the 0.032 option. Nonetheless, alternative insulation materials, such as glass wool produced mainly from recycled glass, exhibit an emission intensity of 0.43 kgCO2eq/m2, 59% less than the selected option. Choosing low-emission materials can significantly impact the results, highlighting the importance of such selections (Fuglseth et al., 2020). However, as the technical standard for the building does not specify a preference for recycled-intensive materials, the study relies on general local data.

The third-largest contribution to A1-3 emissions differs among the three scenarios. For the PH scenario, windows have the greatest impact, while concrete plays a more prominent role for the IM and TEK17 scenarios. Despite the buildings being constructed with wood, concrete still significantly impacts the results due to its use in the foundation, even though low-carbon concrete is chosen. This underscores the need to limit concrete use, explore alternatives, as presented in Figure 26, and promote innovation and development in the concrete sector.

The window area remains constant across all scenarios, but different window types are chosen based on technical requirements related to heat conductivity. It is established in literature (Asdrubali et al., 2021; Pereira et al., 2021), Norsk Prisbok, and EPDs in OneClick, that lower u-values could correlate with higher emission factors and costs due to increased thickness or additional layers of glass. Due to limited options in EPDs, which primarily provide information for exact measurements or fixed frames, three different window types have been selected as potential alternatives for the various scenarios. The emissions factors for the respective windows are 113, 70, and 57 kgCO_2eq/m^2 for PH, IM, and TEK17 scenarios, respectively. It would be preferable to have one window type produced for all u-value scenarios to ensure a fair comparison, as windows exert a considerable influence on overall GHG emissions. Furthermore, existing literature indicates that there is not necessarily a linear correlation between the u-value and emissions for windows; design choices can have a more significant impact than the u-value (Lolli & Andresen, 2016). However, selecting a constant emission factor for windows across all scenarios would result in even lower life cycle emissions for the PH scenario compared to the others. Choosing windows with varying impact factors is a measure to minimize differences stemming from uncertain factors.

The calculations conducted to assess energy consumption and energy-related emissions reveal that a major portion of the energy consumption stems from direct electricity usage, including lighting, electrical appliances, and hot water, which remains relatively consistent across all scenarios. The heat pump system also contributes significantly to electricity consumption, while the remaining energy consumption is attributed to heating through district heating. It is worth noting that heating, energy consumption, and the use of heat pump systems exhibit a decline from the TEK17 to the Passive House and Intermediate scenarios due to higher energy efficiency in the buildings. Furthermore, the solar panel system employed in the studied scenarios generates negative emissions by offsetting electricity imports from the grid through local production and exports.

The solar power production results in a significant reduction in electricity import for all scenarios, where the PH scenario exhibits negative net energy consumption (- 4.4 kWh/m$^{2\ BRA}$) due to reduced heating requirements compared to the TEK17 and IM scenarios, which have annual consumption levels of 10.3 and 3.5 kWh/m$^{2\ BRA}$, respectively. However, negative values are observed across all scenarios when considering energy-related emissions. This can be attributed to the lower emission factor associated with district heating compared to electricity, underscoring the significance of emission factors in LCA calculations for all phases. These findings emphasize the importance of energy consumption and the associated emissions in the operational phase of the building's life cycle. The energy efficiency measures implemented in the Passive House scenario demonstrate the potential for reducing energy consumption and related emissions. However, it is crucial to consider the context-specific factors influencing energy use and emissions, such as local energy mix and climate conditions, when interpreting the results, something further discussed in Section 6.3 Sensitivity.

In addition to energy consumption during operation, emissions associated with replacements in operation are considered the source of about 15% of the life cycle emissions from the different scenarios due to the replacement of windows and PV system. The replacement of PV system and windows is based on the average lifespan and the assumption of the exact same product installation. However, operational energy justifies these replacements both from an environmental and cost perspective. However, this phase presents the importance of durable products, where the best solution is no need for replacements at all.

In conclusion, the results reveal that the Passivehouse scenario has the highest total embodied emissions, followed by the Intermediate and TEK17 scenarios. The primary sources of production stage emissions include elements for local power generation, foundation and footing, exterior walls, floor structures, and roof. The PH scenario shows increased embodied emissions for exterior walls, floor structures, and roofs compared to TEK17 and IM due to a more insulated structure. Operational emissions, particularly from energy consumption, also play a significant role in the total emissions of the building. However, the analysis shows that when accounting for local power production and energy export, all scenarios exhibit negative emissions, indicating a net positive effect in phase B6, where PH is presented as the best alternative due to less energy consumption. The study's findings also demonstrate that all scenarios examined in this research align with the emission reduction goals outlined in the Ydalir Masterplan. This provides support for the proposition to remove the passive house claim, as it can be achieved through the current technical building regulations. However, the passive house is still presented as the best solution from an environmental perspective.

6.1.2 Costs

Shifting the focus to costs, the analysis examines the initial investment, operational, and total costs from a life cycle perspective. The results show that the TEK17 scenario has the lowest initial investment costs, while the Passivehouse scenario is the most expensive. However, the differences between the scenarios are relatively small (1-2%). The cost distribution analysis reveals that house costs, particularly building costs, constitute the largest proportion of investment expenses. Loan interest and operational costs associated with B6 and B4 also contribute to the overall costs. Considering the total net present value of the expenses, including operational costs, the findings indicate that the expenses are smaller than the initial investments, primarily due to lower loan interest compared to price growth.

As the difference in price are only slight, small additional costs linked to either energy or taxation would level the scenarios. One example that might affect the emission-affiliated costs of the three scenarios would be carbon taxation, such as through the European Union Emission Trading System (EU ETS). The energy efficiency and lower emissions of a passive house may result in reduced compliance costs, while a baseline building with higher energy demands may face higher costs due to the need for additional emission allowances (European Commission, n.d.). Careful consideration of these factors is essential when evaluating the financial implications of energy-efficient buildings under the EU ETS framework. Considering a simplified calculation regarding the price and emission difference in the three scenarios, taxation of 22.4 NOK/kgCO_2eq would make the expenses linked to the Intermediate scenario comparable with the TEK17 scenario, while a tax rate of 17.6 NOK/kgCO_2eq would achieve comparability for the Passivehouse scenario. Another aspect that could level the price difference is the potential higher willingness to pay given the association with low-energy buildings labeled Passivehouse, which increases the market price (Bruegge et al., 2015).

The results regarding element costs and emissions present differences in top impacting elements where floors, interior- and exterior-walls together present 78% of costs but only 35-38% of the emissions. One of the reasons for this could be because materials like laminated timber, parquet flooring, sidings, and board panels are associated with high prices and relatively low emissions. Insulation is another product with high costs and is required in large volumes in various scenarios. These are all materials presented in large quantities in walls and floors and explain why these elements exhibit relatively low emissions during the production stage while their costs remain high.

Conversely, the foundation and footing primarily rely on concrete and steel, which are considerably more emission-intensive than wooden products. While these materials contribute to a significant share of emissions, they represent a lower proportion of the overall costs due to their efficiency and widespread availability. Concrete benefits from its abundant supply, and the potential for streamlined and mechanized manufacturing processes, resulting in reduced production costs. Consequently, concrete demonstrates a cost advantage over wood. This presents a potentially viable investment solution in low-carbon concrete, as concrete represents a substantial share of overall emissions while accounting for a lower proportion of costs. It is worth noting that the concrete chosen for the project already falls within the category of low-carbon concrete class A. However, as illustrated in Figure 26, there is room for further improvements.

This study differentiates between the buildings mainly by increasing the volume of isolation to conduct an overview of how minor changes might affect emissions and costs, however, other actions might be just as efficient. Materials and products have different abilities both regarding energy (storage, transmitting, isolation) and emissions, as seen for the windows, which are the only product differing from the three scenarios. The windows' pricing shows increased cost and embodied emissions given a higher u-value. This is also something that goes for other products, where transitioning into a less emission-intensive alternative would further reduce the emissions (Fuglseth et al., 2020). Extending the analysis also to cover different material alternatives would present a broader range of options for a green transition in the building sector and address what solution is most efficient from a cost and emission perspective.

In conclusion, the findings suggest that the Passivehouse scenario offers the least emission-intensive option for construction in the Ydalir zero-emission neighborhood but at the highest cost. Energy savings and local energy production is presented as significant positive influence on the emissions and costs deriving from the building, but they also have great importance regarding energy security in the transition toward a more electrified society. However, all construction scenarios analyzed in the thesis comply with the emission limits set by the Ydalir Masterplan. Nevertheless, the cost differences between the scenarios are relatively small, while the difference in emissions is higher. The results underscore the importance of balancing environmental considerations and cost implications in decision-making processes related to low-emission building construction.

6.2 Comparison with literature

Comparing the findings from LCA and LCCA studies with existing research is crucial for understanding a building's performance in terms of environmental impact and economic feasibility. Through this, valuable insights can be gained, leading to more informed decision-making in sustainable building design and management. As the findings from existing studies present significant variations due to differences in reporting, design, scope, and other parameters, a direct comparison is unfair. However, by comparison, it becomes possible to identify common trends, patterns, and areas of divergence. It is also important to note that some of the values presented are based on an average result in comprehensive literature studies, which is deemed sufficient since they conclude that the variation due to different parameters in the studies makes it hard to generalize and directly compare the results.

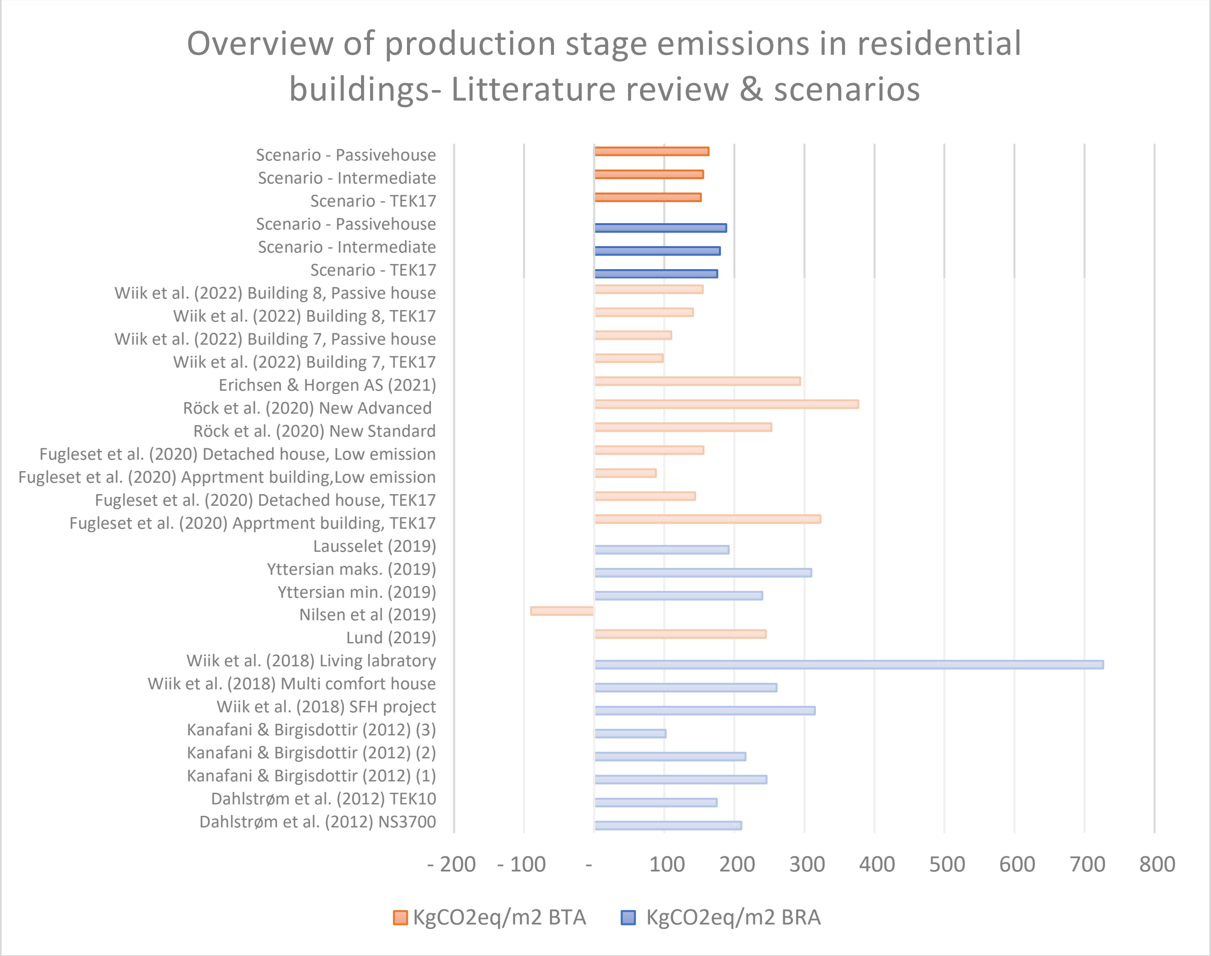


Figure 21: Overview of production stage emissions presented in the literature review compared to results in this thesis

Figure 21 compares this study's production stage GHG emissions with existing studies presented in the literature review. As discussed, the analysis makes it hard to read a common trend as the individual cases rely highly on timing, location, scope, assumptions, and design, presenting room for uncertainty. However, as the figure presents, the embodied emission from this thesis is close to, but below, the average in the presented studies. This could be expected due to the wooden structure and an early-stage inventory only including building shell and excluding surface treatment and inventory (Goverse et al., 2001; IEA, 2016). However, there are studies presenting less emissions, something which might be explained by emission-intensive solar panels. Furthermore, one only sees a slight difference between TEK17, IM, and PH, whereas other studies show a more considerable difference when comparing energy efficiency and baseline scenarios. This could be explained by this study only differentiating between thickness in outer shell and windows, but using the same products, limiting the differences. Also, the updated building regulation, TEK17, already has relatively high energy requirements (Huynh et al., 2021). There are uncertainties linked to this as the scopes and level of detail in the studies differ, however, the results from this study fall within the expected range and support the general picture of reduced emissions from phase A1-3 compared to industry standard due to less emission-intensive wooden construction, as well as increased emissions for more energy efficient buildings.

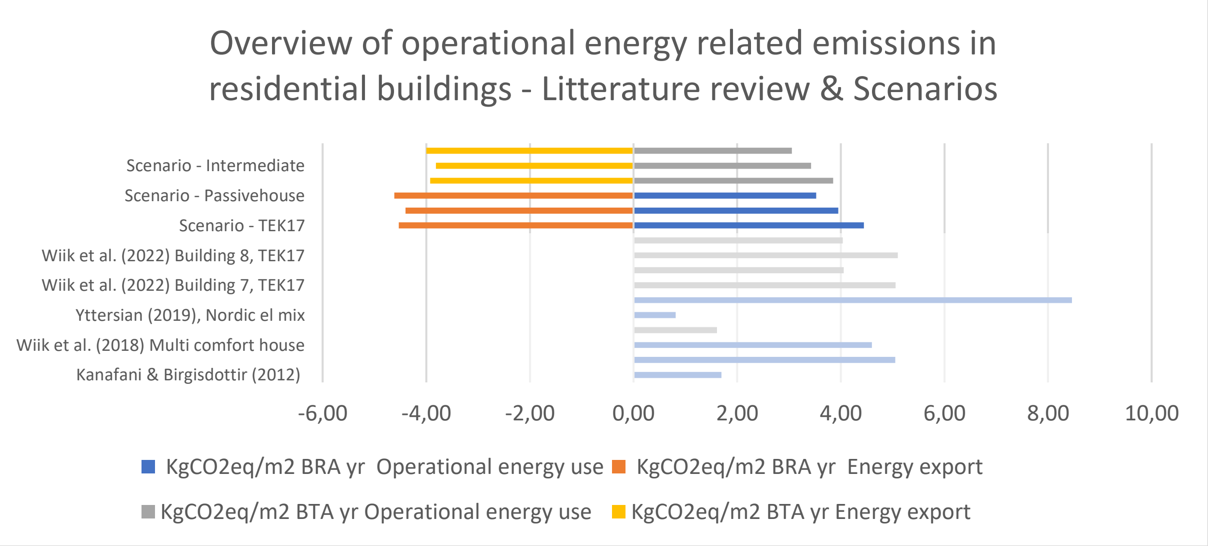


Figure 22: Overview of emissions from operational energy use presented in the literature review for Nordic studies compared to results in this thesis

In addition, this study addresses the operational emissions associated with energy use, presented in Figure 22. Considering the substantial influence of energy mix, as Yttersian (2019) demonstrated, the selection of studies is limited to those conducted in the Nordic region. The findings from this study align with the average emissions reported in the literature and support the general understanding that choosing a more energy-efficient design leads to significant emission reductions in phase B6. However, it is important to note that the results of this study also encompass emissions reductions resulting from the consumption of locally produced power. If these reductions are excluded, the emissions values would fall within the higher range. Additionally, a potential compensation is presented due to power export, emphasizing the effect of PV systems. Nevertheless, the analysis of energy-related emissions with PV system, as presented by Wiik et al. (2022), yields similar results, providing further support to the findings.

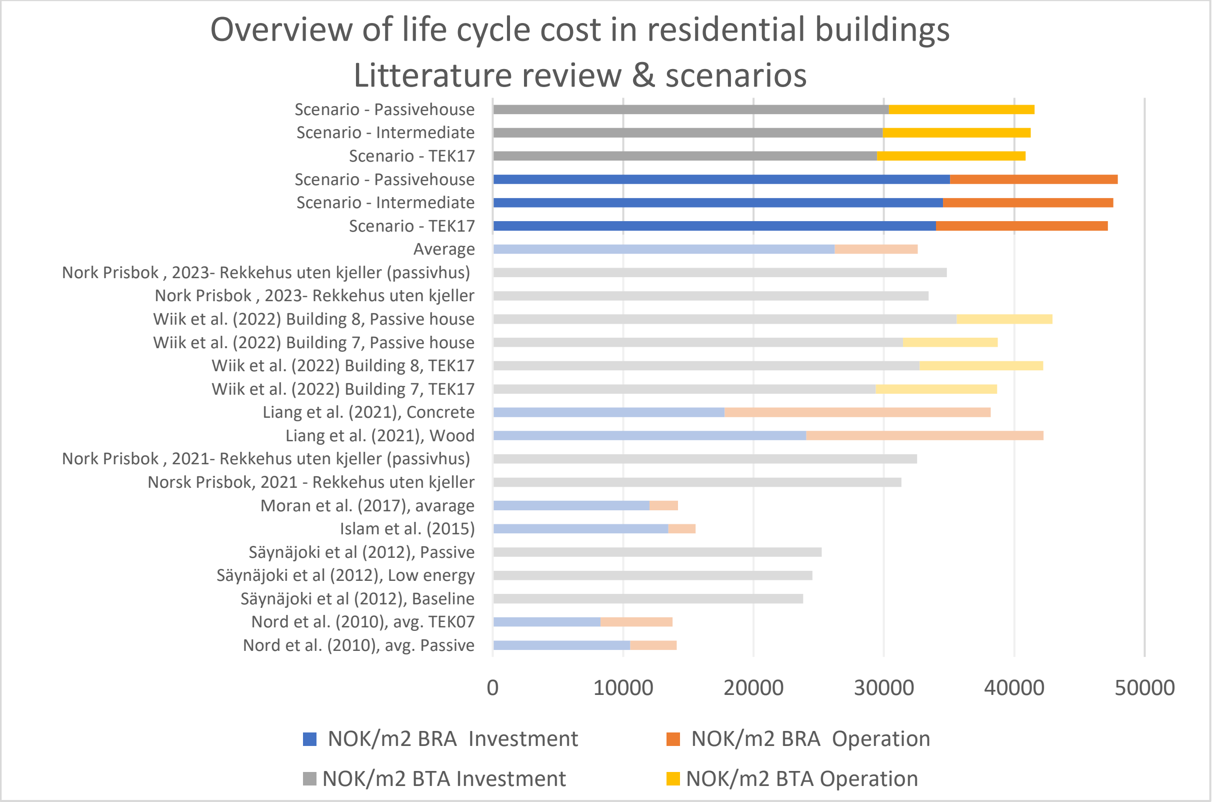


Figure 23: Overview of investment and operational costs presented in the literature review compared to results in this thesis

The cost analysis presented for previous studies (Figure 23) reflects the influence of various factors, including the year, design, and location, contributing to deviations in the results and difficulties in stating a general trend. However, one could see an increase in price over time, which could be explained by price growth in the market, however, there would need to be more data points to conclude this. When examining the investment costs, this study demonstrates costs that align with the most recent Norwegian case studies. However, the differences between the scenarios in this study are not as distinct as reported in other studies, which could be explained by only slight changes biggest cost item, the building structure. The findings also exhibit high deviations when compared to a range of other studies. Possible reasons for these deviations include older technical building regulations, price growth, or analyses conducted outside of Norway. However, even if it is difficult to identify a general trend in this regard, and the results align with the most recent and comparable study by Wiik et al. (2022) and values provided by Norwegian industry average Norsk Prisbok (2021, 2023), providing robust verification.

Regarding operational costs, the analysis reveals values that are generally higher than most studies, with the exception of Liang et al. (2021), even when considering negligible energy costs. This discrepancy may be attributed to the high replacement costs of windows and the PV system. Additionally, this study includes expenses linked to loan interest, which further contributes to the higher operational costs. It is important to note that the values presented in this study are not based on net present value (NV) calculations, where the loan costs would be significantly reduced due to price growth, resulting in overall lower operational costs.

The comparison of findings from LCA and LCCA studies with existing research provides valuable insights for sustainable building design and management. The findings support the understanding that energy-efficient solutions may initially have higher emissions and costs but demonstrate lower overall emissions during operation and the positive impact of choosing less emission-intensive materials. The study also highlights the favorable GHG investment of PV systems over their life cycle. However, it is essential to acknowledge that variations in results are influenced by factors such as timing, location, scope, and design. This complexity makes it challenging to generalize both costs and emissions within the building sector, emphasizing the need for further research on the subject and consistent, standardized, and transparent reporting.

6.3 Sensitivity

To uncover uncertainties linked to the analysis, some aspects of the input data used in the analysis are inspected in detail. This is especially important to address for energy as this is one data input presenting a significant impact on costs and emissions over the life cycle of the building.

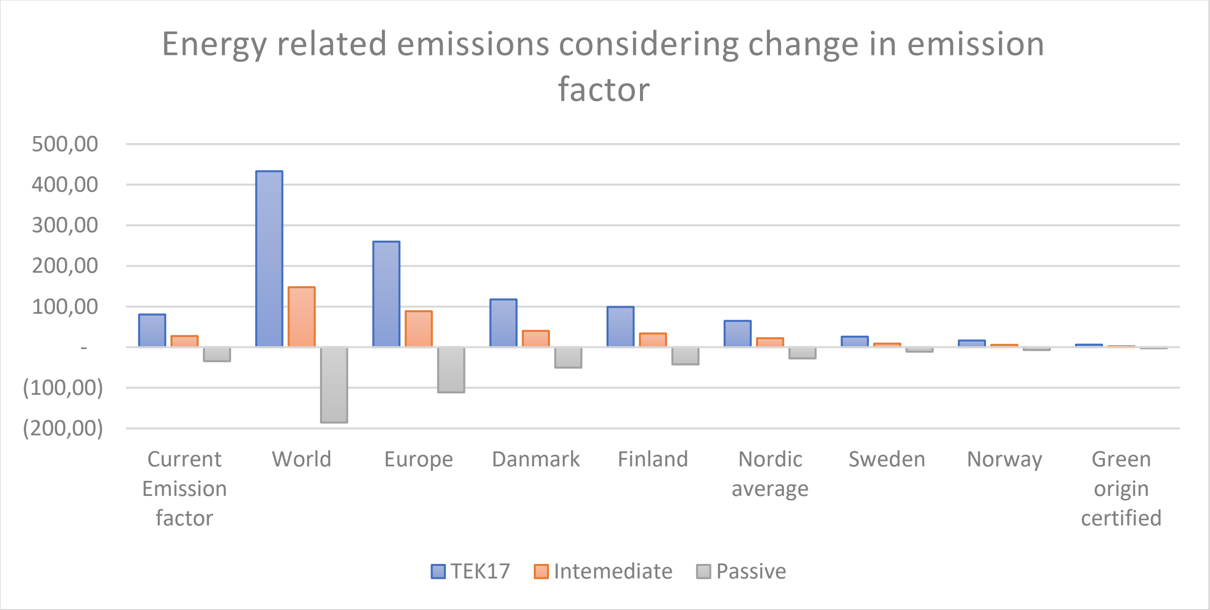


Figure 24: Comparison of energy-related emissions given a change in emissions factors

Figure 24 illustrates the total energy-related emissions from net delivered energy to the buildings over a 60-year period, given changes in the electricity mix. The figure shows that despite the PV system contributing significantly to the overall electricity consumed and exhibiting low annual net consumption, it is important to recognize that incorporating these values would have resulted in substantial changes to the results and amplified the differences between the different scenarios. As the figure presents, the emission factor heavily influences the results and increases the differences between the scenarios, where the European mix presents a difference of 285 and 618 kgCO_2eq/m$^{2\ BRA}$ for IM and PH compared to TEK17 over the lifecycle of the building, while it for Norwegian el. mix only differs 11 and 23 kgCO_2eq/m$^{2\ BRA,}$ respectively. This is if assuming all net energy use in the building is provided by electricity. This underscores the critical importance of selecting an appropriate electricity mix for accurate calculations, as emphasized by multiple sources in the literature (Dahlstrøm et al., 2012; Lund, 2019; Nord et al., 2010; Yttersian, 2019).

Electricity mix is an important and complicated aspect as Norway stands out with considerable proportion of renewable energy production, resulting in a relatively low emission factor (NVE, 2021) and production sufficient to supply most of Norway's energy consumption (SSB, 2022a, 2023e). However, it is essential to acknowledge that the Norwegian grid does not exclusively consist of electricity generated solely within Norway, primarily due to a substantial degree of import and export (IEA, 2022). Consequently, for this study, the chosen electricity mix combines sources from both the European Union (EU) and Norway, taking into account the current composition of the grid as well as incorporating a projected future development with an increased share of renewable energy sources, which provides a basis for assuming even lower emission factors in the future (Röck et al., 2020). By considering these aspects concerning the electricity mix and recognizing the dynamic nature of the energy sector, the study acknowledges the potential impact on energy-related emissions and their implications for building operations. This understanding contributes to a more nuanced assessment of the environmental performance of the examined scenarios and offers valuable insights for future decision-making processes aimed at promoting sustainable and low-emission buildings.

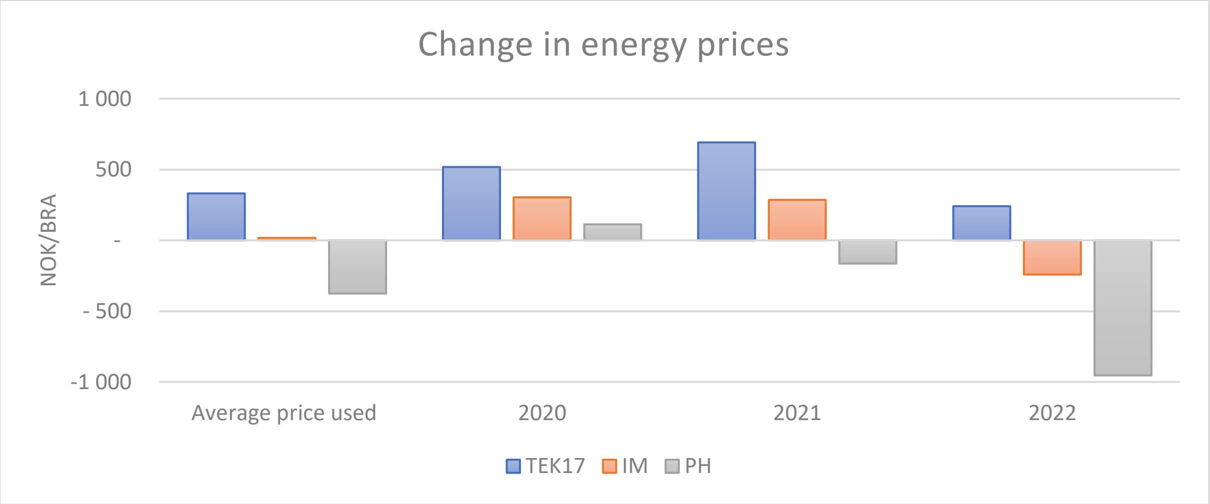


Figure 25: Energy prices given more updated prices instead of average

The change in energy prices is also an essential topic, where the data used for the LCCA is based on an average of the last three years of domestic heating and electricity prices. Figure 25 presents energy prices if considering the yearly average instead of the three-year average. The graph shows significant variations for the different years, mainly due to energy price fluctuations. The prices are not considerable compared to the overall costs, as much of the expenses are offset by local production. However, it helps equalize the differences between the scenarios, where a higher energy price is shown to benefit a low-energy building due to less energy consumption and higher energy export.

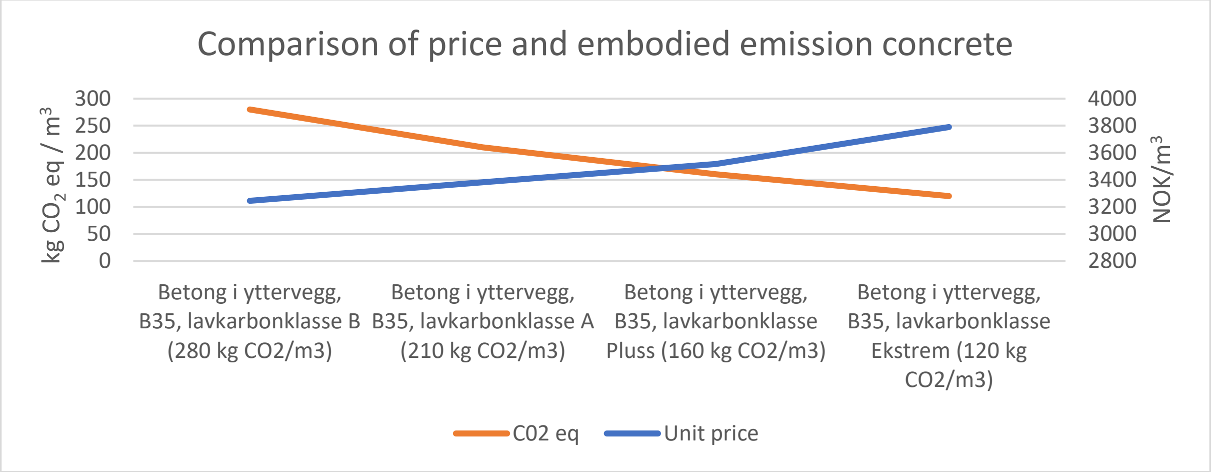


Figure 26: A comparison of costs and emissions of different concrete types, based on data gathered from Norsk Prisbok (Norconsult Digital AS, 2023).

Another aspect to address is the material choice, where a range of products of the same quality has less emission-intensive alternatives. Figure 26 presents this for concrete, where price and emission factors are gathered from Norsk Prisbok (Norconsult Digital AS, 2023). The figure shows that the emissions intensity of different concrete categories is strongly correlated with price. However, concrete makes out a greater fraction of the total regarding emissions than for costs, where additional investment in less emission-intensive concrete would therefore present a higher effect on emissions than costs. Less emission-intensive materials are available for many building elements and should be considered in new construction. The figure shows an average change in emission intensity of 33% between the products, which would considerably affect the overall material-related emissions.

A sensitivity analysis was conducted in OneClick to verify the findings, presented in Appendix 12, revealing that most material quantities align with the threshold values presented in OneClick. However, some deviations were observed, particularly in the amount of insulation, which exceeds the average value of 1-21 kg/m^3. Passive houses have a value of 31.6 kg/m^3, while TEK17 stands at 28.0 kg/m^3. This discrepancy can be attributed to the insulation requirements imposed by TEK17 and Passive House standards and a significant wall area. One potential opportunity to reduce this deviation would be to decrease the amount of insulation in interior load-bearing and lightweight walls, however, this would be constant for all scenarios.

Another material that deviates from expectations is gypsum board mass, measuring 48 kg/m3 for all scenarios, just outside the threshold range of 3-40 kg/m^3. The preference for gypsum boards as interior surfaces instead of alternatives like chipboard contributes to this deviation. Although this choice may impact the results, the effect is considered minor, given the emission factors of 2.45 and 2.19 kgCO2eq/m^2 for chipboard and gypsum board with a thickness of 12.5mm, respectively, however, if also accounting for biogenic carbon storage this might affect the result further. The remaining materials fall within the presented threshold values.

6.4 Limitations

One limitation or simplification of the analysis is considering the size of the building. The calculations are based on the same BRA (net floor area) for all buildings while maintaining the same BTA (gross floor area). This introduces a weakness to the study as the Passivehouse scenario has thicker outer walls, resulting in a larger BTA or a decreased BRA than the other scenarios. Consequently, land use and foundation requirements could be affected. Since the foundation has a high emission factor, an increased amount of foundation could significantly influence the results, where a 5% increase in the amount of foundation leads to a 1% increase in the total production stage emissions. The additional material required for thicker walls may also impact the weight and, consequently, the foundation (Goverse et al., 2001). However, as the mass density of the affected materials (wood and glass wool) is considered low from an industry perspective, the weight change is assumed to be negligible (Liang et al., 2020). Furthermore, since only the outer walls, roof, and floor-to-ground thickness are affected, the impact on floor area is deemed insignificant, justifying the use of a constant area for the different scenarios.

The results obtained from the LCA also shed light on the significant contribution of operational activities, particularly energy use, to the overall emissions of the studied building. However, it is important to acknowledge that these findings are based on a theoretical approach, as energy consumption is influenced by various external factors such as temperature variations, weather conditions, as well as personal preferences and habits (Yu et al., 2022). Additionally, determining precise values for heat storage properties and thermal conductivity requires extensive expertise and more accurate calculations (Mahmoodzadeh et al., 2021). Given the uncertainty in this area, a rough estimation based on NS3700:2013 for Passive Houses, SN-NSPEK3031:2021 for TEK17, and energy properties presented for Skanska modular buildings TG2174 is considered adequate for the purposes of this study.

In addition to energy consumption during operation, emissions associated with replacements in operation are considered the source of about 15% of the life cycle emissions from the different scenarios. Replacements encompass both regular and irregular instances resulting from wear and tear. These can typically include membranes or structural fixtures, extending beyond the elements considered in this study, windows and PV systems. However, this is shown to have little influence on the results and thereby excluded. The replacement of PV systems and windows is based on the average lifespan and the assumption of the exact same product installation. However, this assumption may be flawed as the actual lifespan could deviate from the general average, and the product itself might undergo changes in terms of quality, performance, cost, and emissions over time. Another aspect worth considering is whether the entire element needs replacement. For instance, in the case of a solar panel system comprising multiple components with varying lifespans, it may be feasible to retain the wiring while replacing the panel and inverter, factors that might reduce the stated emissions.

There are also some general limitations to the analysis. The Life Cycle Assessment methodology lacks a standardized approach, leading to variations in individual choices, assumptions, and software used for data collection and analysis (Röck et al., 2020; Säynäjoki et al., 2017; Schneider-Marin et al., 2022). Standardizing the process could simplify comparisons and improve reliability (Schneider-Marin et al., 2022). However, as both LCA and LCCA are conducted on various aspects, finding a general solution that fits all scenarios is challenging (Cole, 2009). Furthermore, the complexity of LCA requires a good understanding of the topic, making it time-consuming and challenging to conduct and for decision-makers to interpret the results if not conducted transparently (Zamagni et al., 2008). There are efforts to simplify the process through software and Environmental Product Declarations. However, this might have limitations as it might hide background processes, making it easy to overlook important parameters (Tozan et al., 2022).

Additionally, differences in datasets and software introduce potential errors, where fixed metrics and updated values would be preferable. However, finding one optimized solution for all aspects is difficult, especially since research and knowledge on the topic are constantly updated (Lueddeckens et al., 2020; McManus & Taylor, 2015). The analysis is also heavily reliant on scope and assumptions, where changes could alter the entire outcome (Hoffman et al., 1997). The study's scope, which excludes end-of-life emissions and repairs, limits its analysis, where all phases should be included to address the life cycle performance, however, this measure reduces uncertainty (Roberts et al., 2023). Another example of this could be considering external processes like transportation emissions during the operation phase, something presenting significant emissions (Lausselet et al., 2019; Lund, 2019; Yttersian, 2019), however, as the analysis aims to compare construction scenarios, this would be a factor constant for all scenarios. Despite these limitations, the study utilizes third-party verified EPDs, standardized LCA software, and multiple standards for documenting and analysis, providing a credible basis for analysis.

Another factor not discussed in this paper is the timing of emissions. Early emissions peaks may result in cumulative emissions surpassing global emission strategies, while a solution with lower emissions in the initial phase may exceed thresholds at a later stage. Additionally, early-phase emissions might trigger feedback mechanisms at an earlier stage, potentially amplifying their effect on global warming (Röck et al., 2020). Although this aspect is purely theoretical and falls outside the scope of this paper, it should be considered for future research and analysis.

An aspect that could alter the results and strengthen the study is the consideration of additional impact factors. This study analyzes GHG emissions, which are crucial environmental impacts to address regarding GWP, as outlined in the introduction (IPCC, 2022c). However, exploring other impact factors is valuable, as they may significantly influence specific environmental aspects and potentially alter the distribution of impacts among different elements, as presented in Figure 17, where results are presented for different midpoint indicators. Including multiple impact factors is something essential to address the overall sustainability of a project and could provide a more comprehensive understanding of the environmental impacts associated (Khasreen et al., 2009). This could provide valuable insights for future development and decision-making processes.

Midpoint indicators focus on single environmental problems, for example, climate change or acidification. The alternative, endpoint indicators, show the environmental impact on three higher aggregation levels, the effect on human health, biodiversity, and resource scarcity (RIVM, 2011). The aggregation could be performed using characterization factors presented in ReCiPe 2016 v1.1. (Huijbregts et al., 2017). However, it is important to note that the endpoint approach can lead to high modeling and parameter uncertainties compared with the midpoint approach (Karaman Öztaş, 2018). This is outside of the scope of the study, but important to consider as a sustainable solution should comply with acceptable impact levels for all these factors. Another possibility to address the overall sustainability of the project could be by presenting a sustainability index factor, as presented by (Moran et al., 2017), where social concerns regarding economics and the environment due to emissions and energy use, are gathered to make a complete assessment of the sustainability of the building.

Biogenic carbon storage is another factor presented as an individual impact factor of this thesis. Biogenic carbon storage assumes that carbon harvested (wood) is offset by a similar amount of carbon that is regrown (threes), resulting in a reduction in the impact on the greenhouse gas balance in the forest. Since the carbon is not emitted but stored at the same time as new carbon is harvested by new growth as a part of the natural carbon cycle, this results in negative emissions (Head et al., 2021). This is not included in the results but presented as additional information. If this were to be added, a wider wooden structure, like the Passivehouse scenario, might present better environmental performance due to more carbon storage. However, only a simplified analysis is presented in this thesis.

Regarding the cost analysis in the project, the LCCA is presented with the same scope as the LCA and is limited to this. The data collection for the LCCA is based on the inventory created for the LCA, where similar products presenting general market prices are collected from Norsk Prisbok. This means that assumptions, limitations, and possible errors presented for the LCA also would occur for the LCCA. However, this also presents a strengthened comparison of the two factors. It is important to note that prices are provided for generall marked prices, not product-specific EPDs as for the LCA. Furthermore, the cost analysis also incorporates costs linked to the developer's expenses managing and administrating the project and taxes, factors not included in the LCA.

An aspect of the cost-emission comparison in this study is that the analysis and data collection are conducted separately, whereas an analysis using consistent data and software would strengthen the comparison. This approach is recommended in the literature as it allows for a comprehensive examination of trends and disparities (Schneider-Marin et al., 2022). However, this has been utilized when examining energy-related costs and emissions. In this case, the Simien energy calculation tool analyzes both factors by considering average market prices from Statistics Norway and emissions factors from EPD Norge for electricity and district heating. By employing this tool, the analysis presents the costs and emissions associated with various building scenarios. However, it is worth noting that the energy calculations, like any other estimates, are subject to some degree of uncertainty.

There are also limitations linked to the energy analysis. One limitation in the context of energy assumptions is that surplus energy generated by a PV system is assumed to be exported consistently at a fixed price and emission factor, using average market values. This assumption may pose a weakness as it fails to account for discrepancies between energy production and consumption, which can vary on a daily and seasonal basis (Hammarström, 2012). This issue is illustrated in Appendix 10. Solar power is primarily generated during daylight hours, with peak production occurring around midday on clear summer days. However, it is worth noting that during this time, electricity prices tend to be lower, which means that there is a potential for selling solar power at a lower price and buying energy from the grid at a higher price when solar production is not available, assuming no battery solution is in place (Zheng et al., 2021). For the purposes of this study, average pricing is considered adequate. Nevertheless, conducting additional analysis on a seasonal and daily basis, examining the relationship between price and production/export, could enhance the study's accuracy. It should be acknowledged that issues related to the local grid's capacity to accommodate locally generated power have been reported (Birkeland et al., 2019; Blaker, 2023). However, it is assumed that future developments, grid improvements, and the implementation of battery solutions will resolve this issue, making it only a temporary concern.

Similar considerations apply to emission factors, as there is often a greater production of hydropower and wind power, which are the primary sources of electricity in Norway (NVE, 2021), during periods when solar conditions are less favorable. Consequently, emission factors can fluctuate periodically (Miller et al., 2022). This drawback underscores the limitations of relying solely on average calculations. However, it also highlights the importance of solar cells, as they demonstrate high production levels when reservoirs and rivers have low water accumulation and when wind turbines are stationary, making it complementary technologies (Gerlach et al., 2011). This aspect is crucial for facilitating the transition towards a more electrified society.

6.5 Further studies

It is important to acknowledge that the scope of this research is limited, and there remains room for further research. This section outlines potential areas of further study that can build upon the findings and contribute to the broader understanding of how different aspects of the building sector affiliate with costs and emissions. By exploring these directions, future researchers can discover new solutions, address existing gaps, and enhance the existing knowledge base.

Firstly, it is important to consider extending the scope of analysis to include more life cycle stages. This could involve incorporating additional stages such as raw material extraction, manufacturing, transportation, use phase, and end-of-life scenarios. Considering the entire life cycle of buildings, a more comprehensive understanding of their environmental impacts and costs can be obtained (Hoffman et al., 1997). Furthermore, aggregating the results to endpoint indicators, such as damage to human health or damage to ecosystems, can facilitate easier interpretation and comparison of the overall sustainability performance (Bare et al., 2012).

Another important aspect to explore is the integration of social aspects into the assessment. While this thesis primarily focuses on the environmental and economic aspects, it is crucial to recognize the significance of social factors in sustainable building design and operation. For example, incorporating indicators related to occupant health and well-being, user comfort, community engagement, and social equity can provide a more holistic evaluation of the sustainability performance of buildings (Moran et al., 2017; Valdes-Vasquez & Klotz, 2013).

Incorporating and discussing new technologies also present an avenue for further research. Investigating the potential of emerging technologies, such as renewable energy systems, energy-efficient materials, smart building automation, or building-integrated technologies, can shed light on their effectiveness in reducing environmental impacts and life cycle costs (Fuglseth et al., 2020; Sintef & NTNU, 2021). Furthermore, assessing the impact of integrating these technologies with LCA and LCCA will contribute to the practical implementation of sustainable building practices.

To enhance the robustness of the analysis, conducting more iterations and detailed assessments is recommended. For example, exploring various parameters, assumptions, and data inputs can capture a broader range of scenarios and uncertainties, resulting in more accurate and reliable findings (Heijungs, 1996). Additionally, conducting more detailed analyses within specific life cycle stages or impact categories can provide deeper insights into the environmental and cost implications associated with building materials, construction methods, and energy systems (Thonemann et al., 2020).

Furthermore, including more scenarios and material alternatives in the assessment is important. Evaluating different building designs, construction methods, and material choices can help identify more sustainable options for building projects (IEA, 2016; Röck et al., 2020). This will provide valuable insights for decision-makers and support sustainable building practices.

Another area is accounting for seasonal and daily variations in emissions factors and pricing. Building energy consumption, emissions, and costs can vary depending on weather conditions, occupancy patterns, and time of day (Hammarström, 2012; Miller et al., 2022; Zheng et al., 2021). Adjusting the analysis to incorporate these variations will result in a more realistic representation of buildings' environmental impacts and life cycle costs.

To ensure the reliability and consistency of the analysis, it is recommended to compare the results with those obtained from different datasets and software tools. This comparison will help validate the findings and assess the robustness of the methodology used (Yttersian, 2019). Additionally, using the same datasets and software for both LCA and LCCA assessments will ensure consistency and comparability between the environmental and economic analyses (Schneider-Marin et al., 2022).

By addressing these areas for further study, future research can contribute to advancing LCA and LCCA methodologies in the context of building sustainability.

6.6 Recommendations

The findings of this study underscore the critical role of material choice in minimizing life cycle emissions within the building industry. It is evident that structures with a higher proportion of wood-based materials exhibit reduced emissions during the production stage, which potentially additional emission reduction by considering biogenic carbon storage. Therefore, it is recommended that the building industry focuses on utilizing low-emissions materials such as wood or recycled materials, as they significantly impact overall emissions and offer the potential for further reduction.

In addition to material selection, the study also highlights the importance of district heating and solar panels in reducing operational stage emissions. These technologies have demonstrated their effectiveness in minimizing energy-related emissions and even facilitating negative emissions when surplus solar power is exported. To optimize energy consumption and production, it is suggested that the industry considers incorporating battery solutions to address the mismatch between energy production and consumption associated with solar power generation.

Furthermore, the study reveals that slight modifications in ventilation systems, different window types, and wall thickness can initially increase GHG emissions and economic investments. However, these differences are offset during the operational phase of the building's life cycle, as energy-efficient measures prove to be more emission- and cost-effective. Although achieving greater energy efficiency may involve higher upfront costs, the subsequent reduction in operational expenses almost outweighs the initial investment. To mitigate any potential cost disparities among different scenarios, slight adjustments in energy prices or the implementation of carbon taxation can help level the playing field. Additionally, buildings designed with energy-efficient features, such as those meeting the Passivehouse standard, may attract higher sale prices and increased interest in rental options due to their associated benefits and certifications.

Moreover, the thesis briefly touches upon the subject of extending the scope to include the end-of-life phase of buildings. Implementing measures that promote the use of long-lasting products and designing for reuse can significantly reduce the environmental impact during this phase. Therefore, it is recommended that the building industry considers strategies that prioritize longevity and reuse.

From an economic perspective, the life cycle cost analysis demonstrates that the investment and annual costs associated with the analyzed scenarios align with the theoretical income projections related to sales, rental, and energy export. This indicates that the proposed strategies offer sustainable development opportunities without posing financial risks.

In conclusion, all the scenarios presented in this study showcase significant emissions reduction compared to the industry standard and align with the emission reduction goals set for the area. Therefore, it can be inferred that all the options discussed in this study provide viable solutions for further development within the building industry. However, opting for a Passivehouse design would further enhance emission reduction efforts with only a slight increase in cost, something that might be equalized by price growth in the energy sector, carbon taxation, or by increased interest due to association with an emission-friendly development, presenting Passivehouse as the best option from an environmental perspective, but potentially from the economic side too.

7 Conclusion

This master's thesis aimed to evaluate three building scenarios, TEK17, passive house, and intermediate, using Life Cycle Cost and Life Cycle Analysis. The findings of this study demonstrate that while there are slight differences in cost when considering more energy-efficient buildings, there are considerably greater differences in emission reduction, where the passive house is presented as the best option from an environmental perspective.

The research highlights the significance of selecting less emission-intensive materials, such as wood, and implementing energy-efficient measures to achieve sustainable building practices. Moreover, the study strongly advocates integrating photovoltaic (PV) systems to reduce life cycle emissions, decrease energy consumption, contribute renewable energy to the grid, and enhance energy security.

By demonstrating the potential for small additional investments in energy-efficient measures to lead to further emission reductions, this research provides a compelling argument for prioritizing sustainable building practices. It emphasizes the importance of adopting a long-term perspective that considers both immediate costs and the lifecycle environmental impact of buildings.

While this study focused on specific building scenarios, its findings, and recommendations have broader applicability. They can serve as a valuable reference for architects, engineers, policymakers, and stakeholders in future construction projects seeking to mitigate their environmental impact.

In summary, all three building scenarios examined in this research meet the criteria for emission reduction mandated by the local authorities (Elverum Vekst) and align with the Norwegian government's objective of limiting global warming to 2 degrees Celsius, as outlined in the Paris Agreement. However, further emission reductions can be achieved by making a slight additional investment in more energy-efficient solutions.

This study emphasizes the importance of considering both cost and environmental impact when making decisions regarding building scenarios. Investing in energy efficiency, utilizing sustainable materials, and integrating renewable energy systems can create healthier, more resilient, and environmentally conscious communities. In conclusion, this master's thesis underscores the potential of energy-efficient buildings, sustainable materials, and renewable energy systems to contribute significantly to emission reductions and environmental sustainability. The research serves as a call to action for stakeholders across various sectors to embrace sustainable building practices, not only to meet emission reduction targets but also to foster a more sustainable future.

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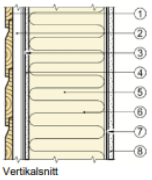
9 Appendix

Appendix 1: Building materials list for modular building (Hrnjicevic, 2021)

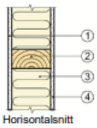
Materiale/Komponent	Spesifikasjon(Ikke spesifiserte materialdimensjoner skal være angitt i produktbeskrivelse eller i samlingen avkonstruksjonsdetaljer.)
Bærende komponenter	
Trevirke i vegger, bjelkelag og tak	- Konstruksjonstrevirke i henhold til EN 14081-1 med fasthetsklasse C24 i henhold til NS-EN 338 og fuktinnhold maks. 18 %. C18 brukes i veggelementer og bjelkelagselementer med små spenn.
	- Kerto LVL bjelker av parallellfiner i henhold til SINTEF Teknisk Godkjenning 2142.
	- Hunton I-bjelker i henhold til SINTEF Teknisk Godkjenning TG 2503.
Bygningsplater	
Undergulv	- 22 mm Forestia gulv sponplater i henhold til SINTEF Teknisk Godkjenning 2280.B11
	- Alternativt 22 mm gulvsponplater type P4 eller P6 i henhold til NS-EN 13986, formaldehydklasse E1, og med dokumentasjon for at platene tilfredsstiller kravene til undergulv som angitt i EN 12871, inkludert maks. nedbøyning 2,0 mm under 1 kN punktlast. Fuktbestandige sponplater type P5 eller P7 i våtrom.
	- Til flytende gulv brukes minst 15 mm spon- eller OSB-plater med not og fjær, .formaldehydklasse E1
Mot hulrom i skillevegger	- 9 mm Norbord Europe Ltd OSB/3 plater i henhold til NS-EN 13986, formaldehydklasse E1
Taktro	- 18 eller 22 mm Forestia gulv sponplater i henhold til SINTEF Teknisk Godkjenning 2280.
	- Alternativt 16 - 22 mm sponplater, klasse P5 eller P7 i henhold til NS-EN 13986, eller rupanel i henhold til Byggforskserien 525.861
Kledninger	
Utvendig kledning	- Min. 19 mm liggende eller stående trepanel i henhold til SN/TS 3186. Normalt leveres utvendig panel grunnet med Gori 730 industribeis.
	- Cembrit fibersementplater i henhold til SINTEF Teknisk Godkjenning 20085
Innvendig kledning	- 12 mm Forestia sponplate vegg, klasse P2 i henhold til NS-EN 13986, formaldehydklasse E1
	- 12 mm Huntonit bygningsplate i henhold til. SINTEF Teknisk Godkjenning 2038
	- 12,5 mm Norgips Standard gipsplate, type A i henhold til NS-EN 520
	- 12,5 mm Gyproc GN 13 gipsplate, type A i henhold til NS-EN 520
	- 15 mm Norgips Fireboard/Brann gipsplate, type F i henhold til NS-EN 520
	- 15 mm Gyproc Fireboard GF15 gipsplate, type F i henhold til NS-EN 520
Sperresjikt	
Vindsperre i yttervegger	- 9,5 mm Norgips Windliner-X gipsplater, type EH2 i henhold til NS-EN 520
	- SIGA Majvest vindsperre i henhold til SINTEF Teknisk Godkjenning 20131
	- Alternativt vindsperremateriale på rull i henhold til NS-EN 13859-2 med luftgjennomgangstall maks. 0,05 m^{3} /m^{2} hPa og vanndampmotstand s_{d} ≤ 0,5 m.
Kombinert undertak ogvindsperre	- Icopal Brettex i henhold til SINTEF Teknisk Godkjenning 2058
	- SIGA Majcoat i henhold til SINTEF Teknisk Godkjenning 20131
	- Alternativt andre kombinert undertak og vindsperrer med SINTEF Teknisk Godkjenning for produktet
Dampsperre	- 0,15 mm Gram Dampsperre i henhold til SINTEF Teknisk Godkjenning 2554
	- Isola AirGuard® Smart i henhold til SINTEF Teknisk Godkjenning 20321
	- Protan SE i henhold til SINTEF Teknisk Godkjenning 2010
	- Protan Takfuktsperre med vanndampmotstand s_{d} > 10 m.
Stubbloft	- Vindsperreduk i henhold til NS-EN 13859-2 med luftgjennomgangstall maks. 0,05 m^{3} /m^{2} hPa og vanndampmotstand s_{d} ≤ 0,5 m.
	- Hunton Sutak i henhold til SINTEF Teknisk Godkjenning 2344
	- 3 mm trefiberplate, type MBL.H i henhold til NS-EN 13986
	- Ranit Undertak i henhold til SINTEF Teknisk Godkjenning 2019
	- 9 mm Metsä Wood Spruce konstruksjonskryssfiner i henhold til SINTEF Teknisk Godkjenning 2059
Isolasjonsmaterialer	
Varmeisolasjon	- Glava eller Rockwool mineralull i henhold til NS-EN 13162 med deklarert varmekonduktivitet λ_{D} = 0,033 – 0,037 W/(mK).
	- Ved krav til brannmotstand benyttes steinull med romvekt ≥ 26 kg/m^{3} .
Trinnlydplater	20 mm Glava eller Rockwool trinnlydplater belagt med glassfiberduk.
Mekaniske festemidler, lim, fugemasse og tape	
Festemidler generelt	- Spiker og skruer i henhold til NS-EN 14592 med korrosjonsbeskyttelse. Forbindelsesmidler til utvendig bruk skal minimum være varmforsinket i henhold til EN ISO 1461 eller tilsvarende.
	- Lydbøyler til bjelkelag skal være i henhold til spesifikasjon fra AS Rockwool eller Glava AS.
Lim, fugemasse, fugeskum	- Motek Trelim - ute
	- Sikaflex AT-Connection fugemasse
Tape	- Wigluv i henhold til SINTEF Teknisk Godkjenning 20134
	- Corvum i henhold til SINTEF Teknisk Godkjenning 20134
Våtrom	
Fallplate	KUNZ MDF trefiberplatetype MDF.H i henhold til NS-EN 13986, formaldehydklasse E1.
Våtromsmembraner til golvog vegg	PCI Lastogum ® påstrykningsmembran i henhold til ETA-12/0578 og PCI Pecitape Tettedetaljer
Våtromsplater, vegg	16 mm Fibo Trespo Baderomspanel i henhold til SINTEF Teknisk Godkjenning 2289
Vannrør	- Uponor Tappevannsystem PEX i henhold til Teknisk Godkjenning 20013
	- JRG Sanipex rør-i-rør-system i henhold til SINTEF Teknisk Godkjenning TG 2464
Avløpsrør	Plast avløpsrør og deler fra Pipelife Norge AS i henhold til NS-EN 1451-1
Golvsluk	Purus Joti plast golvsluk, type A, L, K og KS i henhold til SINTEF Produktsertifikat 1129

Appendix 2: Building element composition (Hrnjicevic, 2021)



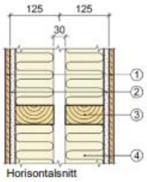
1	Dobbelfalset trekledning, 19 mm	5	Stendere, c/c 600 mm
2	23x48 mm lekter	6	Varmeisolasjon
3	Vindsperreduk	7	Dampsperre
4	Gipsplate, 9,5 mm	8	Innvendig platekledning

Fig.1
Prinsipiell utførelse av standard yttervegger med liggende utvendig kledning



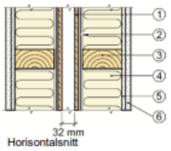
1	Innvendig platekledning	3	Isolasjon
2	Stendere, c/c 600 mm	4	Innvendig platekledning

Fig. 2
Prinsipiell oppbygning av standard innervegger



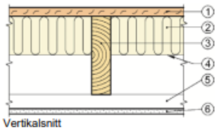
1	12 mm sponplate eller 13 mm gipsplate	3	Stendere, c/c 600 mm
2	Gipsplater, 13 mm	4	Isolasjon

Fig. 3
Prinsipiell oppbygning av standard leilighetsskillevegger med elementer.



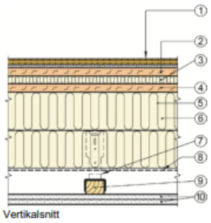
1	OSB-plate, 9 mm	4	Isolasjon
2	Vindsperreduk	5	Innvendig platekledning
3	Stender, c/c 600 mm	6	Gipsplater, 13 mm

Fig. 4
Prinsipiell oppbygning av standard skillevegg mellom ulike boenheter i modulbygg.



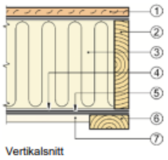
1	Sponplate, 22 mm	4	Ståltrådnett, elementer med brannmotstand REI 30
2	Isolasjon, min. 70 mm	5	Lekter, 36 mm x 48 mm, c/c 600 mm
3	Gulvbjelker, c/c 600 mm	6	Himlingsplater

Fig. 5
Prinsipiell oppbygning av standard gulvelementer til mellombjelkelag.



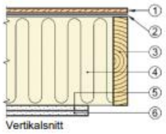
1	Parkett, 14 mm, på parkettunderlag	6	Gulvbjelker, c/c 600 mm
2	Sponplater, 22 mm	7	Lydbøyler, c/c 1200 mm
3	Trinnlyplate av mineralull, 20 mm	8	Ståltrådnett
4	Sponplater, 22 mm	9	Lekter, 36 mm x 48 mm, c/c 600 mm
5	Fullisolert med mineralull	10	Himlingsplater

Fig. 6
Prinsipiell oppbygning av standard golvelementer mellom boenheter.



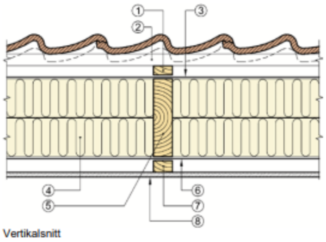
1	Sponplate, 22 mm	5	Huntonit Vindtett, 3 mm
2	Kantbjelke	6	Svill, 36 mm x 98 mm
3	Tverrbjelker og isolasjon	7	Lekter over plateskjøt, 19 mm
4	Vindsperreduk		

Fig. 7
Prinsipiell oppbygning standard golvkonstruksjon i modulbygg.



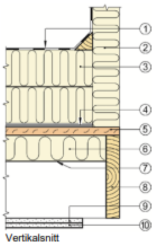
1	Sponplate, 12 mm	4	Tverrbjelker og isolasjon
2	Vindsperreduk	5	Gipsplate, 13 mm
3	Kantbjelke	6	Evt. gipsplate, 13 mm

Fig. 8
Prinsipiell oppbygning av modulenes takkonstruksjon.



1	Sløyfer	5	Takbjelke, c/c 600 mm
2	Lekter	6	Dampsperre
3	Kombinert undertak og vindsperre	7	Himlingslekter
4	Mineralull	8	Himlingsplater

Fig. 9
Prinsipiell oppbygning av standard takelementer.



1	Taktekking	6	Mineralull, maks. 70 mm
2	Parapet	7	Ståltrådnett
3	Fallisolasjon av mineralull	8	Kantbjelke
4	Dampsperre	9	Gipsplater, 13 mm
5	Sponplate,16 mm, ev. 22 mm	10	Gipsplater, 13 mm

Fig. 10
Prinsipiell oppbygning av yttertak der modulenes takkonstruksjon har redusert isolasjon og suppleres med varmeisolasjon og tekning på byggeplass

Appendix 3: LCA inventory with link to EPDs

Name	**Envrionmental data source**	**Confirmation**	**Year**	**Country**	**Database**	**EPD source**
Balkong av tre, 200 mm	One Click LCA generic construction definitions			europe	Other	
Betong	One Click LCA / Norsk betongförening publikasjon 37, Lavkarbonbetong	Verifisert internt	2019	norway	ecoinvent	
Dampsperre i plast	Gram Dampsperre, Tommen Gram Folie AS (2015)	Verifisert av tredjepart (iht ISO 14025)	2015	norway	ecoinvent	Last ned EPD
Dampsperre i plast	Gram Dampsperre, Tommen Gram Folie AS (2015)	Verifisert av tredjepart (iht ISO 14025)	2015	norway	ecoinvent	Last ned EPD
District Heat, European Union - 27	LCA study for country specific district heating based on IEA, OneClickLCA 2023	Verifisert internt	2019	europe	ecoinvent	
EPS-isolasjon	EPD Lavlambda EPS 80 isolasjon (trykklasse 80) EPS-gruppen	Verifisert av tredjepart (iht ISO 14025)	2017	norway, sweden	ecoinvent	Last ned EPD
Elektrisitet, EU28 + Norge, forventet gjennomsnitt over neste 60 år (IEA/NS3720 energimiks, projeksjon fra 2015-2017 gjennomsnitt)	LCA study for country specific electricity mixes based on NS 3720, IEA and ecoinvent 3.3, OneClickLCA 2020		2020	europe	ecoinvent	
External wood door	OneClickLCA	Verifisert internt	2011	LOCAL	ecoinvent	
Ferdigbetong, normal styrke, generisk	One Click LCA	Verifisert internt	2021	LOCAL	ecoinvent	
Fjernvarme, Elverum, Norge	LCA study for country specific district heating based on Norsk Fjernvarm fuel distribution for Elverum, OneClickLCA 2018	Verifisert internt	2017	norway	ecoinvent	
Forestia Sponplater	NEPD00274E Forestia Particleboard ECO	Verifisert av tredjepart (iht ISO 14025)	2014	norway	ecoinvent	Last ned EPD
Forsterkning stål (armering), generisk	One Click LCA	Verifisert internt	2018	LOCAL	ecoinvent	
Gipsplate	EPD Norgips Standard type A (STD) Norgips Norge AS	Verifisert av tredjepart (iht ISO 14025)	2020	norway	ecoinvent	Last ned EPD
Gipsplate, vindsperre	Norgips Windliner-X/Utvendig-X type EH2 (GU-X), Norgips Norge AS	Verifisert av tredjepart (iht ISO 14025)	2015	norway	ecoinvent	Last ned EPD
Glava glassull	EPD Glava glass wool	Verifisert av tredjepart (iht ISO 14025)	2019	norway	ecoinvent	Last ned EPD
Glava glassull	EPD Glava glass wool	Verifisert av tredjepart (iht ISO 14025)	2019	norway	ecoinvent	Last ned EPD
Gram Dampsperre	EPD Gram Dampsperre	Verifisert av tredjepart (iht ISO 14025)	2021	norway	ecoinvent	Last ned EPD
High density polyethylene single layer nonwooven (HDPE) membrane	EPD Isola Soft Xtra	Verifisert av tredjepart (iht ISO 14025)	2016	luxembourg	ecoinvent	Last ned EPD
Høvellast, bartre	Structural timber of spruce and pine, Norwegian Wood Industry Federation	Verifisert av tredjepart (iht ISO 14025)	2015	norway	ecoinvent	Last ned EPD
Interior door	EPD Climate door / interior door Nordic Dørfabrikk AS	Verifisert av tredjepart (iht ISO 14025)	2018	norway	ecoinvent	Last ned EPD
Kledning av gran og furu med grunning	EPD Kledning av gran og furu med grunning Hasås AS	Verifisert av tredjepart (iht ISO 14025)	2021	norway	ecoinvent	Last ned EPD
Konstruksjonsvirke av gran	EPD Konstruksjonsvirke av gran InnTre Kjeldstad AS	Verifisert av tredjepart (iht ISO 14025)	2021	norway	ecoinvent	Last ned EPD
Laminated veneer lumber (LVL)	Environmental product declaration, Kerto LVL, Laminated veneer lumber (Metsä Wood 2015)	Verifisert av tredjepart (iht ISO 14025)	2015	finland	GaBi	
Laminert kryssfiner, vanntett	Fibo-Trespo wall panels, Fibo-Trespo AS	Verifisert av tredjepart (iht ISO 14025)	2014	norway	ecoinvent	Last ned EPD
Multi-layer parquet flooring	EPD Mehrschichtparkett Parador GmbH	Verifisert av tredjepart (iht ISO 14025)	2017	germany	GaBi	Last ned EPD
Self levelling mortar, for floors, walls and overhead appl.	Oekobau.dat 2017-I, EPD Ausgleichsmörtel PCI Pericret für Boden, Wand und Decke PCI Augsburg GmbH	Verifisert av tredjepart (iht ISO 14025)	2016	germany	GaBi	Last ned EPD
Solar panel photovoltaic system, Finland average	One Click LCA	Verifisert internt	2013	LOCAL	ecoinvent	
Terrassebord, kledning, og høvellast for tømring	Accoya Wood - decking, cladding and planed timber for joinery applications,Scots Pine, NEPD-376-262-EN, Accsys Technologies PLC	Verifisert av tredjepart (iht ISO 14025)	2015	netherlands	ecoinvent	Last ned EPD
Toppsving vindu, tre-alu ramme	EPD Gilje Toppsving eXtra vindu Gilje Tre AS	Verifisert av tredjepart (iht ISO 14025)	2019	norway	ecoinvent	Last ned EPD
Tretak	Kebony Scots Pine Roofing,NEPD-411-288-EN, Kebony	Verifisert av tredjepart (iht ISO 14025)	2016	norway	ecoinvent	Last ned EPD
Utvendig-X typ EH2 (GU-X)	Windliner - X/Utvendig - X type EH2 (GU-X), NEPD-109-177-EN, Norgips AS	Verifisert av tredjepart (iht ISO 14025)	2015	norway	ecoinvent	Last ned EPD
Waterproof, protective, flexible coating	Oekobau.dat 2017-I, EPD Wasserdichte, flexible Schutzschicht PCI Lastogum unter Keramikbelägen in Dusche und Bad PCI Augsburg GmbH	Verifisert av tredjepart (iht ISO 14025)	2015	germany	GaBi	Last ned EPD
Innadslående toveissvingende vindu	NEPD 00176E Rev1 NorDan NTech Inward opening ECOreg	Verifisert av tredjepart (iht ISO 14025)	2014	norway	ecoinvent	Last ned EPD
Vindu, 3-lags, tre/alu-ramme, innadslående	NorDan Ntech Inward opening tilt & turn window 105/80, NorDan AS	Verifisert av tredjepart (iht ISO 14025)	2014	norway	ecoinvent	Last ned EPD

Appendix 4: LCCA Inventory

Material LCA	NOK/unit	Unit	Norsk Prisbok
Høvellast, bartre (Treindustrien) ⍰	395	m2	Bjelkelag av tre utendørs, 48 x 148 mm, c/c 600 mm, impregnerte materialer, spenn inntil 2,4 m
Terrassebord, kledning, og høvellast for tømring, 540kg/m3,	487	m2	Terrassegulv, 28 x 120 mm, royalimpregnert brun
Ferdigbetong, normal styrke, generisk, C30/37 (4400/5400 PSI.	1589	m2	Gulv på grunn, isolert, t = 100 mm + 400 mm isolasjon. 40 kg armering pr m3 betong, B30
Forsterkning stål (armering), generisk, 90% recycled content...			
Self levelling mortar, for floors, walls and overhead appl.			
EPS-isolasjon, T: 10-2400 mm, 600 x 200 mm, 0.031 W/m2K			
Dampsperre i plast, 0.2 mm (Tommen Gram)			
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Gipsplate, vindsperre, 9.5 mm (Norgips)	203	m2	Vindsperre, gipsplate, ikke vannavstøtende overflate, t = 9 mm
Multi-layer parquet flooring, 10.5 - 15mm, 7.01 kg/m2,	979	m2	Parkett, laminert, eik, lakkert overflate, t = 14 mm
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	434	m2	Isolasjon i takstoler/mellom sperrer/i bjelkelag, t = 300 mm, 0,035 W/mK
High density polyethylene single layer nonwoven (HDPE) membrane	158	m2	Dampbrems, t = 0,30 mm polypropylen med copolymer belegg
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm,	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Multi-layer parquet flooring, 10.5 - 15mm, 7.01 kg/m2,	979	m2	Parkett, laminert, eik, lakkert overflate, t = 14 mm
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	366	m2	Isolasjon i takstoler/mellom sperrer/i bjelkelag, t = 250 mm, 0,035 W/mK
Glava glassull, L = 0.032 W/mK, 20 mm, 116 kg/m3	171	m2	Mineralull under flytende gulv. Trinnlydplate med duk, t = 20 mm, 40 kPA
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	366	m2	Isolasjon i takstoler/mellom sperrer/i bjelkelag, t = 250 mm, 0,035 W/mK
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
High density polyethylene single layer nonwoven (HDPE) membrane	158	m2	Dampbrems, t = 0,30 mm polypropylen med copolymer belegg
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm,	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Forestia Sponplater 630 - 700 kg/m3, 6 – 40 mm, Standard (... ⍰	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Glava glassull, L =0.032 W/mK, 100/150/200x600x1200 mm,	196	m2	Isolasjon i innervegg, mineralull, t = 125 mm, 0,037 W/mK
Glava glassull, L =0.032 W/mK, 100/150/200x600x1200mm	196	m2	Isolasjon i innervegg, mineralull, t = 125 mm, 0,037 W/mK
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	165	m2	Isolasjon i innervegg, mineralull, t = 100 mm, 0,037 W/mK
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Waterproof, protective, flexible coating, 1.5 kg/l, Lastogum..	16414	m2	Våtrom. Prefabrikkert våtromsmodul, ca. 5 m2. Komplett inkl. RIV og RIE
Laminert kryssfiner, vanntett, 10.2 mm (Fibo Trespo)			
Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf	4115	stk	Innerdør, tre 8 x 21 M, trekarm, komplett med listverk
Forsterkning stål (armering), generisk, 90% recycled content...	1957	m	Ringmur for småhus, plasstøpt betong. Dim. b x h = 0,15 x 0,6 m. (bruker omkrets på bygg 100m)

Betong, B35 M45/MF45, lavkarbonklass A (2015 NB37)			
EPS-isolasjon, T: 10-2400 mm, 600 x 1200 mm, 0.031 W/m2K,			
Forestia Sponplater, 630 - 700 kg/m3, 6 – 40 mm, Standard	222	m2	Platekledning på innervegg, sponplate, t = 12 mm
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	464,5	m2	Isolasjon i takstoler/mellom sperrer/i bjelkelag, t = 325 mm, 0,035 W/mK
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Gram Dampsperre 0.15 mm, 0.139 kg/m2	94	m2	Dampsperre, t = 0,20 mm plastfolie
Utvendig-X typ EH2 (GU-X), 7.2 kg/m2, 9.5 mm +/-0.5 mm	203	m2	Vindsperre, gipsplate, ikke vannavstøtende overflate, t = 9 mm
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Tretak, 640kg/m3, Moisr. 12%, Scots Pine Roofing (Kebony)	451	m2	Ettlags takbelegg på utendørs konstruksjoner, rotbestandig
Gipsplate, vindsperre, 9.5 mm (Norgips)	203	m2	Vindsperre, gipsplate, ikke vannavstøtende overflate, t = 9 mm
Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm	300	m2	Isolasjon i takstoler/mellom sperrer/i bjelkelag, t = 200 mm, 0,035 W/mK
Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A	219	m2	Gipsplate, et lag på innside yttervegg, t = 13 mm
High density polyethylene single layer nonwoven (HDPE) membrane	158	m2	Dampbrems, t = 0,30 mm polypropylen med copolymer belegg
Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm	124	m2	Utlekting for vertikal trekledning, 36 x 48 mm, c/c 600 mm
Dampsperre i plast, 0.15 mm (Tommen Gram)	158	m2	Dampbrems, t = 0,30 mm polypropylen med copolymer belegg
Laminated veneer lumber (LVL) (Metsä Wood)	31312	m3	Prefabrikerte limtresøyler for massivtrebygg. Inkl. leverandørprosjektering, montasjeplater/forboring og montering
Kledning av gran og furu med grunning,	676	m2	Trekledning, tømmermannspanel, impregnert
Innadslående toveissvingende vindu,Frame/sash: 105/80 mm	5853	m2	Vinduer av tre, åpningsbare, u-verdi < 1,0
External wood door	12906	stk	Ytterdør, tre, 9 x 21 M, utadslående, enfløyet
Solar panel photovoltaic system, Finland average	4283	m2	Solenergianlegg - integrert i fasade, BIPV

Appendix 5: Material specific emissions

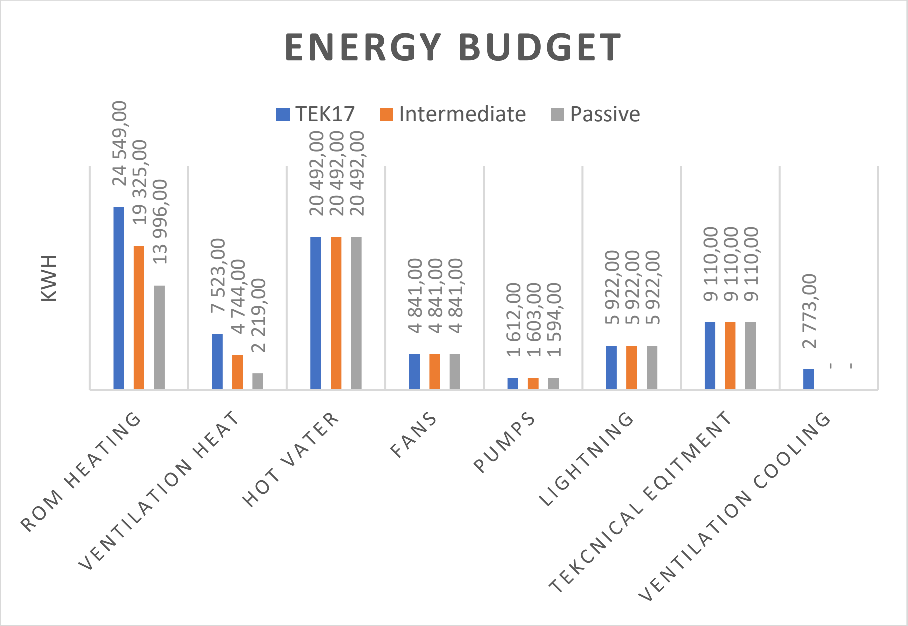
GHG emissions				
		TEK17	IM	PH
Balkong av tre, 200 mm	Høvellast, bartre (Treindustrien)	3,34E+02	3,34E+02	3,34E+02
Balkong av tre, 200 mm	Terrassebord, kledning, og høvellast for tømring, 540kg/m3, ...	1,06E+03	1,06E+03	1,06E+03
Betong grunndeck, 550 mm	Ferdigbetong, normal styrke, generisk, C30/37 (4400/5400 PSI...	1,21E+04	1,21E+04	1,21E+04
Betong grunndeck, 550 mm	Forsterkning stål (armering), generisk, 90% recycled content...	7,57E+03	7,57E+03	7,57E+03
Betong grunndeck, 550 mm	Self levelling mortar, for floors, walls and overhead appl.,...	5,20E+03	5,20E+03	5,20E+03
Betong grunndeck, 550 mm	EPS-isolasjon, T: 10-2400 mm, 600 x 1200 mm, 0.031 W/m2K, 16...	7,98E+03	7,98E+03	7,98E+03
Betong grunndeck, 550 mm	Dampsperre i plast, 0.2 mm (Tommen Gram)	1,91E+02	1,91E+02	1,91E+02
Dekke våtrom	Waterproof, protective, flexible coating, 1.5 kg/l, Lastogum...	1,91E+02	1,91E+02	1,91E+02
Dekke våtrom	Laminert kryssfiner, vanntett, 10.2 mm (Fibo Trespo)	1,05E+03	1,05E+03	1,05E+03
Dør inne	Interior door, 809x2053 mm, 42x92 mm frame, 52 mm door leaf ...	3,17E+03	3,17E+03	3,17E+03
Dør ute	External wood door	5,76E+02	5,76E+02	5,76E+02
Gulv mot grunn	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	1,94E+03	1,94E+03	1,94E+03
Gulv mot grunn	Gipsplate, vindsperre, 9.5 mm (Norgips)	8,10E+02	8,10E+02	8,10E+02
Gulv mot grunn	Multi-layer parquet flooring, 10.5 - 15mm, 7.01 kg/m2, appli...	4,00E+02	4,00E+02	4,00E+02
Gulv mot grunn	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	2,47E+03	2,57E+03	2,67E+03
Gulv mot grunn	High density polyethylene single layer nonwooven (HDPE) memb...	2,77E+01	2,77E+01	2,77E+01
Gulv mot grunn	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	2,25E+02	2,25E+02	2,25E+02
Gulv mot grunn	Laminated veneer lumber (LVL) (Metsä Wood)	2,67E+00	2,67E+00	2,67E+00
Gulv mot grunn	Laminated veneer lumber (LVL) (Metsä Wood)	3,33E+02	3,47E+02	3,60E+02
Gulv mot grunn	Laminated veneer lumber (LVL) (Metsä Wood)	3,86E+01	3,86E+01	3,86E+01
Gulv/tak etasjeskiller	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	1,94E+03	1,94E+03	1,94E+03
Gulv/tak etasjeskiller	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	1,76E+03	1,76E+03	1,76E+03
Gulv/tak etasjeskiller	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	2,07E+03	2,07E+03	2,07E+03
Gulv/tak etasjeskiller	Multi-layer parquet flooring, 10.5 - 15mm, 7.01 kg/m2, appli...	4,00E+02	4,00E+02	4,00E+02
Gulv/tak etasjeskiller	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	2,12E+03	2,12E+03	2,12E+03
Gulv/tak etasjeskiller	Glava glassull, L = 0.032 W/mK, 20 mm, 116 kg/m3, Lambda=0.0...	7,93E+02	7,93E+02	7,93E+02
Gulv/tak etasjeskiller	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	9,57E+01	9,57E+01	9,57E+01
Gulv/tak etasjeskiller	Laminated veneer lumber (LVL) (Metsä Wood)	2,98E+02	2,98E+02	2,98E+02
Innertak 2. etasje	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	1,06E+03	1,06E+03	1,06E+03

Innertak 2. etasje	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	1,99E+03	1,99E+03	1,99E+03
Innertak 2. etasje	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,02E+03	1,02E+03	1,02E+03
Innertak 2. etasje	High density polyethylene single layer nonwooven (HDPE) memb...	2,77E+01	2,77E+01	2,77E+01
Innertak 2. etasje	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	2,25E+02	2,25E+02	2,25E+02
Innertak 2. etasje	Laminated veneer lumber (LVL) (Metsä Wood)	2,68E+02	2,68E+02	2,68E+02
Bærende innervegg, lilihetsskille	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	6,26E+02	6,26E+02	6,26E+02
Bærende innervegg, lilihetsskille	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	6,26E+02	6,26E+02	6,26E+02
Bærende innervegg, lilihetsskille	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	1,19E+03	1,19E+03	1,19E+03
Bærende innervegg, lilihetsskille	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	1,19E+03	1,19E+03	1,19E+03
Bærende innervegg, lilihetsskille	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,17E+03	1,17E+03	1,17E+03
Bærende innervegg, lilihetsskille	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,17E+03	1,17E+03	1,17E+03
Bærende innervegg, lilihetsskille	Laminated veneer lumber (LVL) (Metsä Wood)	1,44E+02	1,44E+02	1,44E+02
Bærende innervegg, lilihetsskille	Laminated veneer lumber (LVL) (Metsä Wood)	1,44E+02	1,44E+02	1,44E+02
Standard innervegg, ikke bærende	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	7,88E+02	7,88E+02	7,88E+02
Standard innervegg, ikke bærende	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,03E+03	1,03E+03	1,03E+03
Standard innervegg, ikke bærende	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,03E+03	1,03E+03	1,03E+03
Standard innervegg, ikke bærende	Laminated veneer lumber (LVL) (Metsä Wood)	1,82E+02	1,82E+02	1,82E+02
Stripefundament på sand	Forsterkning stål (armering), generisk, 90% recycled content...	1,53E+03	1,53E+03	1,53E+03
Stripefundament på sand	Betong, B35 M45/MF45, lavkarbonklass A (2015 NB37)	3,30E+03	3,30E+03	3,30E+03
Stripefundament på sand	EPS-isolasjon, T: 10-2400 mm, 600 x 1200 mm, 0.031 W/m2K, 16...	1,06E+03	1,06E+03	1,06E+03
Vindu	Window	7,73E+03	9,56E+03	1,53E+04
Yttertak	Forestia Sponplater, 630 - 700 kg/m3, 6 - 40 mm, Standard (...	5,29E+02	5,29E+02	5,29E+02
Yttertak	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	2,82E+03	3,26E+03	3,69E+03
Yttertak	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	8,61E+01	8,61E+01	8,61E+01
Yttertak	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	9,57E+01	9,57E+01	9,57E+01
Yttertak	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	9,57E+01	9,57E+01	9,57E+01
Yttertak	Gram Dampsperre, 0.15 mm, 0.139 kg/m2, Gram Dampsperre	1,37E+02	1,37E+02	1,37E+02
Yttertak	Solar panel photovoltaic system, Finland average	4,20E+04	4,20E+04	4,20E+04
Yttertak	Utvendig-X typ EH2 (GU-X), 7.2 kg/m2, 9.5 mm +/-0.5 mm, Wind...	8,64E+02	8,64E+02	8,64E+02
Yttertak	Laminated veneer lumber (LVL) (Metsä Wood)	5,54E+01	6,39E+01	7,25E+01
Yttertak	Tretak, 640kg/m3, Moisr. 12%, Scots Pine Roofing (Kebony)	1,25E+03	1,25E+03	1,25E+03
Yttervegg, Bærende	Gipsplate, vindsperre, 9.5 mm (Norgips)	1,00E+03	1,00E+03	1,00E+03
Yttervegg, Bærende	Glava glassull, L = 0.032 W/mK, 100/150/200x600x1200 mm, 25 ...	2,01E+03	2,61E+03	3,11E+03
Yttervegg, Bærende	Gipsplate, 8.8 kg/m3, 12.5 mm, 704 kg/m3, Standard type A (S...	1,22E+03	1,22E+03	1,22E+03
Yttervegg, Bærende	High density polyethylene single layer nonwooven (HDPE) memb...	3,43E+01	3,43E+01	3,43E+01
Yttervegg, Bærende	Konstruksjonsvirke av gran, 38mm x 48mm-98mm x 223mm, 467.36...	8,37E+01	8,37E+01	8,37E+01
Yttervegg, Bærende	Kledning av gran og furu med grunning, 19mm, 9.78 kg/m2, ave...	1,24E+03	1,24E+03	1,24E+03
Yttervegg, Bærende	Dampsperre i plast, 0.15 mm (Tommen Gram)	1,75E+02	1,75E+02	1,75E+02
Yttervegg, Bærende	Laminated veneer lumber (LVL) (Metsä Wood)	3,62E+02	4,71E+02	5,60E+02
Total		1,37E+05	1,40E+05	1,47E+05
Total/BTA		1,75E+02	1,79E+02	1,88E+02

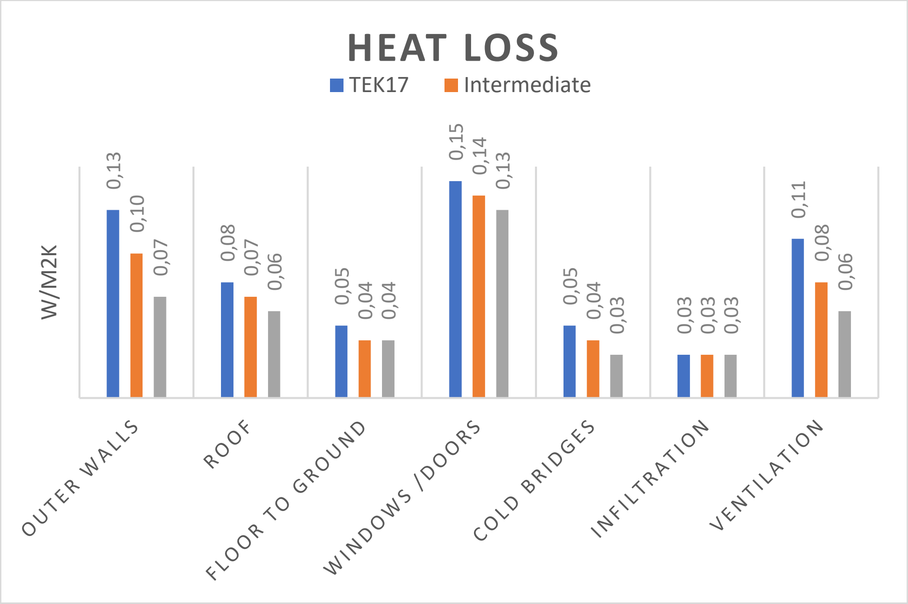
Appendix 6: Energy Analysis Results

	TEK17	Intermediate	Passive
Annual energy budget [kWh]			
Rom heating	24549,00	19235,00	13996,00
Ventilation heat	7523,00	4744,00	2219,00
Hot vater	20492,00	20492,00	20492,00
Fans	4841,00	4841,00	4841,00
Pumps	1612,00	1603,00	1594,00
Lightning	5922,00	5922,00	5922,00
Tekcnical eqitment	9110,00	9110,00	9110,00
Ventilation cooling	2773,00	0,00	0,00
Net energy demand	76822,00	65947,00	58174,00
Delivered exhaust heat pump	18288,00	16061,00	13808,00
Energy use for the operation of the extraction heat pump	6650,00	5757,00	4867,00
Total net energy demand including exhaust heat pump	65184,00	55643,00	49233,00
Heating budget (heat loss figures) [W/m2 K]			
outer walls	0,13	0,10	0,07
Roof	0,08	0,07	0,06
Floor to ground	0,05	0,04	0,04
Windows /doors	0,15	0,14	0,13
Cold bridges	0,05	0,04	0,03
Infiltration	0,03	0,03	0,03
Ventilation	0,11	0,08	0,06
Total	0,60	0,50	0,42
Delivered energy to building [kWh]			
Direct el.	21485,00	21476,00	21467,00
El. To heat pump system	14211,00	12425,00	10609,00
District heating	15046,00	10311,00	7175,00
Solar power own use	-13724,00	-13335,00	-13141,00
Total delivered energy	37018,00	30877,00	26110,00
Solar power eksport	-28975,00	-28137,00	-29557,00
Net delivered energy	8043,00	2740,00	-3447,00
Delivered energy to building [kWh]			
Direct el.	14211,00	12425,00	10609,00
El. To heat pump system	7761,00	8141,00	8326,00
District heating	15046,00	10311,00	7175,00
Annual CO2 emissions [kg CO2 eq]			
Direct el.	2793,00	2792,00	2791,00
El. To heat pump system	1847,00	1615,00	1379,00
District heating	196,00	134,00	93,00
Solar power own use	-1784,00	-1734,00	-1708,00
Total emissions	3052,00	2807,00	2555,00
Solar power export	-3767,00	-3658,00	-3842,00
Net CO2 emissions	-715,00	-851,00	-1287,00
Costs (NOK)			
Direct el.	19336,00	19387,00	19321,00
El. To heat pump system	11368,00	9940,00	8488,00
District heating	12037,00	8259,00	5740,00
Solar power own use	-12352,00	-12032,00	-11827,00
Annual energy costs	30389,00	25554,00	21722,00
Solar power eksport	-26077,00	-25323,00	-26602,00
Net energy costs	4312,00	231,00	-4880,00

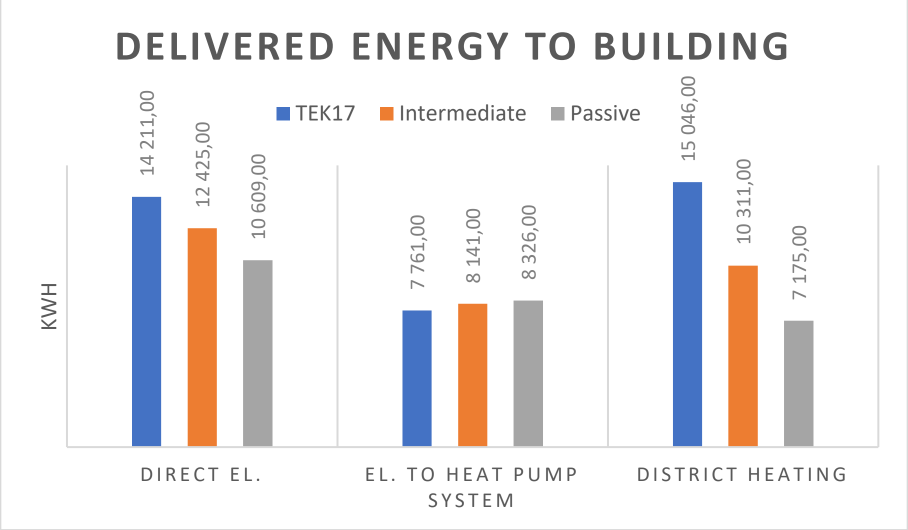
Appendix 7: Energy budget



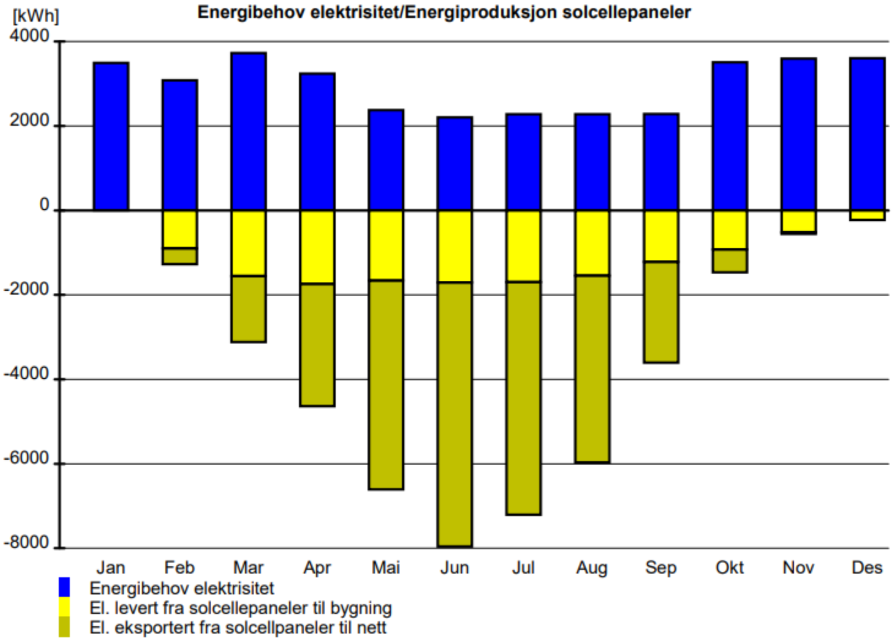
Appendix 8: Heat loss



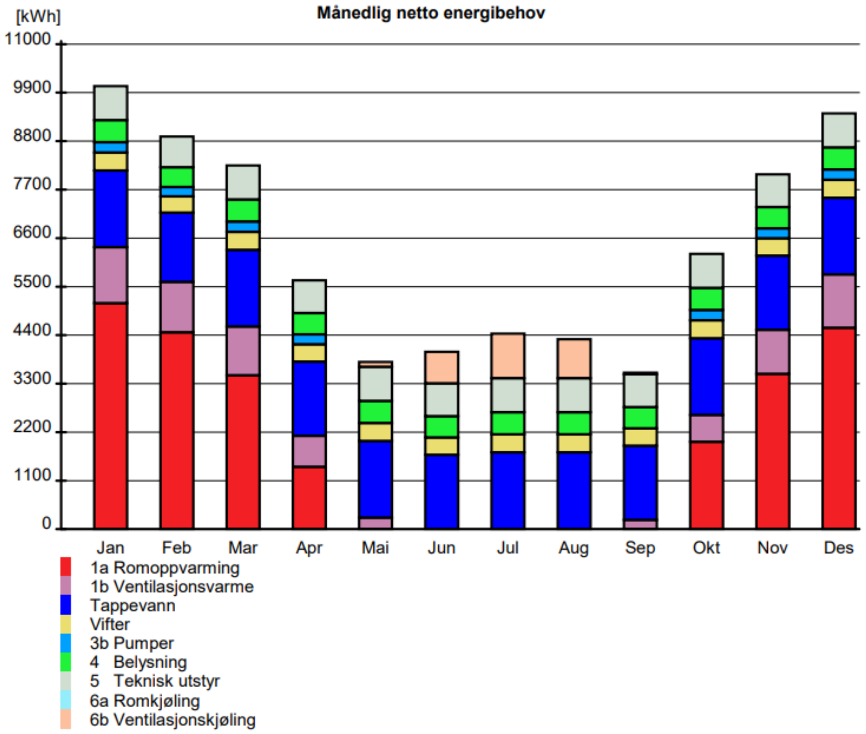
Appendix 9: Delivered energy to building



Appendix 10: Mismatch between energy production and consumption



Appendix 11: Mothly energy consumption



Appendix 12: Sensitivity analysis conducted in OneClick

Check description	Project value - TEK17	Project value - TEK17	Project value - Passive house	Threshold value	Unit
Insulation mass credible: Insulation mass is unusual	28.088	29.978	31.68	44197,00	kg/m^2
Gypsum board mass credible: Value seems unusual, but within accepted deviation range	47.929	47.929	47.929	14671,00	kg/m^2
Validerte sjekker					
Foundation mass credible	502.968	502.968	502.968	greater than 100	kg/m^2
Structure mass credible	199.996	204.953	209.253	greater than 150	kg/m^2
Finishes mass credible	23.744	23.861	29.277	greater than 10	kg/m^2
Embodied carbon credible	258.527	264.961	281.765	150 - 1000	kg CO$_2$e/m^2
Project mass credible	784.549	790.208	827.004	300 - 3500	kg/m^2
Ready mix and reinforcement ratio	4.038	4.038	4.038	45108,00	%
Too few materials to be credible	30	30	30	greater than 20	nr.
Too dominant single material	30.755	30.071	28.654	less than 50	%
Gypsum board and plaster mass credible (no cement)	64.083	64.083	64.083	0.0 - 80	kg/m^2
Glass and openings mass credible	11.461	11.578	16.993	2-25	kg/m^2
Vertical materials mass	77.613	81.154	84.076	50 - 700	kg/m^2
Horizontal materials mass	122.382	123.799	125.178	100 - 1300	kg/m^2
Mortar mass credible	16.154	16.154	16.154	0.4 - 50	kg/m^2
Brick mass credible	0.0	0.0	0.0	0.0 - 100	kg/m^2

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