LCA of screw pile foundation and lightweight constructions in single-family houses

Accommodating future CO_2-demands in the Danish Building Legislation

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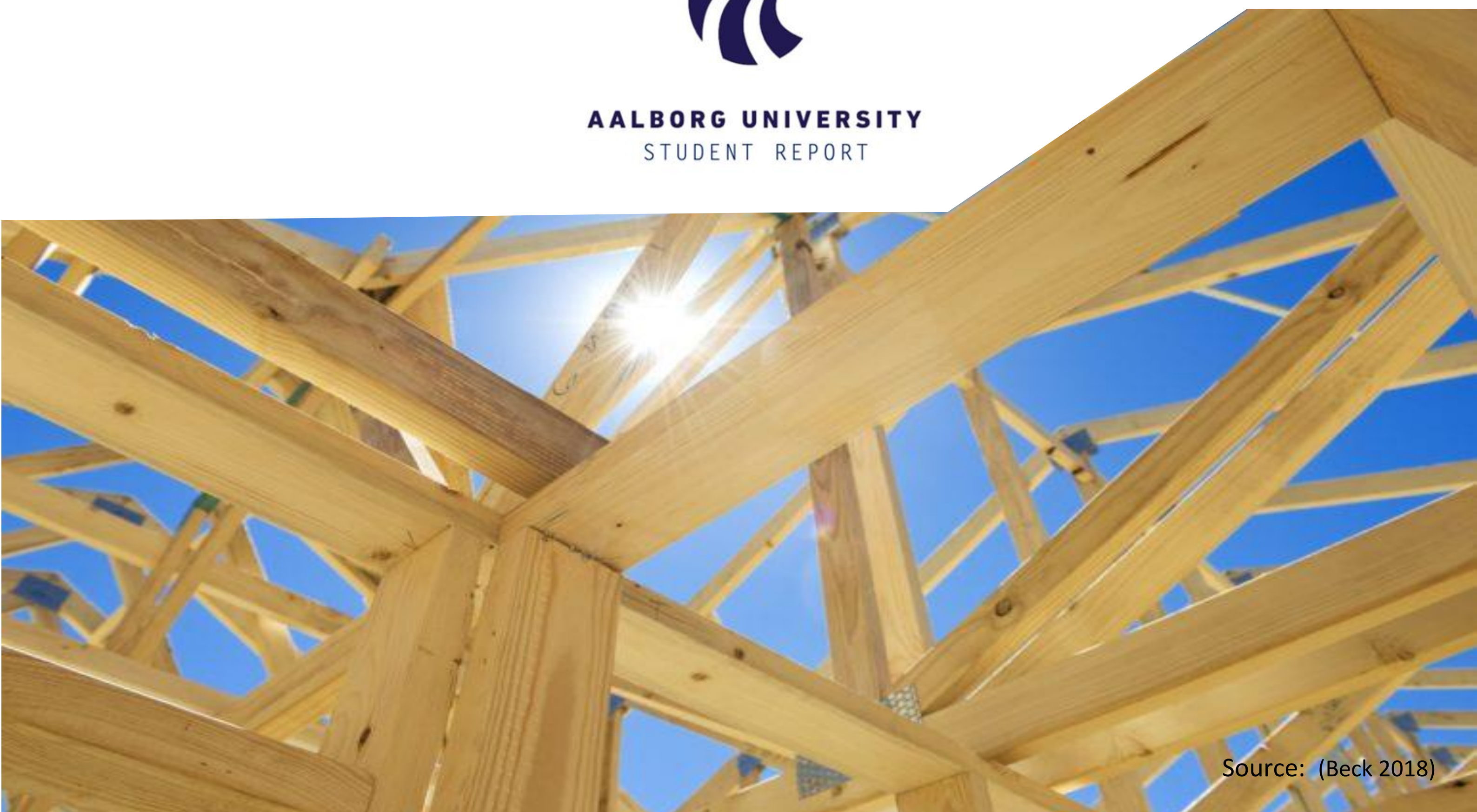
STUDENT REPORT



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Synopsis

Focus on sustainability in terms of operational energy efficiency has been relevant in recent years, but current trends are changing to focus on embodied CO_2 in building materials. Energy efficiency comes at a cost with additional insulation materials used and this project reflects on BR 18 Low Energy Class based buildings. Five different building methods are compared to Voluntary Sustainability Class threshold limit values in terms of a cradle-to-grave Life Cycle Assessment (LCA). The analysis includes rarely calculated transport and excavation processes of soil. Three single-family houses are chosen for the analysis in LCAbyg. Baseline is set as the most used building method currently, with masonry-cavity walls and concrete slab and variation of pitched and flat roofs. An indication for a substitution potential, is 90% of new built single-family houses are built with masonry façade, which can be substituted with wood-based materials. Baseline is therefore compared against defined methods with wood framed structural walls and floor deck, building methods with screw pile foundation is compared against concrete strip foundation and concrete slab. Additional building method with wood fiber insulation is analyzed and compared to mineral wool. Emphasis is placed on most realistically representative definition of the five building methods resulting in scientifically fair comparison.

Preface

This report is the result of a combined work and analysis of the two members/authors in Group 5, 4th Semester at Aalborg University, Master of Science (MSc) in Technology (Building Energy Design), Lars Dalsgaard Jensen and Laurynas Laivys. The report shows the effort and skills of the group, during the semester, meanwhile showcasing the student's ability to research, analyze, treat data and inputs for future building legislations, based on a broad perspective of possibilities. Due to the project period, the project group focusses on key areas of LCA and some specific products/concepts that align with the project scope.

Prior to this project, the two members of the group has been working with multiple subjects like design and dimensioning of HVAC systems, energy efficiency and life cycle analysis of economy (LCC) and environment (LCA) as part of introduction to DGNB. This master thesis is to document the authors ability to research, analyze and document complex problems related to the overall topic of the thesis; "*Accommodating future CO_2 demands in the Danish building legislation*".

The purpose of this report is to research and investigate if and how the CO_2-eq.-limits for future Building Regulations is possible to implement and/or if these limits are realistic. The analysis takes offset in three specific buildings of various size and construction methods. These three buildings will each undergo a substitution of CO_2-eq.-heavy building materials to materials with a lower environmental impact. Through literature review two companies are found from which it is possible to get/collect information. The two companies support the group, but the content of the report is neutral and is not affected by any sponsorship or similar from the companies. The support from the two companies is a dynamic cooperation. One company is ACERA who developed a wood-framed construction system with features like limited thermal bridges and designed for disassembly. The second company, BAYO.S, produce, dimension, and install screw pile foundations.

The data, information, and visual representation in parts of this report is provided by ACERA, BAYO.S, whom which we have an agreement to legally use and publish it, with respect to individual agreements.

Acknowledgement

As authors of this report, we would like to thank our AAU supervisors; Rasmus Lund Jensen, Kai Kanafani and Leonora Charlotte Malabi Eberhardt for knowledgeable guidance and discussions but also Lars Bo Ibsen regarding geotechnical discussion.

A big thank you, to ACERA too, Jannike Borg and Finn Borg, for interesting and useful discussions, drawings and sharing knowledge in all phases of the project.

We would also like to thank BAYO.S, Dorthe Skov Zibrandtsen and her colleagues, for static calculations, drawings, and other project relevant materials.

And lastly, we thank Olena Kalyanova Larsen, Thomas Uhrskov and Holm Huse for providing drawings and information about specific case building.

Reader's guide

The following overview is provided to give the reader an overview of the structure within this master thesis. This master thesis consists of the two following:

- → This main report, with an included journal article (Chapter 7)
- → A collection of appendices for this report

This main report is to be read as standalone which includes the following structure and headings. The second document is a collection of appendices, that covers all documentation and detailed calculation alongside with additional results from the calculations. All the appendices referred to, is to be found in the attached document, a collection of appendices. This is done, to ease the process of reading the report, while having the relevant appendix available at the same time.

The thesis structure is based on the following headings:

Introduction: The project is introduced with a presentation of topic/theme and a further explanation of the context. The introduction leads to the main problem of this project, followed by several research questions and a limitation to the research area, where a detailed explanation of the questions is showed, and the arguments and considerations behind the choice of problem. This will explain the theme of the report; "LCA of screw pile foundation and lightweight constructions in single-family houses".

Methodology: Is the second chapter and will explain the approach and methods for the further research. This will be described alongside with expectation for results and limitations. This chapter also includes the set functional units and specified information regarding screw piles and the ACERA building system. The chapter is followed by an introduction of the case buildings.

Sustainability analysis: Is the fourth and largest chapter, covering a detailed description of the three case buildings and the prerequisites of the LCA.

The chapter covers the main part of the analysis. The five methods (Method A to E) are a detailed step-by-step substitution of building materials, to primarily wood-based materials. The effect of this is explained in the respective sub conclusion for every substitution-method.

The chapter furthermore covers an analysis of the sensitivity for different parameters (e.g., transport, energy and EPD´s). This to validate the strength of the results.

Screw pile foundation analysis: Is the fifth chapter and analysis the use and environmental impacts/benefits of using the method.

Sensitivity analysis: A collection of considerations on how calculation prerequisites could differ and what impact it could have on LCA calculation. Some sensitivities are explanation of decision making and why some calculation parameters have or could have been excluded due to negligible impact.

Journal article: Can be read individually but enlighten and discuss the perspective of using screw piles and lightweight constructions. The chapter furthermore discuss perspectives that is beyond the boundaries of this project.

Conclusion: Is the eighth and last chapter and answers the stated problems form the problem formulation. It also summarizes the results of the report.

The Chicago method is used for referencing in the thesis, e.g. (Andersen, 2018) and the references are displayed at the end at Chapter 9, List of references.

For the journal article (Chapter 7), the reference method is IEEE, e.g. [1] or [2], these references are displayed at the end of the journal article.

The project contains multiple graphs, pictures, and drawings. These are referred to as "Figure xx", followed by a number. Some figurers come with a reference, but the material regarding ACERA building system is handed over physically or by e-mail, and do not have a reference. Tables are made and named the same way as Figures.

The attached document is the collection of appendices for this report. There is a total of 33 appendices and the structure of the naming is based on the content of the appendix. This to ease the overview and make a clear structure. The effect of this, is that the order is not chronological according to the reference in this main report. E.g., Appendix 02a, 02b, 02c and 02d is four different appendices about geotechnical data and soil related conditions. Appendix 04a-d is grouped as all appendices concerning Method B of the substitution.

Abbreviations and glossary

All abbreviations and specialized names are listed here. All the words or abbreviations are written here to help the reader understand the project and the way of writing.

AAU	Aalborg University
Be18	Software to calculate the energy frame of a building
BR	Danish Building Regulation
BR18	Danish Building Regulation 2018
BR18 LE	Danish Building Regulation 2018 Low Energy Class
CO_2-eq.	Unit for CO_2-equivalent emissions
DGNB	German sustainability schemes and certification
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene (Insulation)
GHG	Greenhouse Gas
GWP	Global Warming Potential [kg CO_2-eq.]
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCAbyg	LCA Software
LCC	Life Cycle Cost
R&D	Research and Development
SBi	Danish National Building Research Institute
SEL	Specific electrical power requirement for fan-motors [J/m^3]
U-value	Thermal transmittance [W/m^2K]
VOC	Volatile Organic Compound
VSC	Voluntary Sustainability Class
Windoors	Contracted word for windows and doors
λ-value	Lambda value (Thermal conductivity) [W/mK]

Abstract

This study aims to investigate the environmental impact of single-family houses using the LCA calculation method for an investigation period of 50-years. The investigation is conducted as a consequence of upcoming mandatory building regulations from 2023 for buildings over 1000 m^2, and in 2025 for under 1000 m^2 in which single-family houses belong with a threshold limit value of 10.5 kg CO_2-eq./m^2/year and is lowered by 1.5 kg every second year. The research compares the most common building methods used in Denmark with masonry cavity walls and concrete slab to alternatives, mainly wood framing of external walls and floor deck above ground, wood fiber insulation and screw pile foundation. The study has a particular emphasis on Voluntary Sustainability Class (VSC), which is not mandatory, but optional and will be available from 2023. VSC limit thresholds are 8 kg CO_2-eq./m^2/year (lowered by 1 kg every second year) and requires calculation of transport and building phases, as one of the differences compared to mandatory BR calculation.

This study is based on three buildings that represent some of the current typologies, including three different floor plans and floor areas, two shapes, two roof types and different window orientation. All three buildings are adjusted to be built with five different building methods (Method A-E), having the same functional unit. Functional unit consists of BR18 Low Energy Class (BR18 LE) with maximum deviation of -10% and identical constructions, where quantities have been adjusted to match the energy frame requirements. Constructions are substituted with alternatives which represents the five building methods. Technical installations are identical and kept the same for the whole study.

Calculations done by LCAbyg shows the most common building methods currently can only fulfill upcoming 2025 mandatory requirements in 1 out of 3 analyzed case buildings, but no buildings seem to fulfill BR 2027 or VSC requirements. Substitution with wood framing in external walls have showed positive outcomes, where 2 out of 3 buildings can fulfill mandatory BR 2025 threshold limit values. VSC limit values for 2023 could only be fulfilled taking additional measures such as using a method with screw pile foundation and wood framed floor deck, as well as a method with wood fiber insulation and cold bridge interrupted wood framing. Lowest achieved GWP is 7.2 kg CO_2-eq./m^2/year using a method with wood framed external walls and a wood framed floor deck in combination with screw pile foundation. Wood fiber insulation provided the highest recycling potential out of all methods and thus lowest emissions if the end-of-life phase is considered. VSC 2025 and further threshold values were not possible to comply with, and thus further research is needed.

The study also shows that constructions are responsible for majority of emissions, nearly 80% or 4 times higher than operational energy and confirms 50-80% findings from SBI 2020:04.

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1. Introduction

The focus on sustainability and reducing CO_2 emissions has increased during the recent years. In the coming years, Denmark has committed to reduce GHG (Greenhouse Gas) emissions with 70% by 2030 and achieve carbon neutrality in 2050 committed by EU (European Commission). Focus on buildings and their carbon footprint has primarily been based on the operational phase, where buildings account for 39% of the global CO_2 emissions (World Green Building Council 2019, p. 9). In Denmark the buildings, bridges, and roads account for 30% of the total CO_2 emission, and in fact 35% of all waste, generated in Denmark, comes from building and construction projects (Nielsen et al. 2020, p. 4-5). The increased focus on energy use has been intensified and been financially subsidized by the Danish government through different projects/initiatives for instance heat pumps and insulation (Energistyrelsen 2016). Research from UN, (IPCC 2018), states that there is an urgent need to reduce all kinds of climate impact the next decade to prevent the 1.5°C temperature increase. The latest report from (Klima- 2021, p. 87) calls that ongoing actions and plans must continue and be followed but with an increased focus towards 2030 on sustainability and life-cycle aspects in the building industry. There is furthermore a suggestion for increased forestation, to introduce climate-friendly building materials like wood, which correlates to the core-topic of this report.

Sustainability of buildings does however not only include operational energy, but emissions for all used materials, which is as important as operational energy. Although operational energy has been the focus point in themajority of the last decade, tools such as LCAbyg were developed in 2015 to account for cradle-to-grave analysis for the environmental impact and carbon footprint of buildings (Zimmermann et al. 2020, p. 5). The demand for performing LCA (Life Cycle Assessment) documentation has been increased due to sustainability certification schemes, such as the German DGNB (German Sustainable Building Council). The share of emissions from the construction phase will gradually increase, as emissions from the operational phase decrease because of an increasing share of renewable energy sources, and due to the energy efficiency measures. Renewables sources are expected already in 2027 to account for 100% of electricity production and 78% of district heating (Energistyrelsen 2020, p. 50). A report, (SBI 2017:08, Birgisdóttir and Madsen 2017) shows that building materials used for new buildings accounts for 50-80% of CO_2-eq. emissions, compared to the CO_2-eq. emissions due to operations for a 50-year lifespan. Why the incentives are clear - there is an urgent need to focus on building materials, to reduce the CO_2-eq. emissions for especially new builds.

The Danish government has agreed on, to implement obligatory CO_2-eq. limits for new buildings, starting from 2025 with the new BR (Danish Building Regulation) which makes CO_2-eq. limits for building under 1000 m^2. The VSC (Voluntary Sustainability Class) will already start in 2023, as a next step for sustainable building development, from buildings above 1000 m^2. Every year after 2023, the government will reassess the demands and gradually tighten the requirements. To perform representative LCA calculation, the building industry has been developing EPD's (Environmental Product Declaration) and other reference values. However, despite the recent development, reference values have not been standardized why further development is needed, which is a plan with the mentioned report from (Klima- 2021, p. 135). A more sustainable building and construction industry also seeks to comply with some of UN´s 17 Sustainable Development Goals. On national level, multiple organizations, and companies within the industry, works with sustainability in the building and construction process, and especially UN´s 13th goal (Climate Action) is important in this industry. The organization urges that the building owner through decision making prioritize and evaluate sustainable building methods and the related environmental impacts from the building projects, using life cycle assessment throughout the building's lifetime. It is important to choose solutions with a low environmental impact but also designed for the future climate and infrastructure. This can be achieved by demanding architecture and buildings that enhances the energy efficiency, indoor environment, infrastructure, operation and maintenance. It is estimated that these considerations will have impact on multiple other Sustainable Development Goals, like 3, 7-9, 11, 12 and 17. The goal being a sustainable solution in multiple parameters, to ensure holistic sustainable solutions. (Bygherreforeningen 2020).

1.1. Literature review

This project focuses on investigating the environmental impact of alternative building materials as a substitution to CO_2-eq.-heavy materials and parts of the VSC (Voluntary Sustainability Class). As inspiration and possible solutions on substitutions, it is needed to make a literature review and investigate existing research within the field.

The authors of this report share an interest for the screw pile foundation method and lightweight wood construction, why it is chosen to use data from two companies, and partly use/implement their products as a part of the analysis and comparison. The following literature review is divided into subchapters, concerning different areas, products, and methods.

1.1.1. Analysis of carbon footprint of current Danish building stock

Research has shown that limited literature is available, as the new requirements in BR are yet in the early stages of implementation. However, experiences exist from other voluntary sustainability schemes as DGNB, where LCAbyg was used and therefore developed over the recent years. It has been a common practice to use LCAbyg-software for analysis covering 50-year building lifetime, following same period as EU level(s). Recent SBi 2020:04 (Zimmermann et al. 2020, p. 8) publication chose both 50- and 80-year lifetime periods and analyzed 60 buildings (37 of them are DGNB certified). 11 of the 60 buildings are single-family houses, which correspond to the focus of this project. LCA consists of multiple phases and sub-phases, all covering the lifecycle, but in Denmark it is not common practice to include all of them, why the included phases in this SBi are; A1-A3 (Product), B4 (Replacements), B6 (Energy for operation) and C3-C4 (Waste treatment and disposal).

This project will include the same phases but include parts of phase A4-A5 due to VSC. For the sustainability perspective, it is also chosen to include phase D. This will result in deviation of the LCA-result, due to the added phases. For instance, will phase A4 (transport and waste to/on building site) and A5 (construction) add CO_2-eq.-emissions to the total GWP (Global Warming Potential). Phase D is currently not a part of either the BR nor the VSC, but to showcase the recycling potential, reuse and recycling scenarios, is calculated and considered in this project.

There is a considerable difference between buildings and their embodied energy including operational energy. For a 50-year expected lifetime, it has been found that median value is 9.5 kg CO_2-eq./m^2/year. Looking at the results, the variation can be ranging up to 2.25 times from lowest to highest carbon footprint building, ranging from 6.5 to 14.5 kg CO_2-eq./m^2/year. Impact of materials is also estimated typically to be 2-4 times higher than the operational energy consumption, as presented in the introduction on previous page.

Single-family houses GWP vary between 6.45 to 12.2 kg CO_2-eq./m^2/year. The house with the lowest emission is based on a lightweight (wood-framing) construction. This results in the lowest carbon footprint for materials of 3.6 kg CO_2-eq./m^2/year, which is possible due to captured biogenic CO_2 in wood-based materials, and low-weight buildings, resulting in overall reduced emissions. Operational energy for this building is very similar to other case buildings built with heavy constructions (masonry walls and slabs). Despite requiring more replacements of building materials even over 80-year period, the lightweight-construction case building still achieve lowest value of 5.8 kg CO_2-eq./m^2/year single-family house category. Results from this report therefore indicates that lightweight construction buildings have the lowest carbon footprint both for embodied CO_2 in materials and operational energy in total.

1.1.2. Screw pile foundations

Research has shown that limited literature is available, the review has been performed by searching literature about how the screw pile foundation method can reduce the CO_2 emissions when constructing foundations. Generally, the search provides only two reports that are scientifically documented and can be related to Danish conditions. The first report compares traditional concrete slabs with screw pile foundations, which estimate an 85% saving, despite the construction phase (A5) is not included. The second report also estimates a saving of 87% for single-family house, and up to 98% for other typologies, again without construction phase (A5). Despite CO_2 savings, critical overall parameter CO_2-eq. was not evaluated, which could suggest that savings would be lower taking other emission types into account (Fremtidens Fundament 2020). Note that the calculations are not based on GWP indicator, or CO_2-equivalents.

A further Danish research was done, and the result is multiple useful articles and journal papers alongside with video-material and interviews, from the company BAYO.S, who are providing material to this report. The topic is still being researched and developed. Some relevant information from BAYO.S resulted in a report with a similar result, showing a saving potential up to 85% for foundation, (Hatic 2021). BAYO.S products are certified with respect to Eurocodes and ISO standards to comply with BR, why the BAYO.S product is approved by insurance companies, (Bøgh 2021). The following results are found through Danish research. There are two bigger projects ongoing at AAU, but there is yet not any publication or material available. (Project*: “Day to Day Foundation”* (Altomteknik 2021b)*,* Project*: “Grand Solution”* (Altomteknik 2021a)).

The research presented at the articles, showed that there are two main areas of CO_2-eq. reduction. The first being the direct substitution of concrete, to use BAYO.S screw pile foundations and the second reduction is found in the construction phase. To create a traditional foundation, it is needed to excavate the soil and dispose it. Then fill the excavated area with gravel and sand to make a stable subbase to build on. Furthermore, the screws have potential to be economically more viable, if the soil is polluted, because it is still possible to build on top of the soil without disposing it. This building method leaves nature “untouched” and original, and after lifetime, it is possible to un-screw the screw piles again, and the nature will look similar as before.

There is a prediction that gravel and construction sand will be in shortage within the next 10 years, (Lindqvist 2021), making it more expensive and more CO_2-eq.-heavy (Andersen 2021) (Pedersen and Møller 2018). The second thought to this, is that the creation of construction site requires heavy traffic to building site with soil, sand and gravel, but also heavy machinery to process these materials - this can be avoided, due to the easy installation of the screw piles. The machinery for this installation is currently diesel powered but will be electrified in 2022.

1.1.3. Lightweight wood construction

The literature review has been performed by searching literature about wood/timber constructed buildings and relationship with environmental impact and indoor climate as keywords. The search was carried out using “search strings” to optimize the search and finding the most relevant and necessary studies, which is further described in Appendix 01. The search provided approx. 250 results, from which 27 studies is relevant and used to gather knowledge and inspiration. Indoor climate is decided to be delaminated from this report.

The literature review arises questions upon which typologies are suitable for substituting with wood in terms of indoor climate and energy flexibility. The answer to this question is that all typologies have some potential for substitution with wood statistically because the use of wood in construction is estimated to be of only 8% (Rasmussen et al. 2020, p. 16) as of today in the Danish building sector. The same report also acknowledged that builders and building owners have limited knowledge about building techniques with wood. It has been common practice to build with brick, concrete, and tile for past the 400 years in Denmark. Studies from United Kingdom and Sweden suggests that carbon footprint can be reduced by 15 to 77% depending on building method and other variables, (Rasmussen et al. 2020, p. 56). Single-family housing is one of the most common new-build typologies in Denmark, due to approx. 99% of buildings being built are 1 to 5 stories, and 33% of them are single-family house in years 2009-2019. Annually there has been built 3500-6000 buildings of this typology (Rasmussen et al. 2020, p. 128). One of the report authors, has expressed himself with the following quote (translated):

“Wait with the wooden skyscrapers - there is far more CO_2 to be saved by reorganizing the construction of single-family houses” (Byrrummonitor 2020) (Own translation)).

However, there are barriers, such as worries from private house owners in Denmark that tend to prefer maintenance-free housing, where the wood can be the opposite of e.g., brick. There can be advantages and disadvantages of the light-weight properties of wood construction, where fast response and temperature regulation in terms of thermal comfort and energy consumption can have negative or positive impact depending on application.

1.2. Problem formulation

The aim of this project is to investigate how conventional constructed single-family houses can undergo a substitution of CO_2-eq.-heavy construction elements, in favor of materials with a lower environmental impact. The analysis is based on specific case houses, presented at Chapter 3. All case houses are single-family houses created with traditional materials and methods. The analysis provides an overview of the environmental impact of different building materials, calculated in LCAbyg, but also demonstrate what alternative building methods to be used in the future, to comply with the future BR.Throughout the process, the Voluntary Sustainability Class (VSC) is used as guidance and inspiration, because this implies an extensive LCA analysis of proposed construction solutions.

Through the literature review it is found that other buildings than single-family houses with ease fulfill the planned CO_2-eq. limit of 12 kg CO_2-eq./m^2/year, by the year 2023. It is also found that single-family houses can fulfill the planned CO_2-eq. limit of 10.5 kg CO_2-eq./m^2/year, by the year 2025, using traditional and known building methods.

This report seeks to challenge the level of ambition in the BR, why the problem formulation for this Master Thesis Project is as follows:

"How can heavy building constructions in single-family houses be substituted with low carbon footprint alternatives, and what impact will the substitution have on the LCA?

Research questions:

1. What constructions have the largest potential for carbon footprint savings in single-family houses?
2. Which alternative solutions are suitable for single-family houses?
3. Which impact will the substitution of construction elements have on the buildings LCA, and does the change affect other sustainability parameters?

1.2.1. Problem delimitation

Through the project, the study-group have delimitated from multiple aspects and areas, which could be relevant to the topic. The first thing to delaminate is the Indoor Environmental Quality (IEQ), well knowing, that it is an important parameter when rating building methods and solutions as a unity, and IEQ also will have a larger influence in future ratings of buildings. Instead, it is chosen to focus on the aspects of LCA and building methods, that both requires an understanding of building systems, materials, and the technical specifications, but also design and considerations regarding the use - and building process of the building. Functional unit is defined and is limited to BR18 LE energy frame threshold limit value.

In addition, there is delimitated from investigating building time, economy, and finances, due to a more technical approach where the environmental impact is priority, and due to a non-developed industry, making comparison hard. Time being building-/installation time, could affect the decision-making process and also be a parameter when rating sustainable solutions as a unity, in order to be able to build efficient and sustainable. Architectural shape and interior design considerations are excluded, and instead existing design choices are being used.

2. Methodology

Method to assess how CO_2-eq.-heavy construction-materials can be substituted with more sustainable and environmental-friendly materials, there is a need to analyze traditional single-family houses and identify the construction elements with the highest environmental impact.

To do this, the project uses the literature review as inspiration, and defines the functional unit and “frame” of which the comparison should be based on. The project will be using three different case-buildings (Building 1, 2 and 3). The buildings will each undergo an analysis process consisting of five methods (Method A-E), see Figure 1. The present report is based on the three real case buildings and their respective LCA calculations. The reference buildings are constructed with commonly used materials, such as masonry facades and concrete slabs, and with three different architectural designs. Building 1 is a H-house with pitched roof. Building 2 is also H-house, but with flat roof and Building 3 is a box-house with flat roof. The buildings will be analyzed with respect to the specific components and the associated Global Warming Potential (GWP), calculated in LCAbyg. The calculation follows the environmental standard DS/EN 15978:2012 for LCA regarding buildings, and DS/EN 15804:2012+A2:2019 for the EPD of building materials. There are some databases for EPD´s like the the German *“Ökobaudat”*, which are to be used in this report. The purpose of this report is to cover areas of the LCA calculations and showcase what is possible with alternative building materials and construction methods, but also to develop awareness and new research within the topic, and how this can be used in LCAbyg. The focus is to show, whether or not the Danish Government could set a more ambitious goals for new build of single-family houses, with stricter CO_2-eq. limits, to intensify the effort towards the goal of reduced CO_2-emissions, while demonstrating the effect, more sustainable building materials have on the total GWP. The analysis will further cover the D-phase of LCAbyg which refers to the potential of recycling and reusability after end-of-life. The results will be used for comparison of the changes in design and materials and the respective impacts, with the expected CO_2-eq.-limits for the future VSC 2023 and BR 2025.

The investigation will be based on the sketch drawing below, Figure 1, first analyzed with respect to traditional building methods e.g., concrete, brick, and steel (Method A), and hereafter step-by-step substituted the CO_2-eq.-heavy construction elements, to primarily wood-based products.

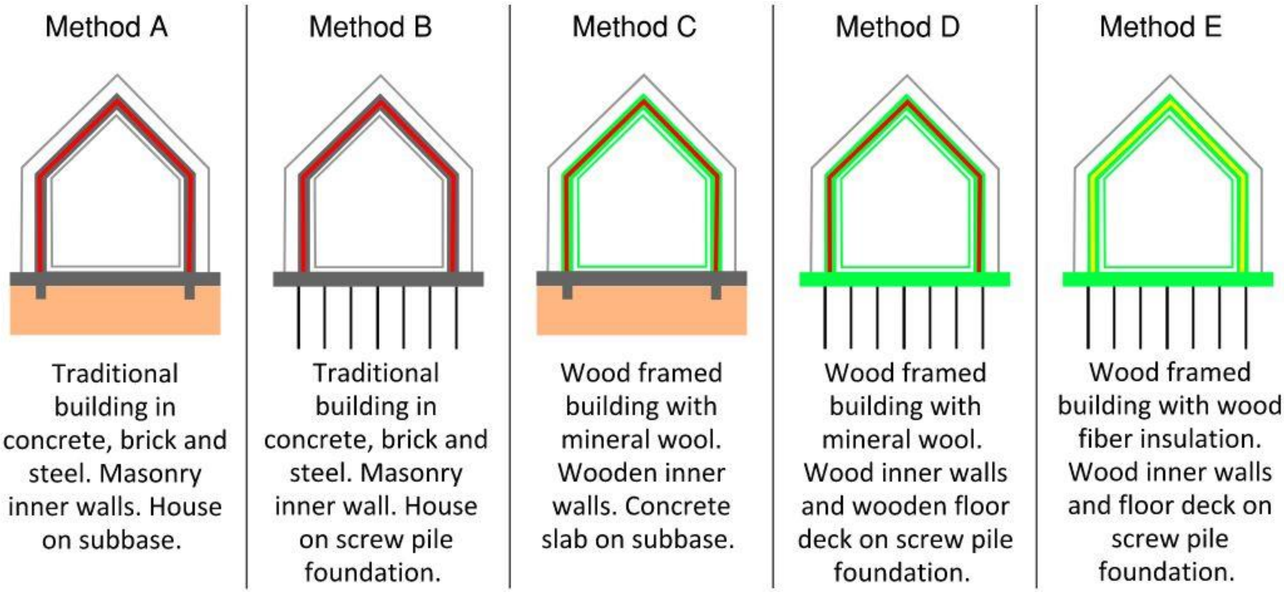


Figure 1 Illustration of analysis Method A-E. Sketch drawing, made with inspiration from *(Sørensen, Collin, and Schack 2020, p.*

For each method, a new layer of comparison is added, and the effect of substitution is visualized. The step-wise changes are made accordingly to the BR and the energy frame - so the function and operation of all buildings/solutions is the same. Note that the wall thickness can vary with the insulation layer, this will not affect the gross floor area, but the net area, the result being a smaller "livable" area. This will not be a part of the analysis but will be discussed later in Chapter 6.5. Performing a Life-Cycle-Assessment (LCA) is about analyzing the environmental impact of the building throughout its lifetime. The buildings investigation period is set to 50 years, as both LCAbyg and DGNB uses this as standard. The analysis includes the raw materials and the production of material, but also the replacement of materials during the lifetime and also the disposal of materials at end of lifetime.

The method, substituting step-by-step, makes it possible to compare different solutions and the environmental consequences by using the LCA. At Figure 1 there are some colors, that change according to the substitution of CO_2-eq.-heavy materials. The different constructions and building parts are calculated according to the specific case building. Only general data is used for technical installations, as they are assumed to not be variables in this project, and technical installations represents a relatively small share of carbon footprint compared to the constructions. General data has a median value of 0.46 kg CO_2-eq./m^2/year from SBi 2020:04 report (Zimmermann et al. 2020, p. 24). The procedure of making the LCA-calculation includes the following phases and is shown at Figure 2 below.

- Phase A1-A3: Raw materials, transport, and production of materials — Product Phase
- Phase A4-A5: Transport of materials to construction and construction site — Building Process
- Phase B4, B6: Replacement of materials and energy for operation — Use Phase
- Phase C3-C4: Waste treatment and disposal — End of life
- Phase D: Potential for recycling and upcycling — Beyond system

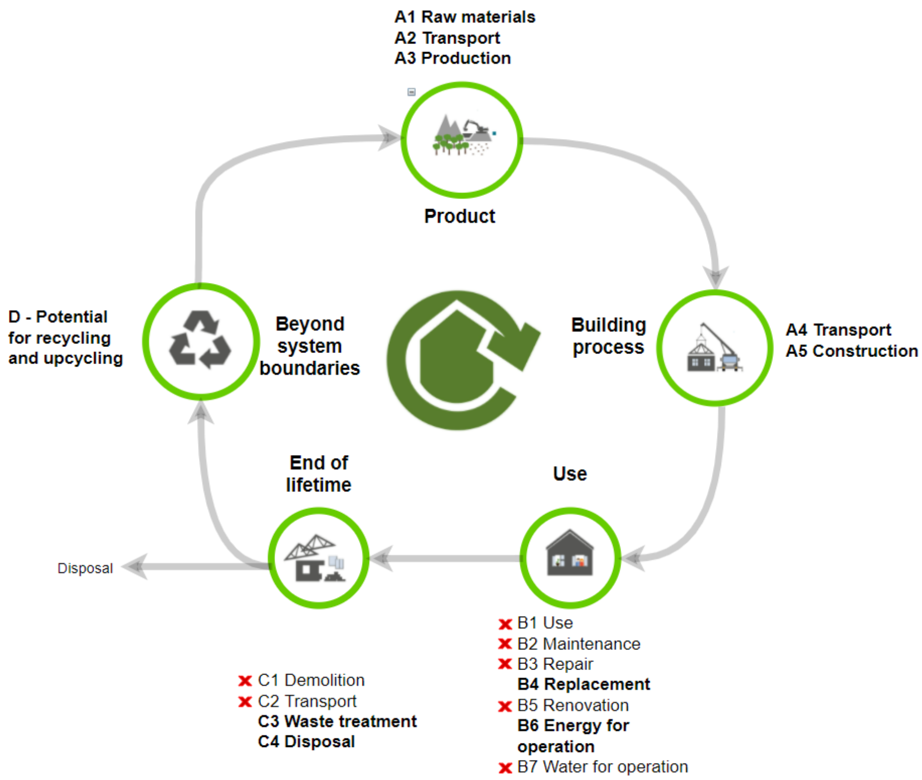


Figure 2 Delimitation of LCA stages, divided in 5 categories

The LCA calculation follows Voluntary Sustainability Class (VSC) why it is chosen to include the transport of building materials to the building site (A4). Phase A4 is expected to provide environmental impact comparison between heavy and light materials used in construction. Phase A5 for single-family house typology has minor impact in overall emissions, compared to other building types and therefore is neglected for building constructions other than floor slab and foundation. Energy used on site is only known for the traditional method, hence why this is excluded, and impact is explained in sensitivity analysis. The two building constructions are estimated to have the highest impact in Phase A5, and relatively precise data was available to estimate emissions, to compare different building methods for these constructions. The project will be a research and development project for the authors. Through the R&D team at AAU and two individual companies showed interest in the topic and are interested in the outcome. The companies are the two following, and they agree to supply the group with relevant material and data:

BAYO.S, who provide knowledge, data, drawings, and calculations regarding screw pile foundations.

ACERA, who provide knowledge, data, drawings, and calculations regarding timber-build houses with limited linear losses, due to an innovative building system.

2.1. LCA and energy performance of single-family house

Certain level of performance is expected in modern buildings by regulations, and two biggest performance indicators are prioritized in this report:

Sustainability – carbon footprint and recyclability
Energy efficiency – primary energy demand

The key goal is to identify how large a potential exists in carbon footprint savings and recyclability. The energy consumption is choen to be a part of the functional unit, fulfilling the BR18 Low Energy Class (BR18 LE) requirements of 27 kWh/m2/year (Bygningsreglementet), which is stricter than BR18 requirements. BR18 LE is chosen due to only 4% higher expected GWP increase for embedded CO2 in materials compared to BR18 but offset by energy efficiency increase resulting in approx. 10% lower overall building GWP found by SBI 2020:04 study (Zimmermann et al. 2020, p. 57).

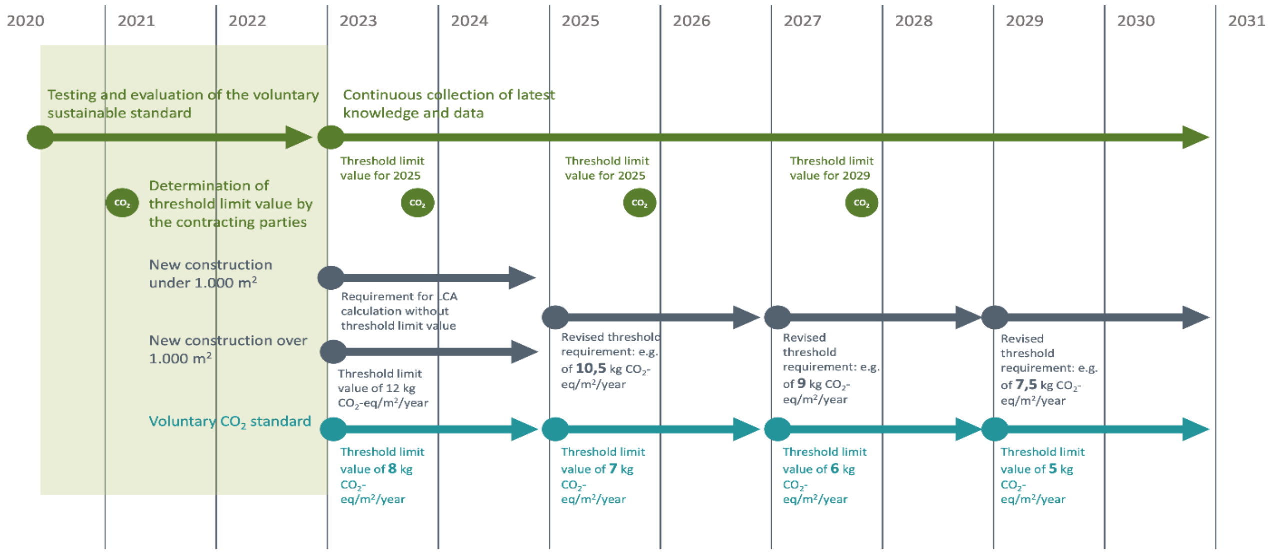


Figure 3 Roadmap of LCA requirement implementation in Building Regulation and Voluntary Sustainability Class (Bolig- og Planstyrelsen 2021)

Relevant mandatory requirements for single family houses are classified as buildings under 1000 m^2, which start from year 2025 with a total GWP of 10.5 kg CO_2-eq./m^2/year as seen on Figure 3. This threshold limit value is revised continuously and is reduced by 1.5 kg every second year. VSC is already available to use, starting with a GWP of 8 kg CO_2-eq./m^2/year and reduced by 1 kg every second year. Last year for projected change is 2029.

The LCA ambition level in this project is chosen as VSC which is above the minimum BR mandatory level. The requirements in VSC are stricter than in BR18, complete list can be found in (Bolig- og Planstyrelsen).

2.2. Shearing layers

The method described at Figure 1, showing a step-by-step substitution. This is chosen as a method due to knowledge of embodied CO_2 in construction materials and inspired by a concept called "Shearing layers". This is a concept by architect Frank Duffy (Foote and Yoder 1999) where building is divided in five layers that evolve in different timescale, in terms of longevity of built components, as seen on Figure 4. The reason being as described in Chapter 2 for analysis of structural parts, is due to high carbon footprint. These building parts are commonly built with high-density materials for structural and load-bearing reasons. Masonry walls, roof, concrete slabs, and foundations all have high carbon footprint as most high-density materials are in the structural layers. Structure will be the main focus area with different variables, where services, space plan and stuff remain identical throughout the substitutions.

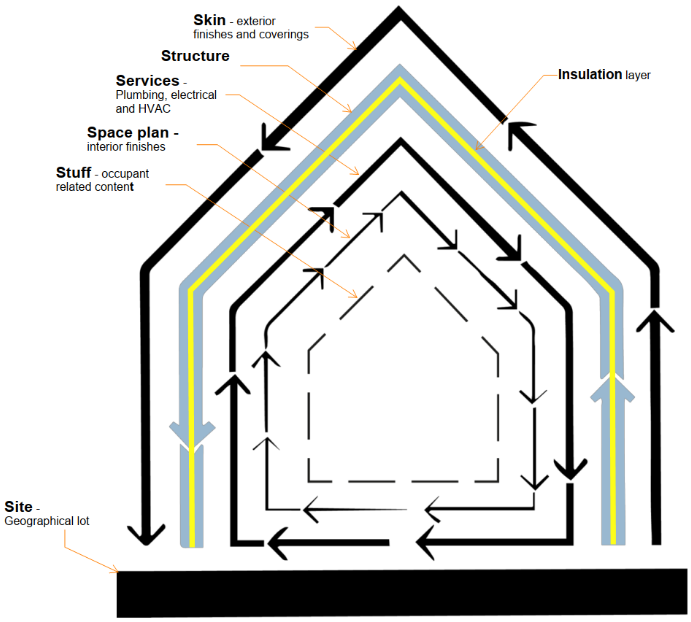


Figure 4 Illustration of the concept "Shearing layers"

Analysis from SBi 2020:04 have shown on how CO_2-eq. emissions are distributed between different constructions for 11 single-family houses that represent the current building trend. Figure 5 creates an overview of median values for all 11 buildings. The biggest share is represented by roof construction, where roofing material is the biggest contributor with 29%. Screw pile foundation and wood framing would help reduce emissions of the three constructions: foundation, slab (floor) and outer walls which all together result in 36% share of all constructions.

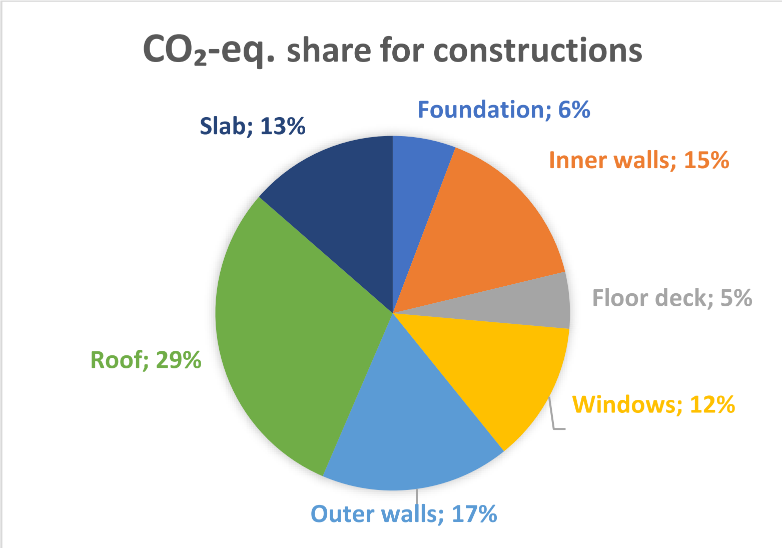


Figure 5 Share of GWP CO_2-eq. for 11 buildings from SBi 2020:04 report (Zimmermann et al. 2020, p. 41). Calculated average value of share for each building.

2.3. Functional unit and building method definition

Sustainable building methods are gradually introduced step-by-step, where CO_2-eq. heavy constructions are substituted with low carbon-footprint construction methods. Each step represents a building model system. Building methods will be compared in terms of total GWP in LCA calculation. In order to compare different buildings and methods, the functional unit is established. Despite changes in construction methods and materials, all building model systems will follow the same functional unit, some requirements are stated locally at the specific method-analysis, but generally defined to comply with the following requirements on Table 1. All building methods will feature identical interior and exterior finishes, resulting in an adjustment of the original building system.

BR18 Low Energy Class *(BR18 LE)*		
Energy frame	27	[kWh/m^2/year]
Window energy balance (E_{ref})	0	[kWh/m^2/year]
Infiltration	0.7	[l/s/m^2]

Table 1 Requirements with highest importance for BR18 Low Energy Class (maximum values)

Based on the requirements, the energy-frame of the single-family houses in this project is set to maximum -10% deviation from BR18 LE limits, giving the span to be 24.3-27.0 kWh/m^2/year. Windows and technical installations are fixed. Windows are triple glazed with U-value of 0.8 W/m^{2}K and g-value of 0.53. Technical installations are of most representative type and are identical for all buildings, described in Chapter 3. The case buildings are adjusted to match the functional unit, so the energy frame complies with BR18 LE energy frame in terms of building envelope, window energy balance and infiltration.

Structural- and insulation methods are the only variables as presented in Table 2 below. In terms of shearing layers, mainly the structural layer of the building is the variable. The reference Method A is constructed with very common building methods and in general representative for current Danish market for single-family house new builds. Every substitution of the original construction elements is described in detail in Chapter 2.

Construction	Type	Method A	Method B	Method C	Method D	Method E
Foundation	Strip (concrete)	X		X		
	Screw pile		X		X	X
Floor	Slab, EPS	X	X	X		
	Floor deck, mineral wool				X	
	ACERA framing, wood fiber					X
External wall	Masonry, cavity mineral wool	X	X			
	Wood framing, mineral wool			X	X	
	ACERA framing, wood fiber					X
Roof and ceiling	Mineral wool, drywall	X	X	X	X	
	ACERA framing and wood fiber					X

Table 2 Sustainable building method implementation steps for building methods

Alternatives to Method A needs to be readily available and accessible in the Danish market, tested and approved according to standards required from BR18 and Eurocode to be considered as a realistic alternative. Materials in the methods are defined as generic, so that no product brand is favored. However, depending on data availability, manufacturer specific data is used if no generic or other representative data is available.

2.4. Sustainable building methods

Analyzing according to find the CO_2-saving potential for the three buildings, three focus areas is chosen. The areas are, as described earlier but are generally based on 1) screw pile foundation method. 2) Traditional wood framing of bearing construction and 3) ACERA building system. These three solutions are to be described in the following subsections, answering research question 2, regarding what alternative sustainable solutions are available.

2.4.1. Screw pile foundation method

One of the alternative buildings methods to improve sustainability is screw pile foundation. In principle this method simplifies construction in several ways by a significant margin compared to traditional strip foundation. First, soil remains in its original condition when screws get screwed into the ground. Processes associated with concrete foundation preparation are eliminated. Second, fewer material quantities can be used for the products compared to concrete strip foundation, however that is directly dependent on geotechnical soil conditions. Downside is that soil samples have to be analyzed for each screw location.

Figure 6 BAYO.S extendable screw pile foundation (BAYO.S)

Economic sustainability can be potentially improved due to fewer construction processes and thus less labor-intensive work. Both environmental and economic sustainability difference between traditional vs. screw pile foundation amplifies when soil conditions get more complicated. Screw piles can simply be extended (Figure 6) to desired length to achieve the required torque for load-bearing capacity, and with minor modification even very complicated soil conditions can be solved. Therefore, it is important to establish a correlation for sustainability depending on soil conditions. In this report, screw pile foundation applicability as sustainable method will be determined by:

- **Impact of load-bearing soil depth**
  Different depths of load-bearing soil will be used as range for best- and worst-case scenarios for each building method.
- **Applicability for masonry building vs. wood framed stud bay**
  Taking soil conditions into account, report will investigate if screw pile foundations can be more sustainable for masonry buildings, as well as applicability for stud bay external wall and floor buildings compared to traditional concrete strip foundation.
- **Impact on energy frame calculations**
  Conditions for transmissions losses are different compared to concrete strip foundation. The change in transmission losses, changes the energy frame, which will be compared in Chapter 5.

There are several installation methods available for floor construction, which will be used throughout building methods in the report. The most suitable and used methods for single-family housings are wood framing joists. The top head can be attached to the framing with brackets and bolts. The construction imposes a floor deck above ground level with ventilated crawlspace. The gap between floor joists and ground can be covered with waterproof boards, rigid or foam insulation with plaster finish or left uncovered. Crawlspace can be helpful in areas with high risk for flooding. Steel beams are normally used in industrial applications.

As an alternative to wood joists, heavy constructions with concrete slab and masonry walls can be an option. In this case, screw pile heads are embedded in the concrete in traditional EPS-insulated concrete slab and the foundation is supported by screw piles with custom made supports.

2.4.2. Traditional wood framing

Alternative to masonry load-bearing framing is wood framing. Wood is a sustainable building material because it captures CO_2 from the atmospheric during growth, and stores CO_2 (e.g., in a building construction), until decay or burning. During wood-decay or burning, CO_2 is released again into the atmosphere. However, wood is not completely CO_2-neutral, as processes for forest felling and transportation involves CO_2-emissions. Construction on Figure 7 represents a wall stud bay with stud members of typically cc 600 mm, where members are continuous from interior to exterior filled with mineral wool batt insulation (λ-value of 0.032-0.040). In exterior the stud members are covered with a wind/rainproof membrane and wood furring (vertical spacers) to create a ventilated cavity for siding. Air and vapor barrier (typically PE foil) is installed on interior side of stud members for cold climate, accompanied with installation bay of 50-100 mm created by wood furring. Installation bay is used for accommodating electrical and plumbing installations. Airtightness is important in this type of construction, and is achieved by taped seams, sealants, and rubber boots on penetrations.

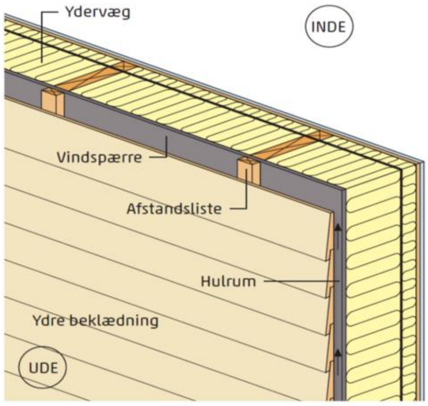


Figure 7 Traditional wall stud bay example with wood siding

Interior finish can be board-based material such as drywall or wood panels. Advantage of this construction is a mainly use of standard and widely available building materials, together with relatively simple workflows on building site. However, main disadvantage is thermal bridging due to inhomogeneous insulation layer.

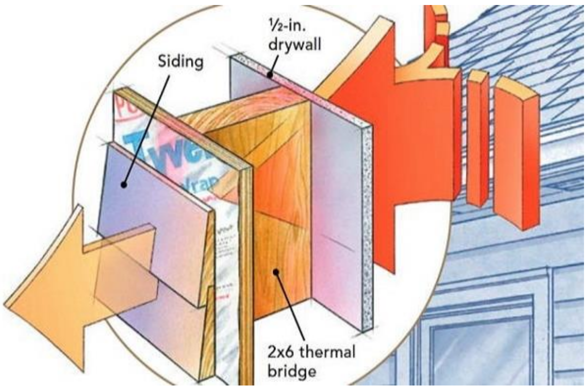


Figure 8 Thermal bridging of wall stud bay (Engineers forum)

Figure 8 shows one of the most common thermal bridging areas in stud bays. There are more problematic, such as bottom and top plate, window headers and external corners. Due to the inhomogeneous constructions, wood represents a significant share of heat loss with a λ-value of 0.12 W/mK, which affects the overall U-Value for the construction. Therefore, overall insulation layer thickness must be increased accordingly, to compensate for the inhomogeneous layer to match the desired U-value. The result is an increased overall wall thickness.

2.4.3. Advanced wood framing with ACERA building system

ACERA has a goal of building constructions that are sustainable. ACERA's framing system consists of prefabricated panels structurally framed with wood. The main feature of the framing system is thermal bridge interrupted framing members in both floor, wall, and roof. The required thickness of the thermal bridge interruption layer directly affects U-value and the final energy frame.

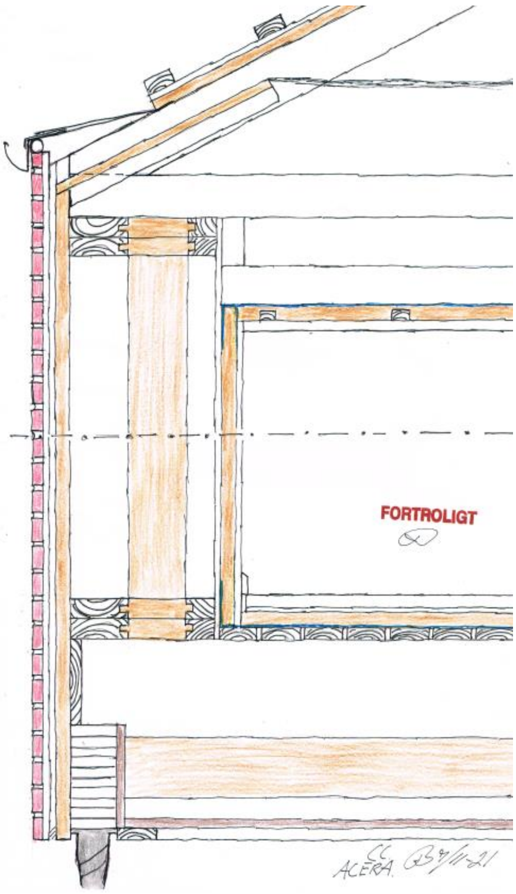


Figure 9 ACERA framing system

LCA calculation will compare this building method to traditional ones and optimal adjustment of thermal bridge interruption layer. The building system sustainability aims simple and readily available lightweight materials, compared to concrete and brick. Almost all parts of the construction are for these reasons made from construction wood or wood-based panels.

Materials such as blow-in wood fiber insulation with low CO_2-eq. footprint are the key in ACERA system to achieve the ambitious level of sustainability. Weather barrier and airproofing layer are wood-based materials as well.

Chemicals and hazardous substances are kept to very minimum, and where necessary, low-VOC products are used both in respect to indoor climate and recyclability. Recyclability is expected to be high, as the constructions are built with ability to be relatively easily disassembled and with a high share of wood-based materials.

2.5. LCA prerequisites

The functional unit is described in Chapter 2.3, alongside with the focus areas of the five different stages the case buildings will be analyzed with respect to. The following three buildings (five cases each) is analyzed independent of each other, but all follows the method described in this section.

This analysis covers the phases pictured at Figure 2, (p.7), and the phases for CO_2-eq. is as follows.

- Phase A1-3: Raw materials, transport of- and production of materials — Product Phase
- Phase A4-5: Transport of materials to construction site and construction — Building Process
- Phase B4, B6: Replacement of materials and energy for operation — Use Phase
- Phase C3-4: Waste treatment and disposal — End of life
- Phase D: Potential for recycling and upcycling — Beyond system

As described in Chapter 2, the LCA follows VSC, whereas the LCAbyg-calculation will include Phase A4 and A5. Furthermore, there will be used material specific EPD´s, to comply with the VSC, and transport will be added with respect to the building and method. Decision making is explained further in Chapter 6 (Sensitivity Analysis) but can be seen at Table 3 below.

<table>
<tr><th></th><th>A1-3</th><th>A4</th><th>A5</th><th>B4-6</th><th>C3-4</th><th>D</th></tr>
<tr><td>Generic building materials</td><td rowspan="3">Ökobaudat</td><td>100 km transport</td><td>Excluded</td><td rowspan="3">Ökobaudat + Be18</td><td colspan="2" rowspan="3">Ökobaudat</td></tr>
<tr><td>Foundation and floor slab</td><td>100 km transport</td><td>Calculation for soil re-moval</td></tr>
<tr><td>Screw piles</td><td>1100 km transport</td><td>Calculation of screw in-stall</td></tr>
<tr><td>Construction wood</td><td>Træ.dk/ EPD DK</td><td>600 + 170 km transport</td><td>Excluded</td><td colspan="3">Træ.dk/ EPD DK + Be18</td></tr>
</table>

Table 3 Overview of prerequisites for LCA phases. Other miscellaneous product specific EPD's in Appendix 08a.

Table 3 shows an overview of prerequisites for LCA calculation in respect to each phase. All generic building materials use Ökobaudat data from LCAbyg for all phases and estimated 100 km transport to the building site for transport A4. These generic materials have been excluded from Phase A5.

Foundation and floor slab are however included in A5 phase, where calculation of soil removal from building site is included, and for another building method, screw piles include emissions from machinery installing the screws into the soil. Screw piles include 1100 km transport from BAYO's factory in Prague, Czech Republic. For construction wood, it is chosen to use an updated EPD, made by EPD Denmark, which includes recom-mended values for transport of wood from Sweden, consisting of 600 km truck and 170 km ship transport. There are two options for end-of-life, C3-4 and D phases, energy incineration and reuse. Energy incineration is chosen as default scenario, but reuse scenario is considered in sensitivity analysis (Chapter 6) as well. For other materials than structural wood, default scenario of generic Ökobaudat EPD's is chosen.

3. Building types

The building types are based on drawings and technical information from the three different case houses.

Building 1: The first house is located in Klarup, being a single-family house, a type called H-House, due to the architectural shape. The house is made with open gable roof, and a total of 185 m² (hereinafter referred to as "Building 1"). This house is considered as the most representative and standard building type. The floor plan drawings can be seen at Figure 11 below. Quantity statements and drawings are adjusted to match the functional unit. The soil conditions are challenging why Building 1 originally is built on a subbase of sand and gravel, these geotechnical conditions can be found in Appendix 02a together with soil excavation and gravel fill quantity calculation method that is used for two other buildings as well.

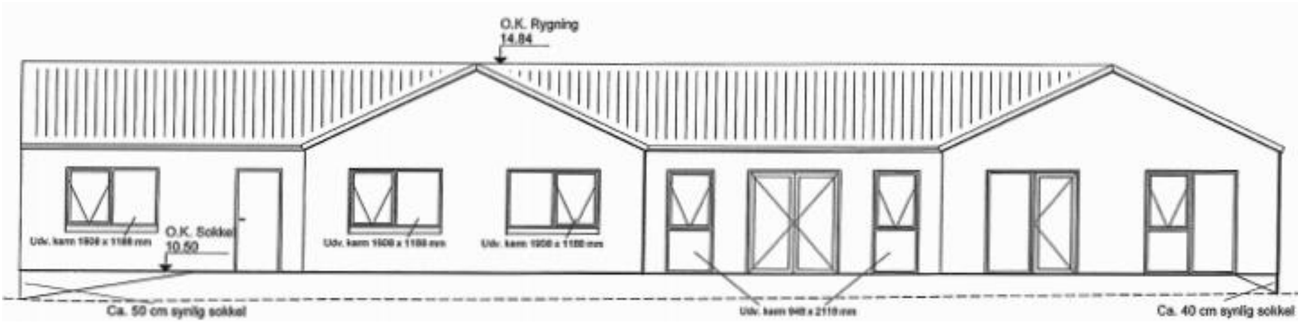


Figure 10 Building 1 section drawing of south façade

Floor plan:

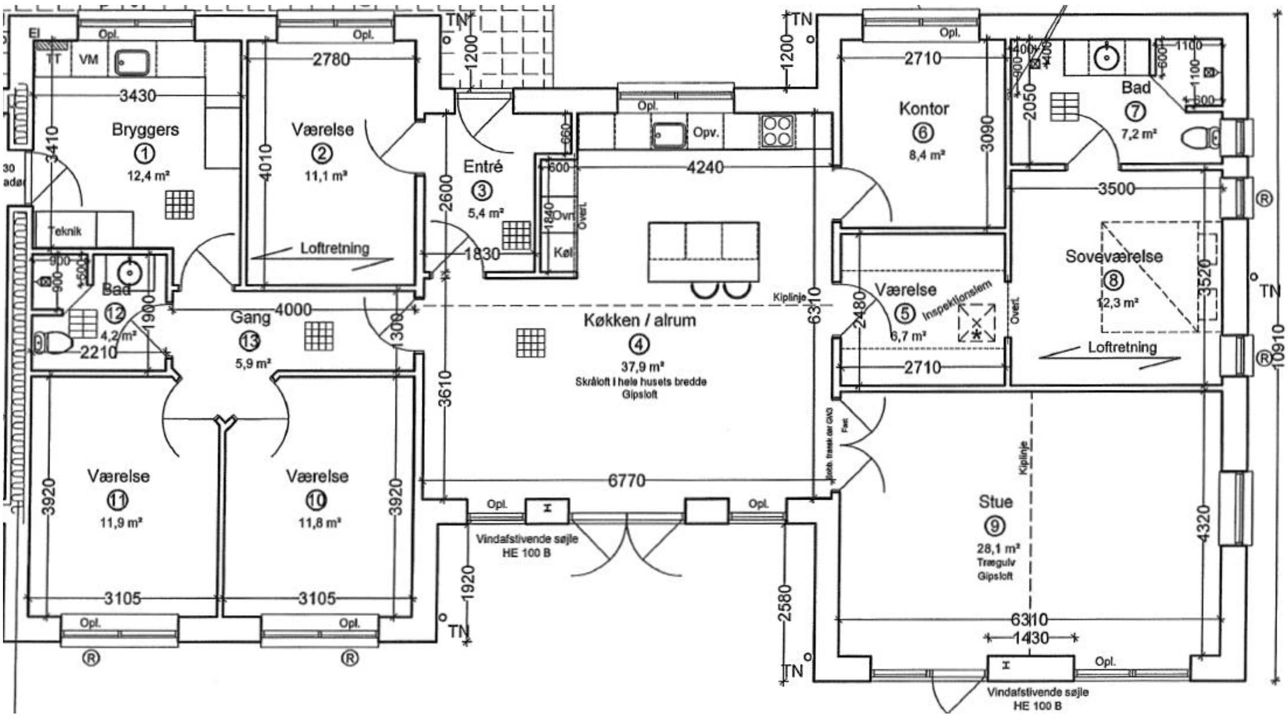


Figure 11 Building 1, floor plan

	Architecture	Gross area [m²]	Location	Soil conditions
Building 1	H-shape, open gable roof	185	Klarup	Level of excavation: medium

Table 4 Parameters of Building 1

Building 2: The second house is similar in architecture to Building 1, and is located in Klitmøller built as a single-family house, made entirely of concrete. The H-house is made with flat roof, and a total floor area of 150 m² (hereinafter referred to as “Building 2”). The floorplan drawings can be seen at Figure 13 below. Quantity statements and drawings are adjusted to match the functional unit. Soil conditions are unstable, due to the location in the dunes relatively close to the sea. These geotechnical conditions can be found in Appendix 02b.

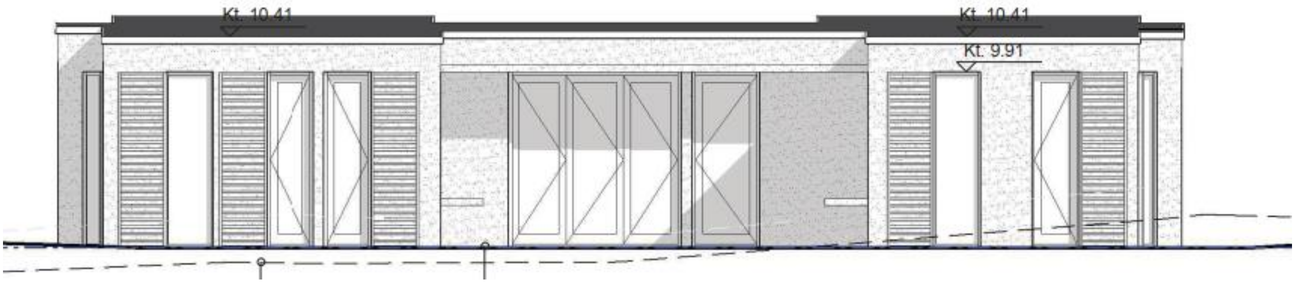


Figure 12 Building 2 section drawing of south façade (glazing to floor area ratio adjusted to 19%)

Floor plan:

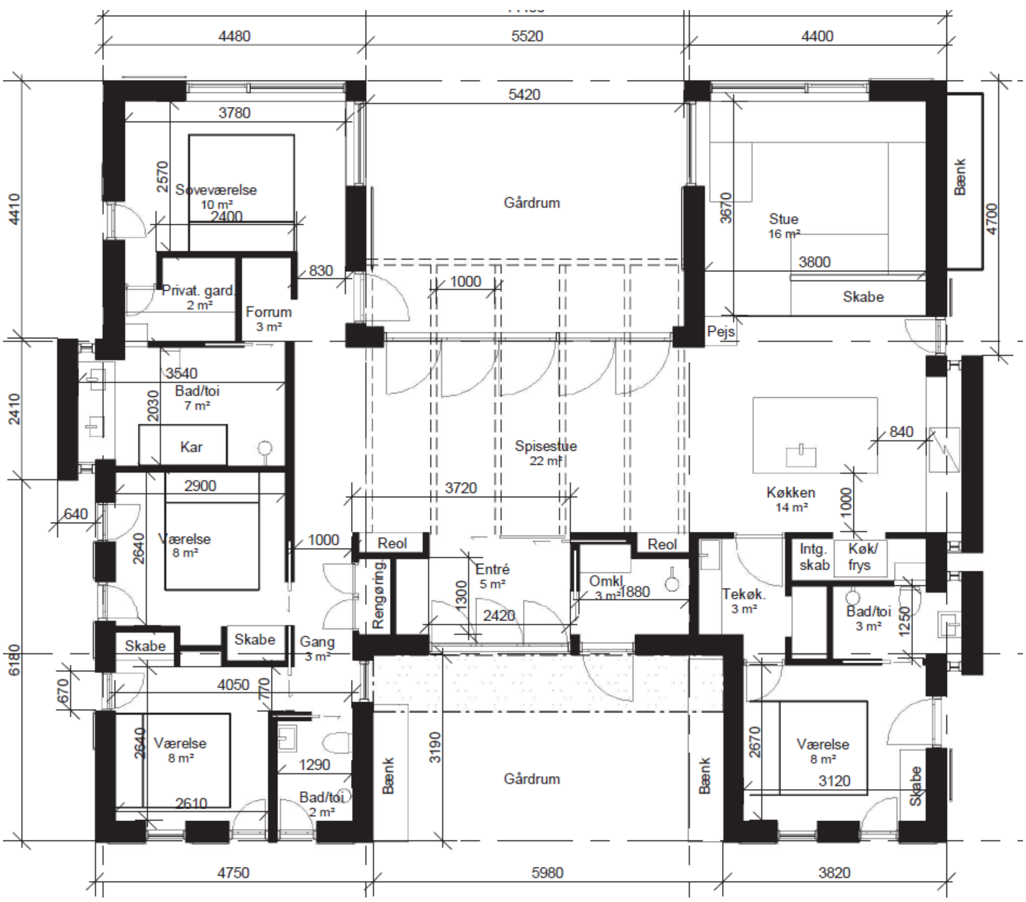


Figure 13 Building 2, floor plan

	Architecture	Gross area [m²]	Location	Soil conditions
Building 2	H-shape, flat roof	150	Klitmøller	Level of excavation: very high

Table 5 Parameters of Building 2

Building 3: The third house is located in Solrød Strand, also a single-family house, but with a different architectural expression to help analyze the importance of the shape. The house is a rectangular box-house with flat roof, and a total of 169 m^2, (hereinafter referred to as “Building 3”). The floor plan drawings can be seen at Figure 15 below. Quantity statements and drawings are adjusted to match the functional unit. Soil conditions are good, due to a solid stable underground. The geotechnical conditions can be found in Appendix 02c.

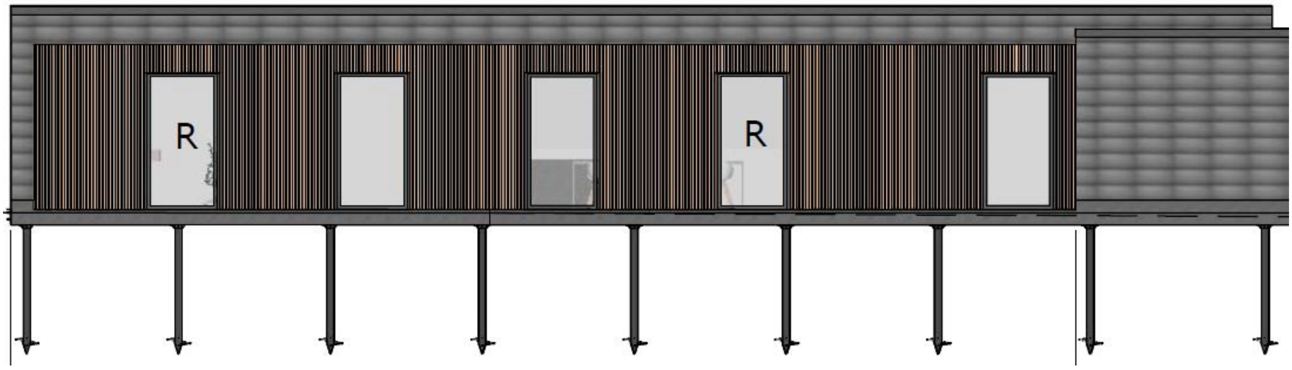


Figure 14 Building 3 façade drawing of south facade

Floor plan:

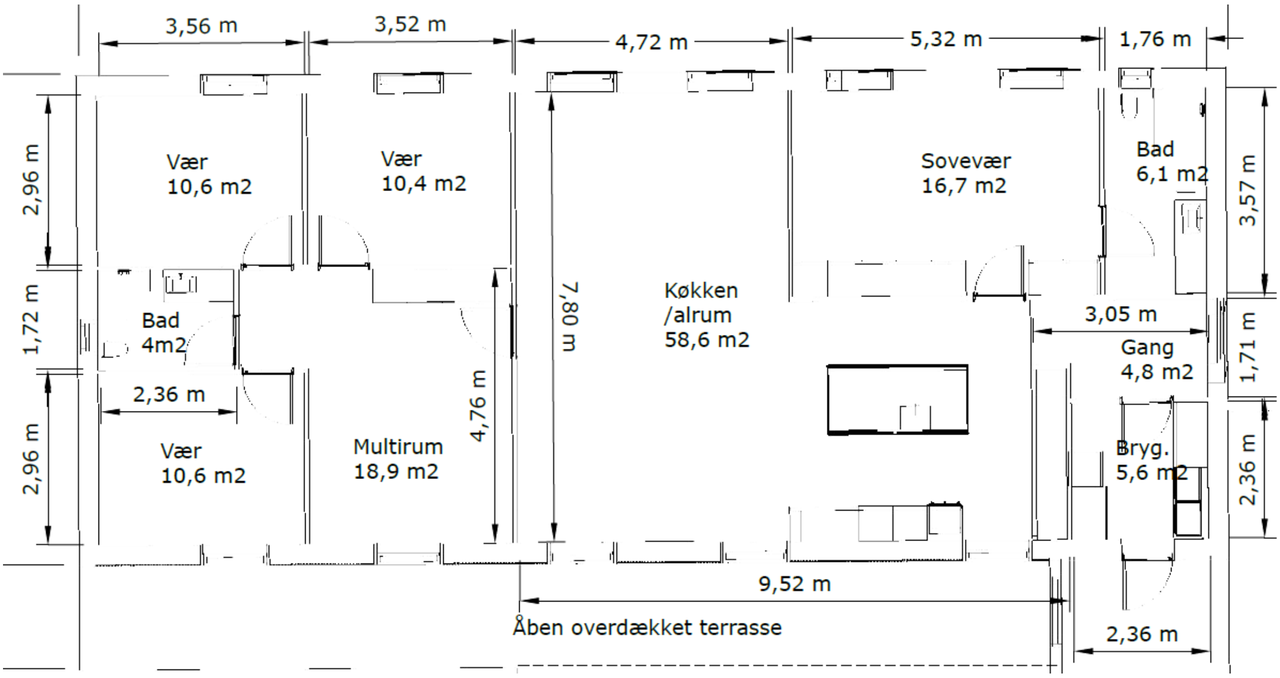


Figure 15 Building 3, floor plan

	Architecture	Gross area [m^2]	Location	Soil conditions
Building 3	Box-shape, flat roof	169	Solrød Strand	Level of excavation: low

Table 6 Parameters of Building 3

Technical installations are identical for all buildings and all building methods. Mechanical ventilation with heat recovery efficiency of 89% and SEL-value of 1000 J/m3 (Nilan). Heating is supplied by districting heating, through heat exchanger to floor heating in all rooms. DHW is produced through a district heating exchanger.

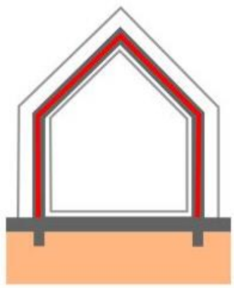
Technical installations are set to fixed at 0.4 kg CO2-eq./m2/year, according to average SBi 2020:04 values (Zimmermann et al. 2020, p.24). Window to floor area ratio is of 20%, 19% and 15% for Building 1, 2 and 3 respectively. Deviation of 5% is set as acceptable. LCAbyg calculation input for reference Method A can be found in Appendix 08b, 08c and 08d.

4. Sustainability analysis

This chapter analyze the change in environmental impact, for each step of the substitution method, described in methodology chapter. Throughout the first section regarding Method A, the goal is to answer the first research question, concerning the largest potential for CO_2-eq. reducing alternatives. Method A, and the following step-by-step substitution is a part of the recommendation from UN, regarding the 17 sustainable development goals, especially goal 13 about climate action.

4.1. Method A – Reference building with masonry external walls

Method A



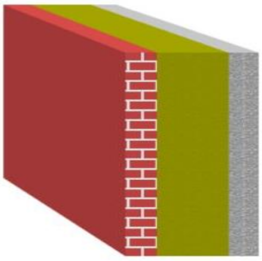
In Method A, constructions are as described in the table below, mainly from high-density constructions materials. Buildings 1, 2 and 3 share the same general building methods for foundation, floor, external wall, and roof. A detailed description and visualization are shown with the respective nametag as presented below. U-value calculation is to be found in Appendix 03a.

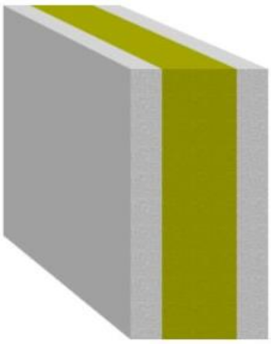
Overview	**Type**	**Description**	**U-value** [W/m²K]	**Method** A, B, C, D, E
Building 1 - Klarup				
External wall construction	EW.1	Cavity wall, brick-lightweight concrete, 235 mm insulation class 34.	0.128	A
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (pitched) construction	RP.1A	Pitched roof (attic) flat ceiling, 390 mm insulation class 37. cc 1000.	0.095	
Building 2 - Klitmøller				
External wall construction	EW.2	In-situ casted concrete cavity wall, 235 mm insulation class 34.	0.139	A
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (flat) construction	RF.1A	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 1000.	0.061	
Building 3 - Solrød Strand				
External wall construction	EW.1	Cavity wall, brick-lightweight concrete, 235 mm insulation class 34.	0.128	A
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (flat) construction	RF.1A	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 1000.	0.061	

Table 7 Method A construction types

4.1.1. Building envelope

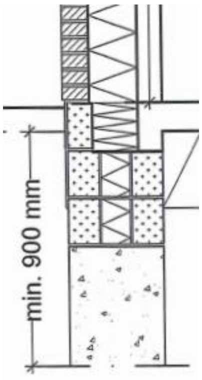
All building types feature masonry walls either with brick and lightweight concrete blocks or with in-situ casted concrete walls with cavity insulation. All three buildings feature 235 mm insulation class 34, that matches the required functional unit U-value of 0.128-0.139 W/m²K. Internal walls are not included in the energy frame but are built from lightweight concrete blocks (Building 1 and 3) and from in-situ casted concrete in building 2. Internal- and external walls have interior finish e.g., plaster and acrylic paint. The following construction types each come with a unique nametag, to ease the understanding of the future substitution from e.g., concrete to wood. A nametag is for example EW.1 (*External Wall type 1*) or RP.1 (*Roof Pitched type 1*).

<table>
<tr><td colspan="2">EW.1 - External wall type 1 – Cavity insulation with lightweight concrete and brick</td></tr>
<tr><td>
Figure 16 External wall with cavity insulation (Rockwool)</td><td>Inner leaf, lightweight concrete block
235 mm class 34 Mineral wool insulation
Outer leaf, brick

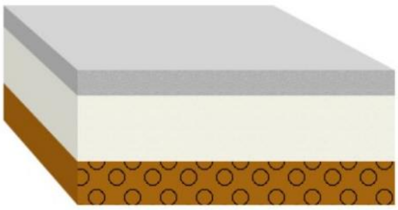
U-value: 0.128 W/m²K</td></tr>
<tr><td colspan="2">EW.2 - External wall type 2 – Cavity insulation with in-situ casted concrete elements</td></tr>
<tr><td>
Figure 17 External wall with cavity insulation (Rockwool)</td><td>Inner leaf, in-situ casted concrete
235 mm class 34 Mineral wool insulation
Outer leaf, in-situ casted concrete

U-value: 0.139 W/m²K</td></tr>
</table>

External walls are built on concrete strip foundation from Leca thermal blocks, with 190 mm EPS insulation in between. Exterior finish is limestone plaster. Linear losses equal to Ψ: 0.120 W/mK.

SF.1: Strip foundation type 1 - Foundation with Leca thermal blocks	
 *Figure 18 Foundation, with center insulation of 190 mm (Dansk Standard , Table 6.13.1, p. 46).*	390 mm center insulated Lecablock 190 mm EPS insulation Ψ-value: 0.120 W/mK

Floor construction is built as 120 mm concrete slab with 300 mm EPS insulation on Leca fill, with a U-Value of 0.094 W/m^{2}K. Floor finish is installed directly on the concrete screed, tiles in bathrooms and wood flooring in rest of the rooms.

FS.1 - Floor slab type 1 - Insulated concrete slab on EPS and Leca	
 *Figure 19 Floor slab with 300 mm EPS insulation. (Rockwool)*	120 mm concrete 300 mm EPS-insulation Leca and gravel fill U-value: 0.094 W/m^{2}K

The roof on Building 1, is built as standard fink trusses with 390 mm insulation in the flat ceiling with U-Value of 0.099 W/m^{2}K.

The roof on Building 2 and 3, is a built-up flat roof with 585 mm insulation with a U-value of 0.061 W/m^{2}K.

Interior finish of ceilings consists of drywall, plaster, and 2-layer acrylic paint. Roof rafters/mineral wool share is described in Appendix 03b.

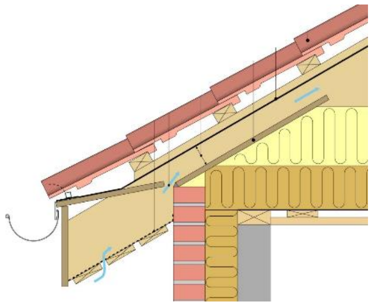
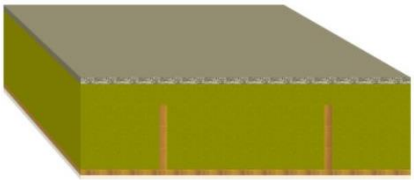
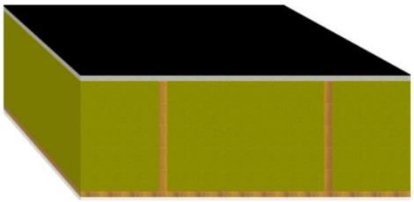


Figure 20 Illustration of fink trusses with flat ceiling ((BUILD)

<table>
<tr><td colspan="2">RP.1A - Roof Pitched type 1 – 390 mm insulated flat ceiling, cc 1000</td></tr>
<tr><td>
Figure 21 Roof with 390 mm insulation. (Rockwool)</td><td>26 mm ceiling
25 mm battens
PE-vapor barrier
390 mm insulation, class 37
Ventilated attic
Tile roof

U-value: 0.099 W/m²K</td></tr>
<tr><td colspan="2">RF.1A - Roof Flat type 1A – 585 mm insulated flat roof, cc 1000</td></tr>
<tr><td>
Figure 22 Roof with 390 mm insulation. (Rockwool)</td><td>26 mm ceiling
25 mm battens
PE-vapor barrier
585 mm insulation, class 34
Plywood and ventilated battens
Roofing

U-value: 0.061 W/m²K</td></tr>
</table>

Air tightness management relies on PE-vapor barrier in the ceiling with taped seams, membranes for penetrations and sealing joints to external walls. Lightweight concrete blocks are serving airtightness purpose for external wall inner leaf, in Building 1 and 3. In Building 2, concrete serves the purpose of airtightness in the building. Joints between concrete slab and external wall are sealed with radon membrane. Using these strategies, BR18 LE requirements of 0.7 l/s/m^2 air infiltration can be met.

4.1.2. Sub conclusion

For the three buildings, an LCA is created and the results ranging from 10.27 to 12.65 kg CO_2-eq./m^2/year. Figure 23 shows the average values for all three buildings, where constructions have the highest share of CO_2 emissions accounting for 82% of total GWP emissions, meanwhile operational energy accounts for 12% and technical installations for 4%. Building process includes removal of soil in the building site for the floor slab, which despite being emission-heavy transport process, results in approx. 1% of lifetime emissions.

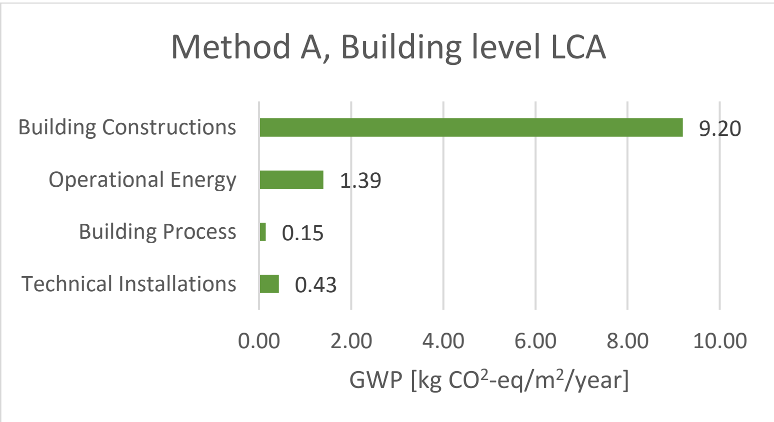


Figure 23 Method A, average building level LCA

Results on Figure 24 show distribution of GWP emissions of 9.2 kg CO_2-eq./m^2/year for building constructions which accounts for the biggest share of total building emissions. The single biggest contributor by construction is the floor slab with 3.16 kg CO_2-eq./m^2/year which equals to 34% of total GWP for materials. External wall is the second with 23%, roof with 18% and foundation with 11%. As a conclusion, the materials with high density account for the largest emissions, and answers directly to research question 1, regarding what construction elements having the larger potential for reducing the total GWP.

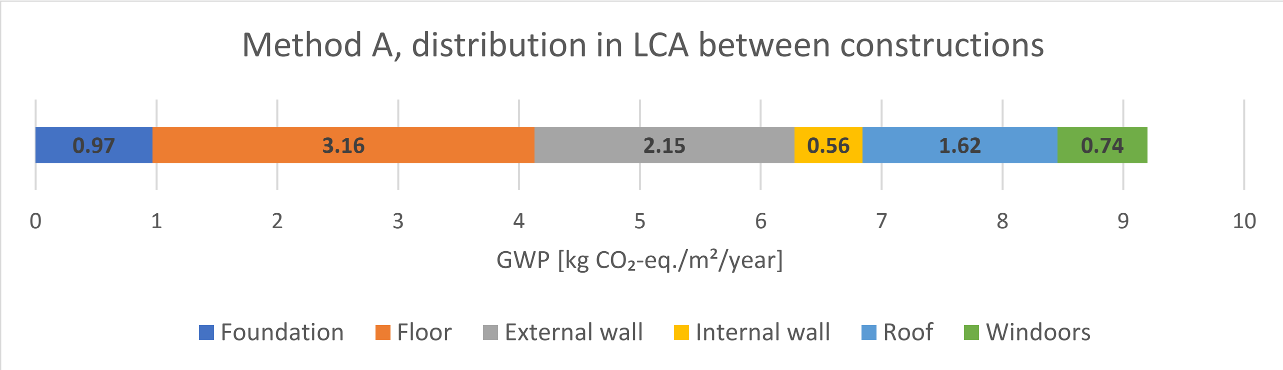


Figure 24 Method A, average GWP distribution in building envelope incl. transport

Distribution across different LCA phases, see Figure 25 below, shows that 4.85 CO_2-eq./m^2/year emissions originate from A1-3 phases. Other phases such as A4, A5, B4 and C4 are of less significance, meanwhile B6 (Energy for operation) and C3 (Waste treatment) have more significance with 1.39 and 1.86 CO_2-eq./m^2/year emissions respectively. Overall, the operational energy is relatively low compared to other phases, which is partly caused by strict BR18 LE requirements, and partly due to low emissions of Danish energy mix for electricity and district heating being 264 g CO_2-eq./kWh and 131 g CO_2-eq./kWh respectively, while in for projections in 2030 this is reduced significantly to 47 g CO_2-eq./kWh and 71 g CO_2-eq./kWh respectively (COWI 2020) discussed in Chapter 6.3.

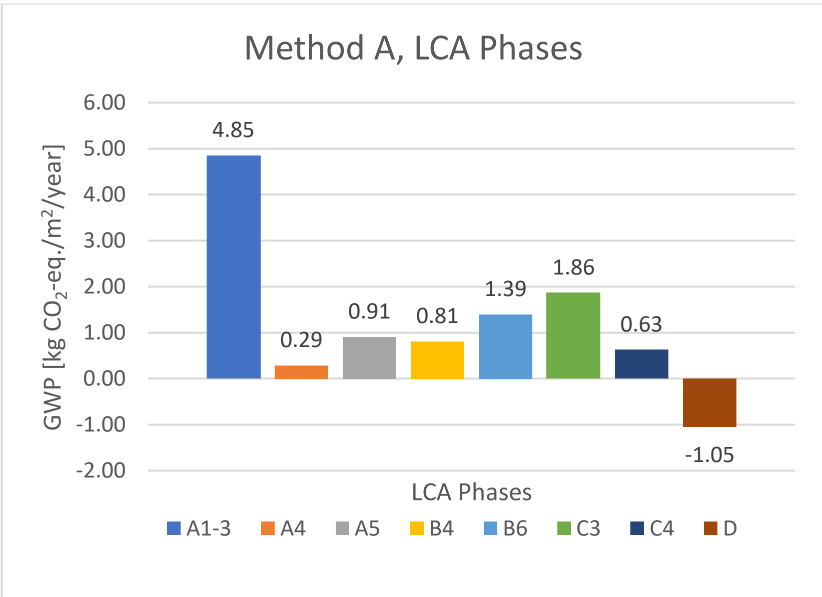


Figure 25 Method A, distribution between phases

4.1.3. Transport and building process

External walls, internal walls, and roof construction

All processes described in the problem delamination are included and used with standard EPD's in LCAbyg, except Phase A5 which could not be estimated precisely according to Chapter 6.2. Transport distance is estimated to be 100 km for all materials, phase A4, as a representative distance from building- and construction supplier, except structural lumber used in the roof construction, which is product specific and originate from Sweden. Transport includes 600 km truck and 170 km ferry transport as per EPD datasheet, which is evaluated to be representative for average distance from Sweden to a typical Danish building site, hence why specific distance is used for this material.

Foundation and floor slab

Floor and foundation calculation of processes associated with removal of soil and replacement with sand and gravel are calculated by Phase A5 which consists of consumption for machinery on site, and phase A4 includes transport of materials (gravel, sand, concrete etc.) to the building site with estimated distance of 100 km. The impact of other than 100 km transport distances are described in Chapter 6.1.

A4 Transport		
Gravel, sand, concrete – materials delivery		100 km
Soil removal for foundation and floor slab	69.4 m^3/ 104,059 kg	100 km
Soil moved with machinery in property	273.3 m^3	

Table 8 Method A, Phase A4 transport calculation for foundation and floor slab

In building process for foundation and slab, there has been excavated 273.3 m^3 of soil, of which 69.4 m^3 is removed from property by 100 km truck transport. The remaining soil is deposited in the property. Average transport to building site for materials (A4) are calculated GWP emissions for the three buildings ranges from 0.19 to 0.45 kg CO_2-eq./m^2/year. Meanwhile building process (A5) ranges from 0.05 to 0.29 kg CO_2-eq./m^2/year.

4.2. Method B – Reference buildings with screw pile foundation

Method B differentiates with another type of foundation. Strip foundation is replaced by screw pile foundation combined with Sundolitt F-Element foundation blocks. This solution can advantageously be applied in building sites with complex soil conditions where traditional strip foundation would result in extraordinary amounts of excavation of soil, to create a stable subbase to build on. The substitution is the floor slab, changing from type FS.1 to FS.2. The remaining constructions are identical to Method A, which can be seen in at Table 9 below. U-value calculation is to be found in Appendix 04a.

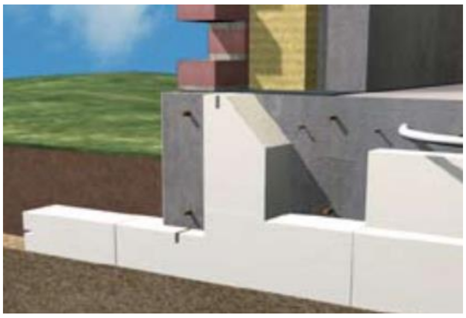
Overview	Type	Description	U-value [W/m²K]	Method A, B, C, D, E
Building 1 - Klarup				
External wall construction	EW.1	Cavity wall, brick-lightweight concrete, 235 mm insulation class 34.	0.128	B
Floor slab construction	FS.2	Slab, concrete on 300 mm EPS with screw pile foundation.	0.105	
Roof (pitched) construction	RP.1A	Pitched roof (attic) flat ceiling, 390 mm insulation class 37. cc 1000.	0.095	
Building 2 - Klitmøller				
External wall construction	EW.2	In-situ casted concrete cavity wall, 235 mm insulation class 34.	0.139	B
Floor slab construction	FS.2	Slab, concrete on 300 mm EPS with screw pile foundation.	0.105	
Roof (flat) construction	RF.1A	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 1000.	0.061	
Building 3 - Solrød Strand				
External wall construction	EW.1	Cavity wall, brick-lightweight concrete, 235 mm insulation class 34.	0.128	B
Floor slab construction	FS.2	Slab, concrete on 300 mm EPS with screw pile foundation.	0.105	
Roof (flat) construction	RF.1A	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 1000.	0.061	

Table 9 Method B construction types

The screw pile foundation is a unique solution for each house and the respective geotechnical conditions. These can vary, dependent on the underground in the specific area. For the three buildings covered by this report, the length, number, and placement of the screw piles, for Method B, is specified in Appendix 04b and 04c. For Method B, BAYO.S has provided knowledge and calculation on type, length, placement etc. for each individual situation, based on geotechnical samples and surveys, done by company in collaborations with BAYO.S. In certain situations, like Building 3, it was assumed that it uses same location as for Method D, Appendix 06c.

4.2.1. Building Envelope

The foundation is constructed with Sundolitt F-element. In this case, screw piles are used as foundation and casted into the floor slab. The exterior concrete part is shaped by using the Sundolitt F-elements. Outer leaf of brick is located on top of the poured concrete and is separated by EPS from inside. The outer leaf is finished by a layer of limestone plaster. The EPS insulation extends further horizontally to keep linear losses at minimum. This solution has identical linear losses to the standard construction in Method A.

<table>
<tr><th colspan="2">SF.2: Strip foundation type 2 - Sundolitt F-element and screw pile foundation</th></tr>
<tr><td>
Figure 26 Sundolitt F-element (Sundolitt 2020)</td><td>Sundolitt F-element (Sundolitt 2020)
600 mm width, 400 mm height

Ψ-value: 0.120 W/mK</td></tr>
</table>

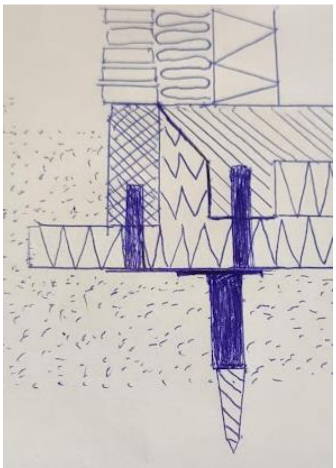
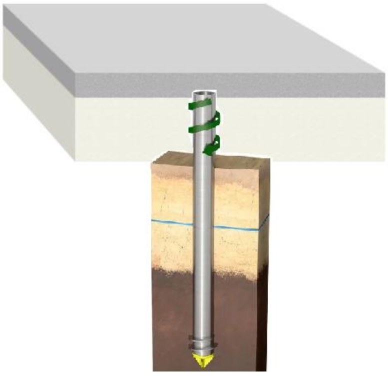
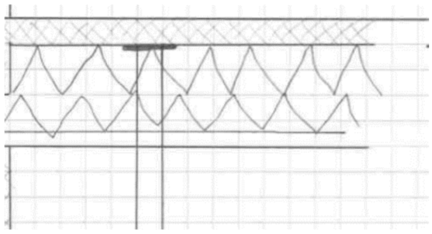


Figure 27 Screw pile foundation detail. U-plate and M24 bolts (hand-sketch)

Figure 26 above shows a Sundolitt F-element foundation. However, in this case screw pile foundations are used to anchor the foundation to the ground. In Figure 27 the detail about screw pile foundation can be seen. Custom made U-plate is installed on top of the screw pile hex head, and two M24 bolts extend further to be casted into the concrete that is poured to the F-element. Screw piles are installed for about every 2 meters. Linear losses are documented at 0.340 W/mK for the screw piles, but since the cc is 2 meters, the weighted linear loss results in Ψ: 0.120 W/mK (Appendix 04d). Screw pile material list is found on Appendix 02d.

The floor slab is built on top of gravel sand fill, and concrete poured on top of EPS insulation, and in the allocated space in the F-element. Floor slab is supported by the screw pile hex heads directly, as illustrated at Figure 28. The U-Value is increased as the EPS is built directly on top of gravel sand fill, without Leca. Floor finishes remain the same as for Method A. The U-value is increased from 0.094 to 0.103 W/m^{2}K compared to Method A due to no Leca fill, as further excavation is not needed.

FS.2 - Floor slab type 2 - Insulated concrete slab with screw pile foundation	
  *Figure 28 Visual illustration and hand sketch. Insulated floor slab on screw pile foundation.* *(Rockwool)*	120 mm concrete 300 mm EPS-insulation 600 mm Sundolitt F-element Screw pile Gravel and sand fill U-value: 0.103 W/m²K

The LCA calculations for the two substituted constructions on Figure 29 show varying results. The varying results can be explained by difference in soil excavation for the three buildings to establish foundation and floor slab. Building 1, which has medium excavation level (average 1.28 meters), performs significantly better using Method A than B, the difference being +1.89 kg CO_2-eq./m^2/year higher with Method B. The same tendency is seen on Building 3, where low excavation level (0.9 meters foundation, 0.4 m floor slab) results in +0.33 kg CO_2-eq./m^2/year higher GWP with Method B. However, with worse soil conditions in Building 2, where excavation level is considered very high, Method B results in significantly lower GWP emissions by -0.76 CO_2-eq./m^2/year.

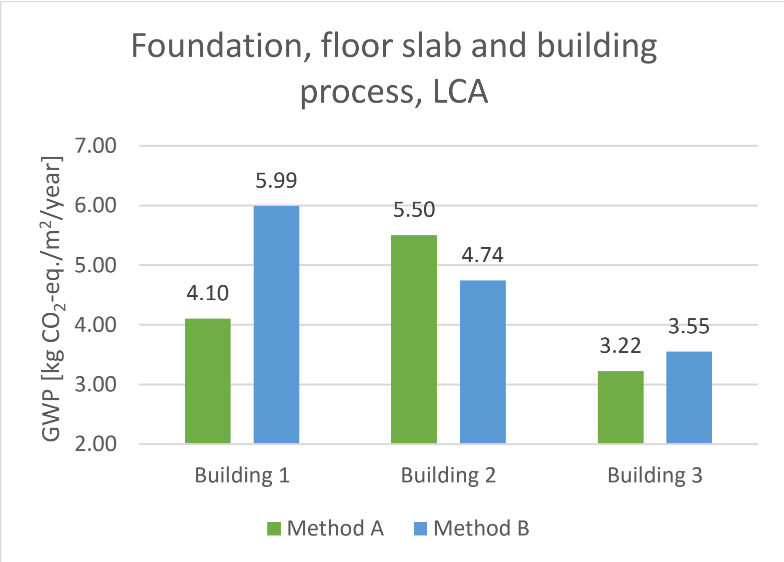


Figure 29 LCA result comparison of Method A and Method B, substitution of foundation and slab

Based on the results of Method B, it can be summarized that screw pile foundation has lower GWP emissions in soil conditions, where high level of excavation is present. Applicability of screw pile foundations for masonry buildings with soil conditions of low to medium excavation level are questionable, as GWP emissions are higher.

4.2.2. Sub conclusion

LCA performed on building level shows results of 10.98-12.21 kg CO_2-eq./m^2/year. The variation is large and is described in building envelope Chapter 4.2.1, as it highly depends on building specific soil conditions. The average values are seen on Figure 30 for a general overview. Constructions have the highest share of CO_2 emissions accounting for 83% of total emissions, meanwhile operational energy only accounts for 12% and technical installations for 4%. Building process has only 1% share compared to total emissions. Building process is almost negligible with 0.07 kg CO_2-eq./m^2/year, as the machinery fuel consumption for screw installation is very low.

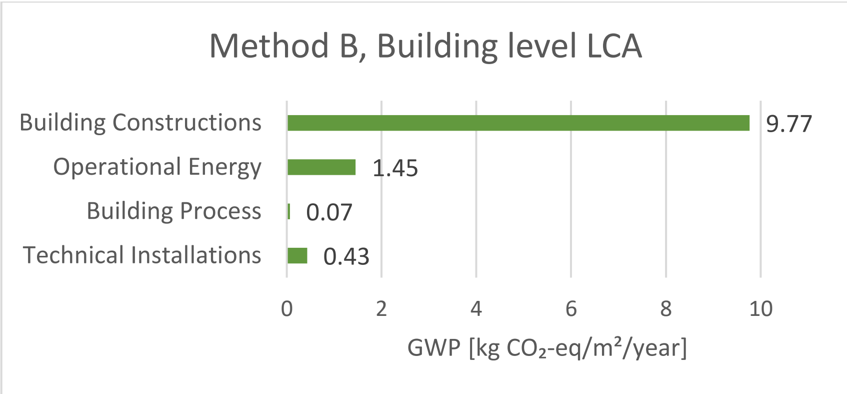


Figure 30 Method B, average LCA results in building level

Results on Figure 31 show the distribution of GWP emissions for building constructions excluding operational energy. The foundation and floor are almost equally sized and are major contributors to GWP, meanwhile external wall is second biggest contributor of 2.15 kg CO_2-eq./m^2/year. The three constructions together account for 70% of total GWP emissions on construction level. There is still potential to reduce emissions for these building construction parts, which are described in upcoming methods.

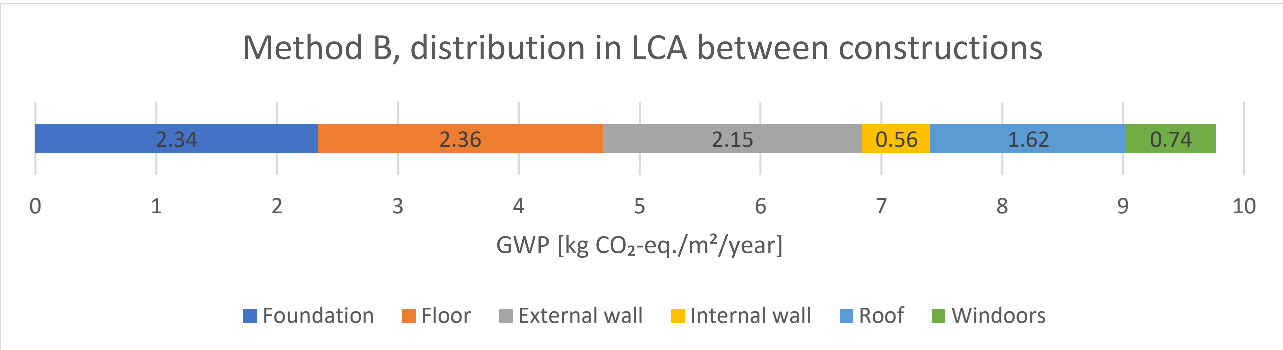


Figure 31 Method B, average GWP distribution in building envelope incl. transport

Distribution across different phases, see Figure 32, shows that 5.49 kg CO_2-eq./m^2/year emissions originate from A1-3 phases. Other phases such as A4, A5, B4 and C4 are of less significance, meanwhile B6 (Energy for operation) and C3 (Waste treatment) have more significance with 1.45 and 1.75 kg CO_2-eq./m^2/year emissions respectively.

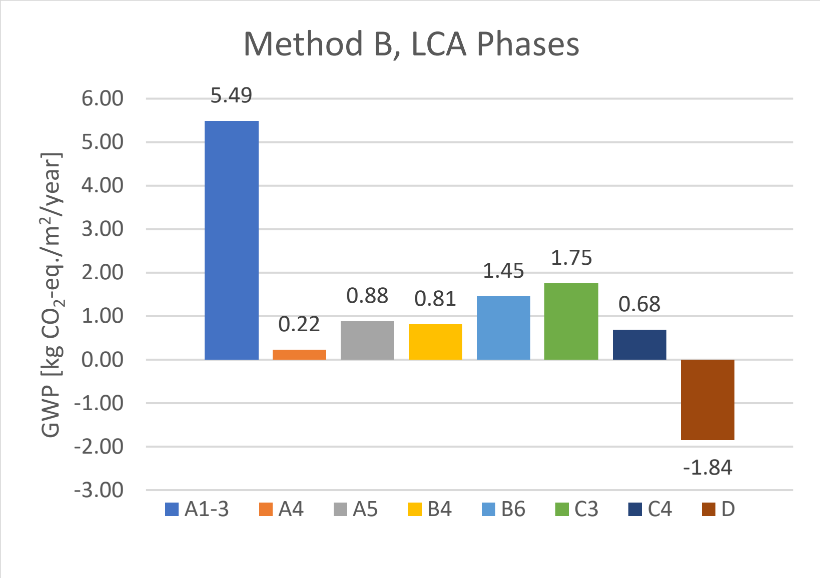


Figure 32 Method B, distribution between phases

Phase D, which is out of the total GWP calculation scope has a remarkably higher potential with -1.84 compared to -1.05 kg CO_2-eq./m^2/year, due to higher recycling potential of screw piles, that are made of galvanized steel. A4 and A5 phases are calculated identically as Method A, Chapter 4.1.3.

Foundation and floor slab

Calculation for screw pile foundation in LCAbyg is done by modifying existing strip foundation with a width of 300 mm concrete and increasing EPS insulation to 300 mm to match overall volume. Rebar and limestone plaster remains unchanged.

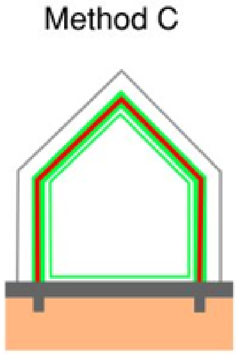
Floor and foundation calculation can now reduce soil removal, as only the top layer gets excavated for the floor slab. Foundation does not require any further excavation than the floor slab depth. A part of the excavated soil gets distributed in the property. Phase A5 consists of consumption for machinery on site, and phase A4 includes transport of materials to the building site with estimated distance of 1100 and 100 km for screw piles and gravel respectively. Overall transport for gravel is reduced, as less quantities are needed to establish the floor slab.

A4 Transport		
Screw pile, delivery from Czech Republic factory		1100 km
Gravel delivery		100 km
Soil removal for foundation and floor slab	27.8 m^3/ 41,625 kg	100 km
Soil moved with machinery	74 m^3	

Table 10 Method B, Phase A4 transport calculation for foundation and floor slab

In building process for foundation and slab, there has been excavated 74 m^3 of soil, of which 27.8 m^3 is removed from property by 100 km truck transport. The remaining soil is deposited in the property. Average transport to building site for materials (A4) calculated GWP emissions for the three buildings ranges from 0.21 to 0.26 kg CO_2-eq./m^2/year. Meanwhile building process (A5) ranges from 0.05 to 0.09 kg CO_2-eq./m^2/year.

4.3. Method C – Wood framing with concrete slab



For Method C, a substitution of the bearing construction is made. The foundation and slab are kept as Method A, strip foundation with Leca thermal blocks. Reference building has been converted to a wood-framed external wall with wood cladding. Internal dimensions of the building remain unchanged. Insulation thickness has been adjusted to the requirements from the functional unit. The change in constructions can be seen on Table 11, where external wall is changed from EW.1/EW.2 to EW.3 or EW.4.

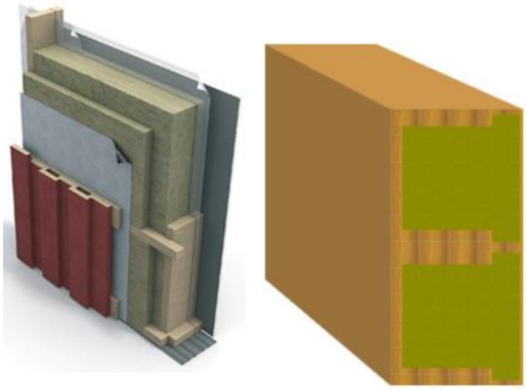
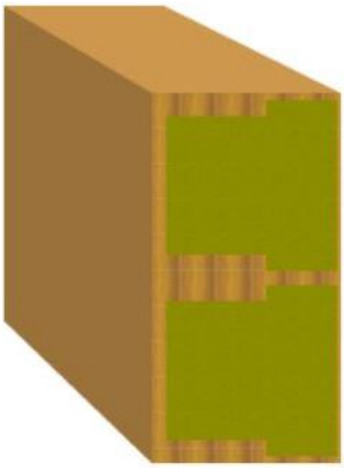
EW.3 and EW.4 differs in insulation layer thickness, which is adjusted for each building to match the energy frame. Another minor adjustment is the roof construction, the cc 1000 (RP.1A) is adjusted to the structural wood framing of cc 600 (RP.1B), which increases the U-value slightly, due to a higher share of wood. U-value calculation is to be found in Appendix 05a.

Overview	**Type**	**Description**	**U-value** [W/m²K]	**Method** A, B, C, D, E
Building 1 - Klarup				
External wall construction	EW.3	Lightweight timber wall, 390 mm insulation class 34, external wood cladding.	0.123	C
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (pitched) construction	RP.1B	Pitched roof (attic) flat ceiling, 390 mm insulation class 37. cc 600.	0.099	
Building 2 - Klitmøller				
External wall construction	EW.4	Lightweight timber wall, 485 mm insulation class 34, external wood cladding.	0.101	C
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (flat) construction	RF.1B	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 600.	0.065	
Building 3 - Solrød Strand				
External wall construction	EW.3	Lightweight timber wall, 390 mm insulation class 34, external wood cladding.	0.123	C
Floor slab construction	FS.1	Slab, concrete on 300 mm EPS and Leca fill.	0.094	
Roof (flat) construction	RF.1B	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 600.	0.065	

Table 11 Method C construction types

4.3.1. Building envelope

External walls are wood framed and insulated with class 34 mineral wool. Interior finish and finish on internal walls are drywall, and plaster with 2-layer acrylic paint on fiber gypsum boards of 15 mm. 95 mm insulation layer is reserved for installations. External façade cladding is installed on horizontal and vertical furring. The following two wall construction types are the substitutions to the constructions described, which is the main change of buildings. Wood and mineral wool share calculation is specified on Appendix 05b.

EW.3 - External wall type 3 – wood framing, 390 mm insulation and wood cladding	
 *Figure 33 Wood framing with wood cladding. Illustration by (Paroc) and (Rockwool).*	15 mm fiber gypsum board 95 mm installation layer with insulation PE-vapor barrier Stud bay: 295 mm wood framing with class 34 mineral wool insulation Exterior: Air and weather barrier 25 + 15 mm wood furring 23 mm wood cladding U-value: 0.123 W/m^{2}K
EW.4 - External wall type 4 – wood framing, 485 mm insulation and wood cladding	
 *Figure 34 Wood framing with wood cladding. Illustration by (Rockwool)*	15 mm fiber gypsum board 95 mm installation layer with insulation PE-vapor barrier Stud bay: 390 mm wood framing with class 34 mineral wool insulation Exterior: Air and weather barrier 25 + 15 mm wood furring 23 mm wood cladding U-value: 0.101 W/m^{2}K

The external walls are built on concrete strip foundation from Leca thermal blocks, with 190 mm EPS insulation in between, just like in Method A, where the construction description is located. The linear losses are unchanged. The change in the roof construction, is that the distance between the rafters is reduced from cc 1000 (1 m) to cc 600 (0.60 m). Structural wood/mineral wool ratio is explained in Appendix 05c. The roof construction is the same but with more wood, and the change in U-value is as follows.

RP.1A cc 1000, U-value: 0.095 W/m²K → RP.1B cc 600, U-value: 0.099 W/m²K
RF.1A cc 1000, U-value: 0.061 W/m²K → RF.1B cc 600, U-value: 0.065 W/m²K

LCA results are compared on Figure 35 to assess difference in external wall GWP between Method A/B and Method C. Results shows savings in rage of -0.86 to -1.53 kg CO_2-eq./m^2/year when traditional reference wall with masonry construction is substituted with wood framing. Savings are in other words from 40-59% depending on building typology.

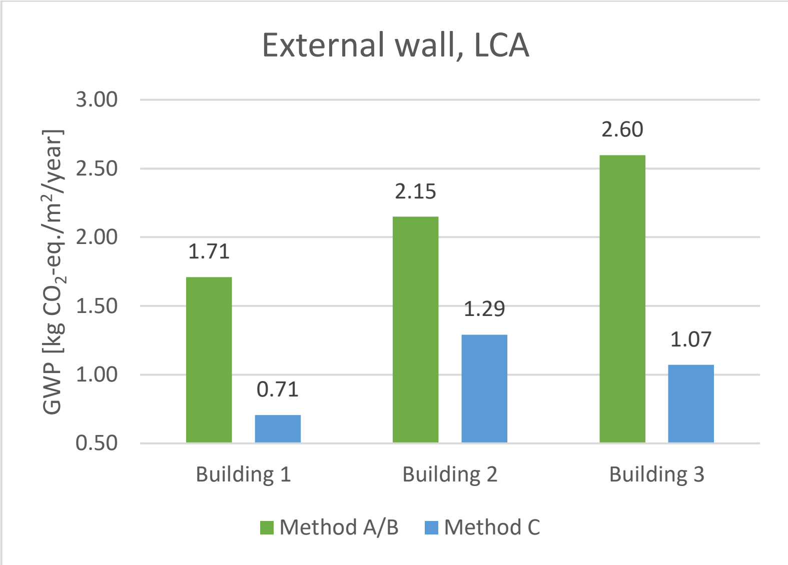


Figure 35 LCA result comparison of Method A/B and Method C, substitution of external wall with wood framing

Difference in savings between building typologies is impacted by differentiation in architecture and window sizes, which influences area of the walls. Another factor is different wall type (EW.4) used in Building 2. The reference wall (EW.2) has benefited from concrete walls with resulting heat capacity of 144 Wh/K·m^2, where Building 1 and 3 was 59.3 Wh/K·m^2 with EW.1 wall type. Together with different architecture, window size and orientation, the energy frame required lower U-value of constructions and therefore the construction thickness is increased for EW.4 wall.

4.3.2. Sub conclusion

LCA performed on building level shows results for the three respectively buildings of 8.95-11.55 kg CO_2-eq./m^2/year. The variation is relatively large and is described in building envelope Chapter 4.2.1, as it highly depends on building specific soil conditions. The average values are seen on Figure 36 for a general overview. Constructions have highest share of CO_2 emissions accounting for 80% of total emissions, meanwhile operational energy only accounts for 14% and technical installations for 4%. Building process has only 1% share compared to total emissions. The operational energy share is increased slightly due to generally lower total GWP.

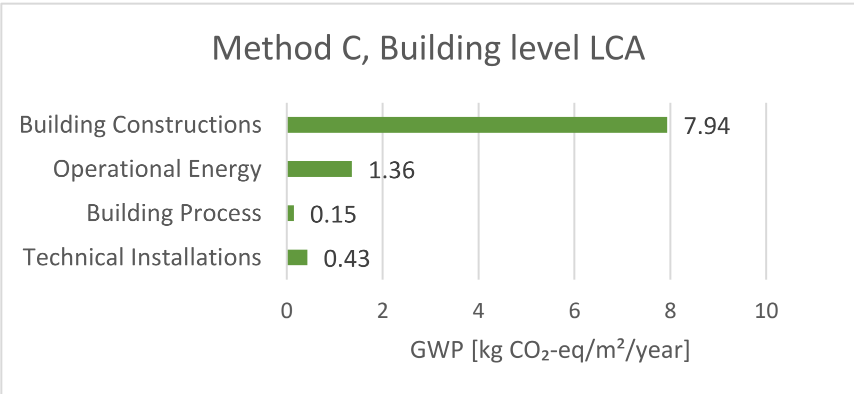


Figure 36 Method C, average LCA results in building level

Results on Figure 37 show distribution of GWP emissions for building constructions excluding operational energy. The distribution has changed remarkably compared to previous methods. The floor is still the biggest contributor to GWP, followed by roof. External wall, which has been replaced with structural wood now accounts only for 10% GWP compared to buildings total GWP. Floor and foundation are responsible for 42%. Therefore, it can be concluded, that there is still potential to reduce emissions for floor and foundation.

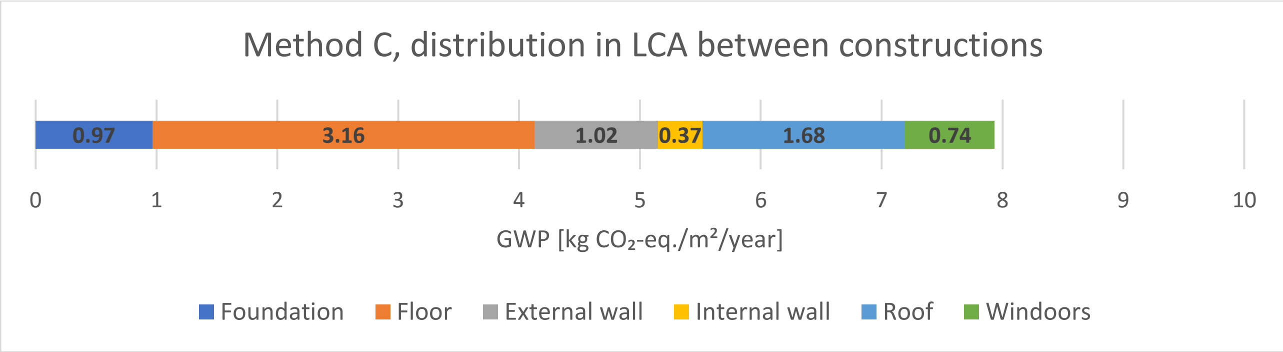


Figure 37 Method C, average GWP distribution in building envelope incl. transport

Distribution across different phases on Figure 38, shows that 1.28 kg CO_2-eq./m^2/year emissions originate from A1-3 phases, which is lower by a considerable margin compared to previous methods A/B. The distribution is heavily impacted by substitution of external wall and internal walls with wood framing. This is mainly due to wood biogenic properties that results in negative GWP for wood products used in the external wall. Phase C3 has the highest GWP, which consists mainly of waste processing the structural wood. Wood at end-of-life will release the biogenic CO_2 that has absorbed in the growing process included in A1-3 phase and therefore C3 phase is the highest in terms of GWP, with 4.2 kg CO_2-eq./m^2/year. In this calculation, wood has not been considered to be recycled in C4 phase, but instead incinerated in waste-to-energy plant. GWP from phases such as A4 and A5, associated with transport and building process are generally reduced, due to lower transportation weight.

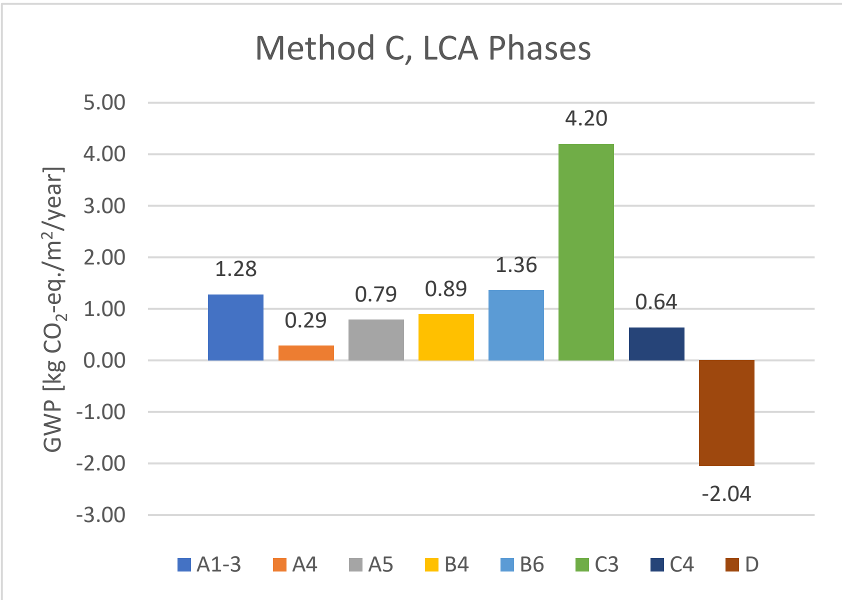


Figure 38 Method C, distribution between phases

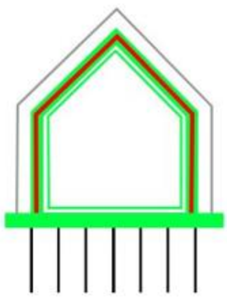
Phase D, which is out of total GWP calculation scope, has slightly higher recycling potential compared to previous methods due to contribution of waste-to-energy incineration. This generally shows that wood has greater recycling potential.

External walls, internal walls, floor, foundation, and roof construction

Phase A4 and A5 are calculated identically as Method A and B, Chapter 4.1.3. The average transport to building site for materials (phase A4) has been calculated. The GWP for the three buildings ranges from 0.21 to 0.40 kg CO_2-eq./m^2/year. Meanwhile building process (A5) ranges from 0.05 to 0.29 kg CO_2-eq./m^2/year.

4.4. Method D – Wood framing with screw pile foundation

Method D



The reference buildings with primarily brick, concrete and steel have been substituted with wood-based materials and converted to a wood-framed construction with wood cladding. Comparing Method C and D, Method D substitutes the concrete slab with a wood-framed floor deck. The deck is supported by beams on screw pile foundations. In general, all structural building constructions are made from wood and wood-based materials, except for screw piles, the change is from FS.1 to FS.3 and FS.4. The floor slab is now a floor deck with ventilated crawl space, with a screw pile foundation. The insulation in all constructions is mineral wool, class 34, see Figure 39 below. U-value calculation is to be found in Appendix 06a.

Overview	**Type**	**Description**	**U-value** [W/m²K]	**Method** A, B, C, D, E
Building 1 - Klarup				
External wall construction	EW.3	Lightweight timber wall, 390 mm insulation class 34, external wood cladding.	0.123	D
Floor slab construction	FS.3	Slab, wood joists with 415 mm insulation class 37 on screw pile foundation.	0.106	
Roof (pitched) construction	RP.2	Pitched roof (attic) flat ceiling, 590 mm insulation class 37. cc 600.	0.065	
Building 2 - Klitmøller				
External wall construction	EW.4	Lightweight timber wall, 485 mm insulation class 34, external wood cladding.	0.101	D
Floor slab construction	FS.4	Slab, wood joists with 535 mm insulation class 34 on screw pile foundation.	0.078	
Roof (flat) construction	RF.1B	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 600.	0.065	
Building 3 - Solrød Strand				
External wall construction	EW.3	Lightweight timber wall, 390 mm insulation class 34, external wood cladding.	0.123	D
Floor slab construction	FS.3	Slab, wood joists with 415 mm insulation class 37 on screw pile foundation.	0.106	
Roof (flat) construction	RF.1B	Flat roof, 585 mm insulation class 34, ventilated roofing on battens. cc 600.	0.065	

Figure 39 Method D construction types

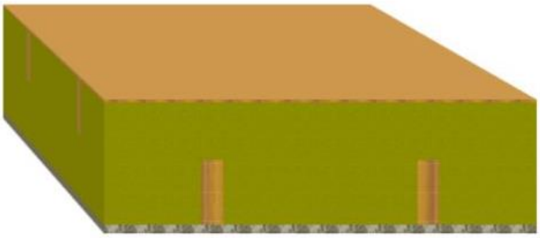
The screw pile foundation is a unique solution for each house and the respective geotechnical conditions, why these can vary, dependent on the underground in the specific area. For Method D, BAYO.S has provided knowledge and calculation on type, length, placement etc. for Building 1 (Appendix 06b) and 3 (Appendix 06c), based on geotechnical samples and surveys, done by a company in collaborations with BAYO.S. A material list is available in Appendix 02c. Building 2 was not able to calculate due to BAYO.S limited resources and short notice, why there is made assumptions, all explained in the appendix, where Method B placement and quantities are used (Appendix 04c).

4.4.1. Building envelope

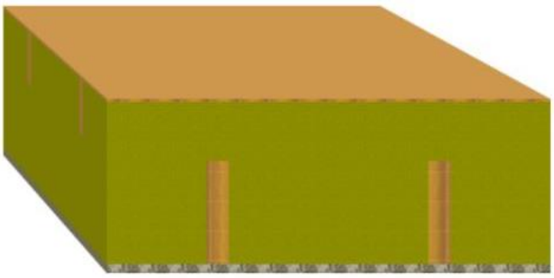
The method is similar to building Method C, but the floor slab is changed to a floor deck. The deck is built in joist bay with insulation and finish on external and internal side of the construction. The change in construction affects the U-value and the floor decks is shown below, with the respective U-value. Building 1 and 3 is built with FS.3 and Building 2 is built with FS.4. The insulation thickness varies due to the need of fulfilling the energy frame and the set functional unit. Roof share of structural wood/mineral wool is explained in Appendix 06e.

Figure 40 Floor deck illustration. Wood joist on screw pile foundation. (Goliath Tech)

The floor deck is built on screw piles, as illustrated on Figure 40 here. The pattern and direction of the floor deck can be seen and is also visualized with insulation on the construction-descriptions below.

<table>
<tr><td colspan="2">FS.3 - Floor slab (deck) type 3 – Crawlspace floor deck with screw pile foundation, 415 mm insulation</td></tr>
<tr><td>
Figure 41 Floor deck, 415 mm insulation on wood joist. (Rockwool)</td><td>Floor
22 mm floorboard
195 x 45 mm floor joists with mineral wool insulation
220 x 45 mm triple girder beam

Screw pile foundation on girder beam

U-value: 0.105 W/m²K</td></tr>
<tr><td colspan="2">FS.4 - Floor slab (deck) type 4 – Crawlspace floor deck with screw pile foundation, 535 mm insulation</td></tr>
<tr><td>
Figure 42 Floor deck, 535 mm insulation on wood joist. (Rockwool)</td><td>Floor
22 mm floorboard
195 x 45 mm floor joists with mineral wool insulation
340 x 45 mm triple girder beam

Screw pile foundation on girder beam

U-value: 0.077 W/m²K</td></tr>
</table>

The bearing construction consist of the external wall, which are built on the floor deck. Most of the original building materials is substituted with wood-based materials, except from the insulation layer, made of mineral wool. Specified wood and mineral wool share can be found in Appendix 06d.

LCA results are compared on Figure 43 to assess difference in floor construction GWP between Method C (equivalent to Method A) and Method D. Results shows the range of savings, from -1.18 to -3.24 kg CO_2-eq./m^2/year when traditional reference wall with masonry construction is substituted with wood framing. Savings are in range of 29-59% depending on building typology.

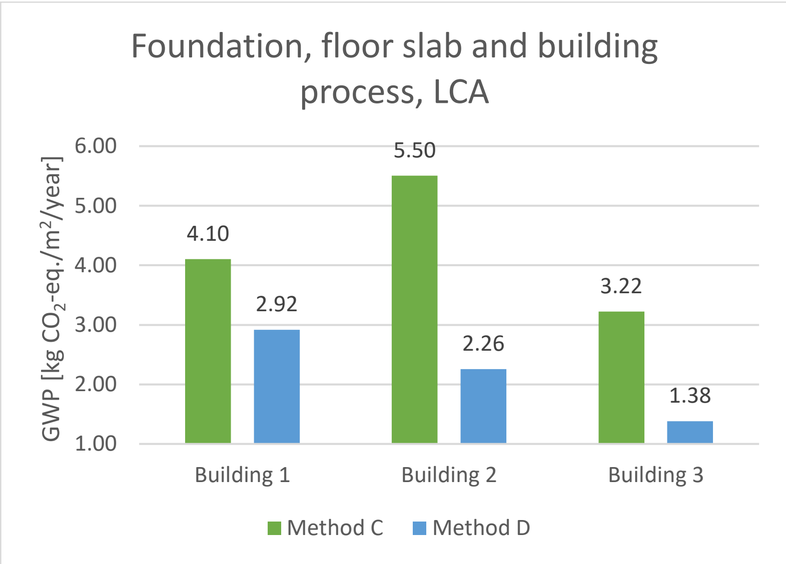


Figure 43 LCA result comparison of Method C with Method D, substitution of floor slab with wood framing

Savings depend on soil conditions in building location. Building 1, with medium level of soil excavation required for traditional foundation, benefits least (29% savings) as the screws also must be accordingly longer in these soil conditions. In the case, where very high-level excavation level is required in Building 2, savings are up to 59% as the amount of soil needed to be removed from the property is very high in concrete foundation/slab, together with the gravel required to establish the floor slab. Building 3 has low level of excavation level, which provides 57% savings, although the GWP is generally lower for traditional concrete foundation/slab as well for the specific soil conditions.

4.4.1. Sub conclusion

LCA performed on building level shows results for the three respectively buildings of 7.2–8.14 kg CO_2-eq./m^2/year. The variation is relatively large and is described above, as it highly depends on building specific soil conditions. The average values are seen on Figure 44 for a general overview. Constructions have the highest share of CO_2 emissions accounting for 77% of total emissions, meanwhile operational energy only accounts for 17% and technical installations for 6%. Building process is almost negligible with 0.02 kg CO_2-eq./m^2/year, as the machinery for screw installation consumption is low.

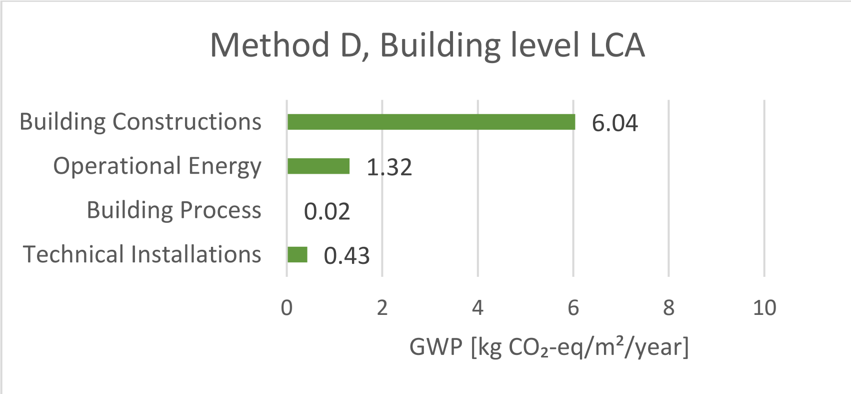


Figure 44 Method D, average LCA results in building level

Results on Figure 45 show distribution of GWP-emissions for building constructions excluding operational energy. GWP of foundation and floor construction has been greatly reduced, and thus now only represents 28% of buildings total GWP. Single biggest contributor to GWP is in this case the roof, with 1.74 kg CO_2-eq./m^2/year or 22%.

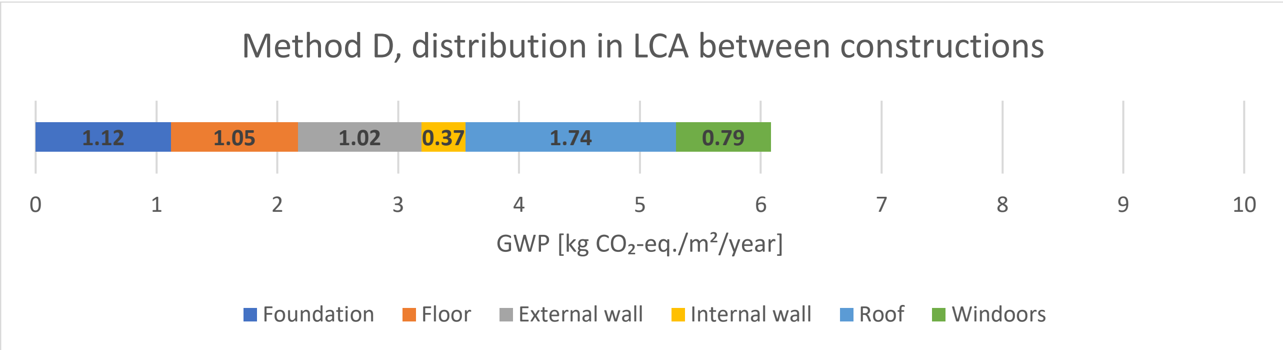


Figure 45 Method D, average GWP distribution in building envelope incl. transport

Distribution across different phases, can be seen on Figure 46 and shows that -0.45 kg CO_2-eq./m^2/year emissions originate from A1-3 phases, which has been reduced more noticeably due to higher share of wood in constructions overall, due to floor construction of wood framing. Phase C3 has even higher GWP of 4.93 kg CO_2-eq./m^2/year, which consists mainly of waste processing the structural wood. GWP from phases such as A4 and A5, associated with transport and building process are generally reduced further. Phase D, which is out of GWP calculation scope, has increased recycling potential of -2.47 kg CO_2-eq./m^2/year. This is another consequence of increased use of wood in constructions.

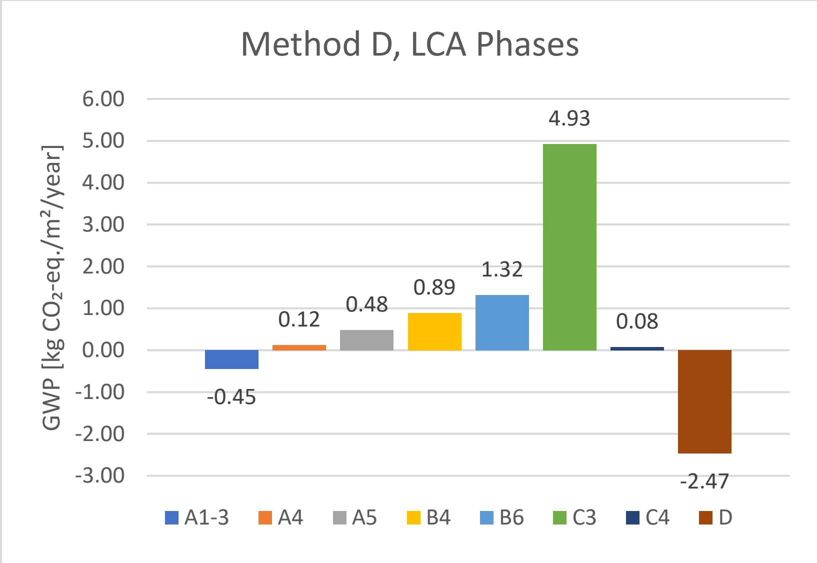
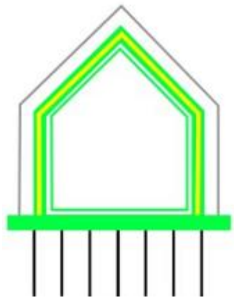


Figure 46 Method D, distribution between phases

External walls, internal walls, floor, foundation, and roof construction

Phase A4 and A5 are calculated identically as Method A, B and C, Chapter 4.1.3. The average transport to building site for materials (phase A4) has been calculated. The GWP emissions for the three buildings ranges from 0.11 to 0.13 CO_2-eq./m^2/year which is significantly lower than the previous methods. Meanwhile building process (A5) ranges from 0.01 to 0.04 CO_2-eq./m^2/year, which could be considered as negligible, as the soil excavation is completely eliminated and only screw installation is remaining. The next method, Method E, is an alternative an innovative building system, which specializes in limiting thermal bridges, and with wood-fiber as insulation which would be the next step to substitute mineral wool insulation.

4.5. Method E – ACERA Wood framing with screw pile foundation



Compared to Method D, this method will introduce a new and patented ACERA wood framing system. It is expected that the majority of the structural components are prefabricated. System structurally uses special wood framing members with thermal bridge break. All constructions are replaced with ACERA wood framing in this method.

Wood fiber boards are used for weatherproofing exterior, and OSB-boards are used for airproofing interior and are installed on-site. Mineral wool insulation is replaced with wood fiber insulation, which is also installed on-site with blown-in method. U-value calculation is to be found in Appendix 07a.

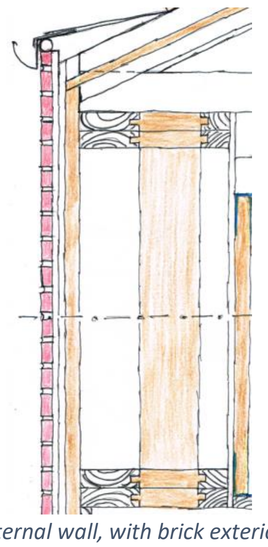
Overview	Type	Description	U-value [W/m²K]	Method A, B, C, D, E
Building 1 - Klarup				
External wall construction	EW.5	*ACERA*: Lightweight timber wall with thermal break, 328 mm wood-fiber insulation class 37.	0.103	E
Floor slab construction	FS.5	*ACERA*: Slab, wood joists with thermal break, 432 mm food-fiber insulation class 37 on screw pile foundation.	0.093	
Roof (pitched) construction	RP.3	*ACERA*: Pitched roof (attic) flat ceiling, 505 mm wood-fiber insulation class 37. cc 600.	0.073	
Building 2 - Klitmøller				
External wall construction	EW.5	*ACERA*: Lightweight timber wall with thermal break, 328 mm wood-fiber insulation class 37.	0.103	E
Floor slab construction	FS.6	*ACERA*: Slab, wood joists with thermal break, 516 mm food-fiber insulation class 37 on screw pile foundation.	0.080	
Roof (pitched) construction	RF.3	*ACERA*: Flat roof with thermal break, 533 mm wood-fiber insulation, ventilated roofing on battens cc 600.	0.068	
Building 3 - Solrød Strand				
External wall construction	EW.5	*ACERA*: Lightweight timber wall with thermal break, 328 mm wood-fiber insulation class 37.	0.103	E
Floor slab construction	FS.5	*ACERA*: Slab, wood joists with thermal break, 432 mm food-fiber insulation class 37 on screw pile foundation.	0.093	
Roof (flat) construction	RF.2	*ACERA*: Flat roof with thermal break, 458 mm wood-fiber insulation, ventilated roofing on battens cc 600.	0.079	

As described for Method D, the screw pile foundation is a unique solution for each house, but due to the similarities of Method D and E, the geotechnical conditions are the same and do not vary from Method D, Chapter 4.4.1, as specified in Appendix 04c, 06b and 06c (same as for Method D).

4.5.1. Building envelope

ACERA framing system is described for external wall, floor deck, pitched roof with flat ceiling and flat roof with flat ceiling. Detailed description of constructions is located in Appendix 07b. External wall (Figure 47) is constructed with equivalent 15 mm fiber gypsum board as in Method C and D. It is attached to battens, which are mounted in grooves of 36 mm floor heating board. Electrical and plumbing installations are installed in the remaining grooves and custom-routed on-site if needed. The floor heating board is therefore not used for heating purpose in walls, but for mounting, acoustic and insulation purposes. Floor heating board is attached to the OSB 3 board (low VOC), which acts as an airproofing layer and vapor retardant in that way, installations are not penetrating the airproofing layer as they are installed in the floor heating board. Moisture levels are acceptable when diffusion resistance (GPa s m²/kg) interior/exterior ratio is minimum 1:5, this can be achieved with OSB +hard wood fiber board on interior and soft rainscreen board on exterior (Marcus Therkelsen 2020, p. 48).

Stud bay as described below is constructed of ACERA studs, which features a combination of 45 mm wood framing members interrupted by 45 mm wood-fiber board as middle part of the stud, which are joined with tongue and groove joints attached with glue. Cavity is filled with blow-in wood fiber insulation. Exterior side uses wood-fiber board as weatherproofing layer providing additional insulation. Façade cladding material is the same as Method C and D. Internal walls are constructed equivalent for Method C/D, except for floor heating board that is installed behind fiber gypsum board. External wall structural wood/insulation ratio is described in Appendix 07d.

<table>
<tr><th colspan="2">EW.5 - External wall type 5 - ACERA wall system</th></tr>
<tr><td>
Figure 47 External wall, with brick exterior finish (replaced with wood cladding in calculation)</td><td>12.5/15 mm fiber gypsum board
36 mm wood fiber floor heating board with battens
11 mm OSB 3 board (vapor retardant)

Stud bay members:
328 mm cold-bridge interrupted ACERA studs
328 mm wood fiber insulation

Exterior (ventilated):
35 mm wood fiber board water resistant barrier
23 mm furring vertical
23 mm furring horizontal
Wood cladding

U-value: 0.103 W/m²K</td></tr>
</table>

The LCA calculation on Figure 48 shows varying results using ACERA wall framing system depending on building. It ranges from 1.18 to 2.03 kg CO_2-eq./m^2/year which is generally higher than Method C or D and lower than Method A/B. Building 1 has lowest result of 1.18 CO_2-eq./m^2/year, which is influenced by beneficial building geometry and window sizes resulting in relatively low external wall area. Building 2 has the highest result among the three buildings, despite having the smallest floor area, it has biggest external wall area. Same tendences can be observed for other methods.

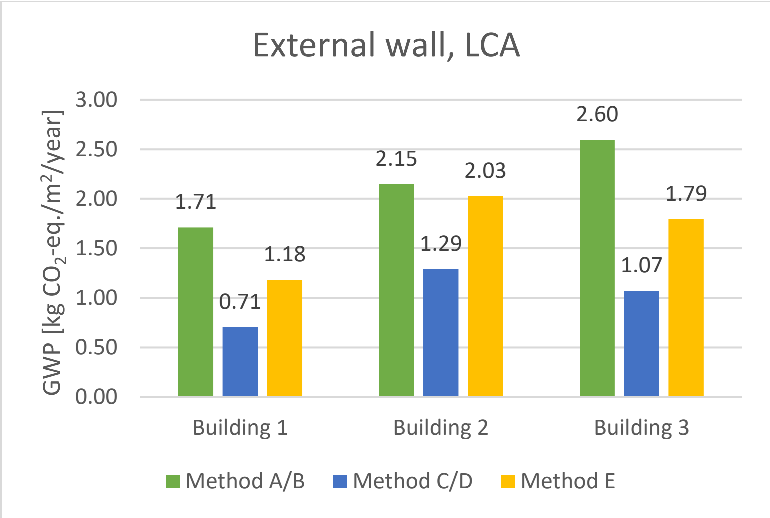


Figure 48 LCA result comparison of Method A, B, C, D and E for external wall options

ACERA wall framing includes use of wood fiber boards on exterior and interior, that has caused the GWP emissions to be higher than Method C/D, despite having overall smaller thickness of only 450 mm compared to up to 563 mm for Method C/D in Building 2.

The foundation is built on screw piles, equivalent to Method D. Floor deck is supported by 3 x 45 mm joined wood joist members as bearing joists, also equivalent to Method D. However, floor deck (Figure 49) is built differently with ACERA method. Instead of fiber cement board as exterior barrier, 18 mm wood fiberboard with bitumen coating is used. Joist bay layer, which is above the bearing layer, consists of ACERA floor joists with cold-bridge interruption. Cavity is filled with blow-in wood fiber insulation. On top of the stud bay, seen on Figure **50**, the 23 mm batten sheathing is attached to the joists. Vapor retardant barrier is located on top of battens. Floor heating board is the next layer, with fiber cement board installed before the finish flooring. In bathrooms, instead of floor heating board and fiber cement board, steel sheeting is used as a base for fiber reinforced concrete pour of 48 mm, with embedded floor heating. FS.5 and FS.6 differentiates with insulation layer thickness, which is adjusted for each building specifically to match the functional unit. Floor structural wood/insulation ratio is described in Appendix 07e.

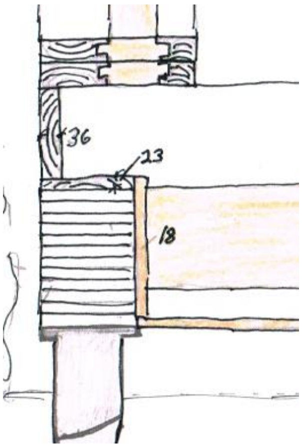
<table>
<tr><th colspan="2">FS.5/6 - Floor slab type 5/6 - ACERA joist framing and screw pile foundation</th></tr>
<tr><td>


Figure 49 Crawl space with screw pile foundation

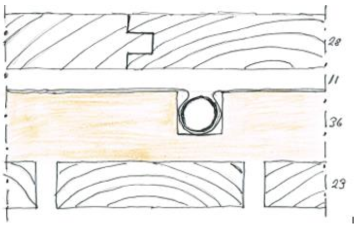


Figure 50 Floor construction above joists
</td><td>
Floor finish (wood or tile floor)
12 mm fiber gypsum-board
36 mm wood fiber floor heating board
Vapor retardant-barrier (membrane)
23 mm batten sheathing

Floor joist member:
432-516 mm cold-bridge interrupted ACERA joists
432-516 mm wood fiber insulation

18 mm wood fiberboard with bitumen coating
Screw pile foundation on girder beam

U-value, (cc 600): 0.079-0.092 W/m^{2}K
U-value (cc 300), bathrooms: 0.085-0.102 W/m^{2}K
</td></tr>
</table>

The LCA results on Figure 51 shows generally low GWP for floor and foundation (incl. building process) for ACERA Method E, compared to Method A, B or C where traditional concrete foundation/slab is used, lowest being for Building 3, with 1.8 kg CO_2-eq./m^2/year. Variation is caused by building specific location (for screw installation) as in Method D and building typology variation in terms of floor deck framing and material consumption. Wood framing with wood fiber insulation of floor deck has similar GWP emissions to Method D, although slightly higher due to the same reasons as for external wall, more board-based material. Wood fiber insulation boards for cold bridge interruption has caused higher GWP emissions than Method D where mostly membrane type material is used for weather and airproofing.

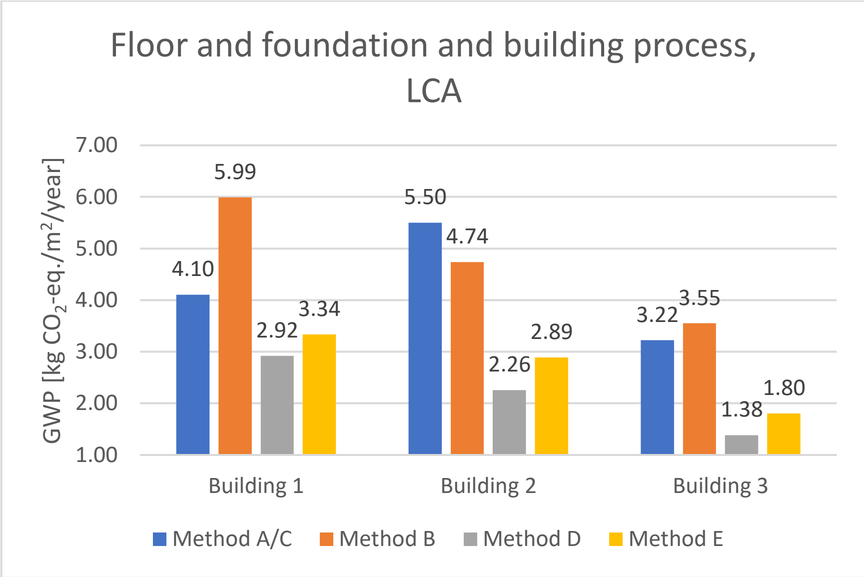
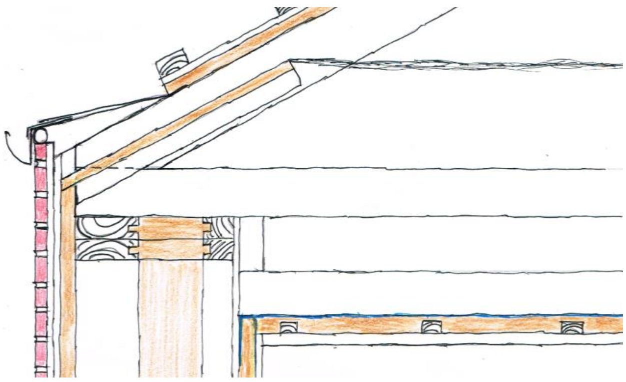


Figure 51 LCA result comparison of Method A, B, C, D and E for floor and foundation options

The ceiling on Figure 52 for pitched roof (Building 1) is constructed with standard framing and cc 600 as in Method A/B/C, D except for floor heating board used in the same manner as in walls, before hanging 25 mm drywall gypsum board. Instead of PE-vapor barrier, vapor retardant from textile materials is used as air- and vapor proofing layer. Ceiling rafters are constructed in two inhomogeneous layers with wood fiber insulation, and one homogenous layer on top of the rafters. Wood fiber weatherproofing board is used as roof decking and waterproofing layer under battens. Roofing material is the same as in other methods. Roof structural wood/insulation ratio is described in Appendix 07c.

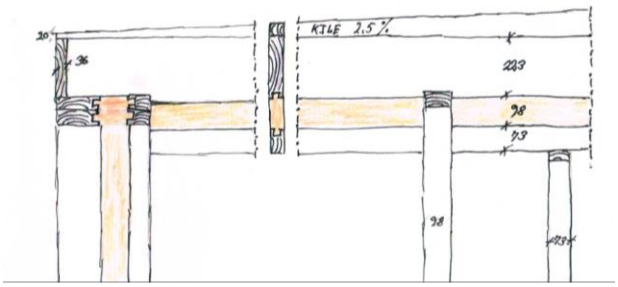
<table>
<tr><th colspan="2">RP.3 – Roof pitched type 3 - ACERA rafters framing, 505 mm wood fiber insulation</th></tr>
<tr><td>
Figure 52 Pitched roof construction with flat ceiling, with external wall joint detail</td><td>26 mm drywall
36 mm wood fiber floor heating board with battens
Vapor retardant-barrier (membrane)

Ceiling rafters-layer:
95 + 215 mm rafters
505 mm wood fiber insulation

Roof:
Ventilated attic
Wood fiber weatherproof board
Roofing tile or wood cladding

U-value: 0.073 W/m^{2}K</td></tr>
</table>

Building 2 and 3 features flat roof type and two different insulation layer thicknesses to match the functional unit. Ceiling rafter layer consist of ACERA joists, in same manner as for external wall and floor, except for vapor retardant membrane barrier is used for airproofing. Additional wedged rafter inhomogeneous layer with insulation is added on top of ACERA joists to create 2.5% slope for roofing. Weatherproofing is achieved with wood fiber weatherproofing board. Roofing consists of 50 mm ventilation cavity and plywood sheathing for asphalt roll roofing.

RF.2/3 – Roof flat type 2/3 with flat ceiling - ACERA framing, wood fiber insulation	
 *Figure 53 Flat roof construction, with flat ceiling, external wall joint detail*	26 mm drywall 36 mm wood fiber floor heating board with battens Vapor retardant-barrier (membrane) Ceiling rafters-layer: 458-533 mm cold-bridge interrupted ACERA rafters 458-533 mm wood fiber insulation Wedged layer, 2.5% slope (top) Wood-fiber weatherproofing board Roof: 50 mm furring ventilated spacing 20 mm roofing plywood Asphalt roll roofing U-value: 0.068-0.079 W/m²K

LCA results, seen at Figure 54 and Figure 55, indicates that GWP is increased with each method, where wood share is higher and the overall building-specific heat capacity is lower, both for pitched and flat roof. Correlation of specific heat capacity and energy consumption is described in Chapter 4.6. Due to the need of improving the U-value of constructions, roof is mainly used to increase insulation thickness, as it is considered the most realistic approach. This is reflected by increasing GWP that is expected. ACERA method has the highest GWP, which follows the same trend as external wall and floor deck due to additional boards in the construction.

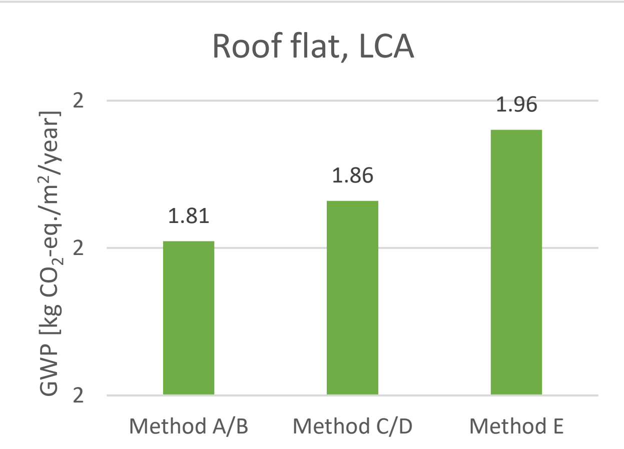


Figure 54 LCA result comparison of Method A, B, C, D and E for flat roof options (Building 2 & 3)

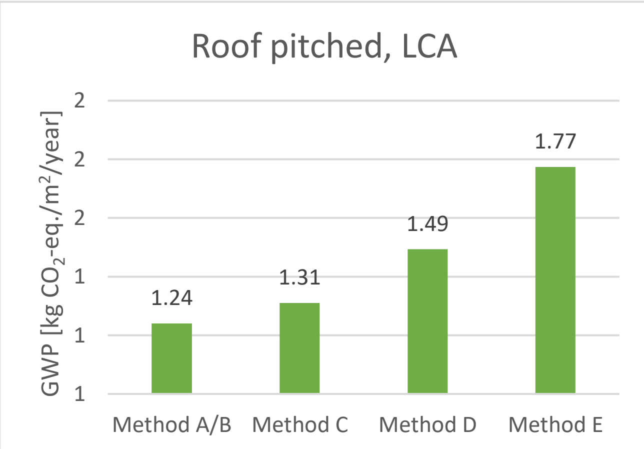


Figure 55 LCA result comparison of Method A, B, C, D and E for pitched roof options (Building 1)

4.5.1. Sub conclusion

LCA performed on building level shows results for the three respective buildings of 8.59-10.04 kg CO_2-eq./m^2/year. The variation is relatively small and is described in building envelope Chapter 4.5.1, as it depends on building specific soil conditions and building typology. The average values are seen on Figure 56 for a general overview. Constructions have highest share of CO_2 emissions accounting for 82% of total emissions, meanwhile operational energy only accounts for 14% and technical installations for 5%. Building process is almost negligible with 0.02 kg CO_2-eq./m^2/year, as the machinery for screw installation consumption is very low.

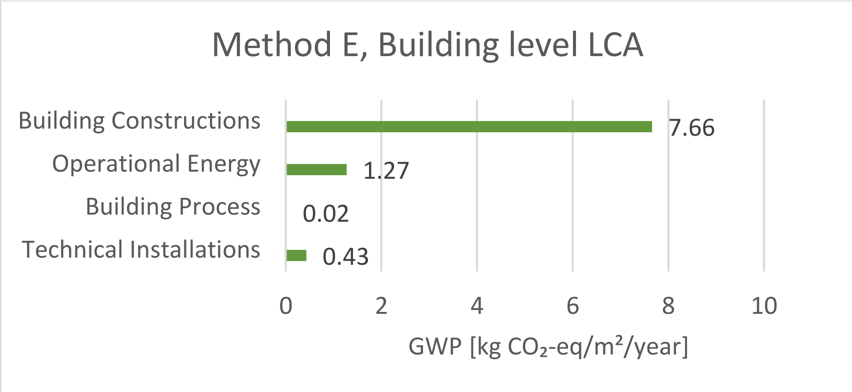


Figure 56 Method E, average LCA results on building

Results on Figure 57 shows the distribution of GWP emissions for building constructions excluding operational energy. The distribution has changed remarkably compared to previous methods. The floor is still the biggest contributor to GWP, followed by the roof. External wall, which has been replaced with structural wood now accounts for only 11% GWP compared to buildings total GWP. Floor and foundation are responsible for 28%.

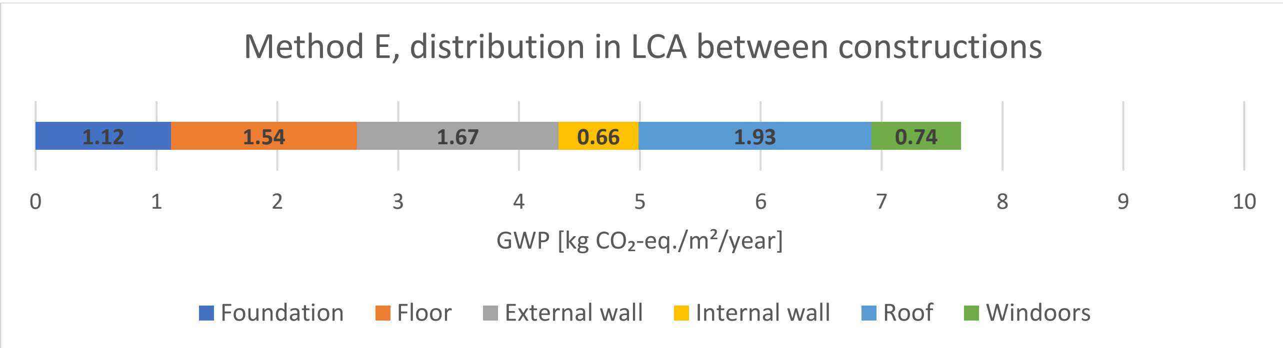


Figure 57 Method E, average GWP distribution on building envelope incl. transport

Distribution across different phases, see Figure 58, shows that -5.25 kg CO_2-eq./m^2/year emissions originate from A1-3 phases, which is lower by a considerable margin compared to previous methods. The distribution impacted is heavily by substitution of external wall and internal walls with wood framing. This is mainly due to wood biogenic properties that results in negative GWP for wood products used in the external wall. Phase C3 is the highest GWP phase, which consists mainly of waste processing the structural wood. Wood at end-of-life will release the biogenic CO_2 that was absorbed in the growing process included in A1-3 phase and therefore C3 phase is the highest in terms of GWP, with 11.35 kg CO_2-eq./m^2/year. In this calculation, wood has not been considered to be recycled in C3 phase, but instead incinerated in waste-to-energy plant. GWP from phases such as A4 and A5, associated with transport and building process are generally reduced, due to lower transportation weight.

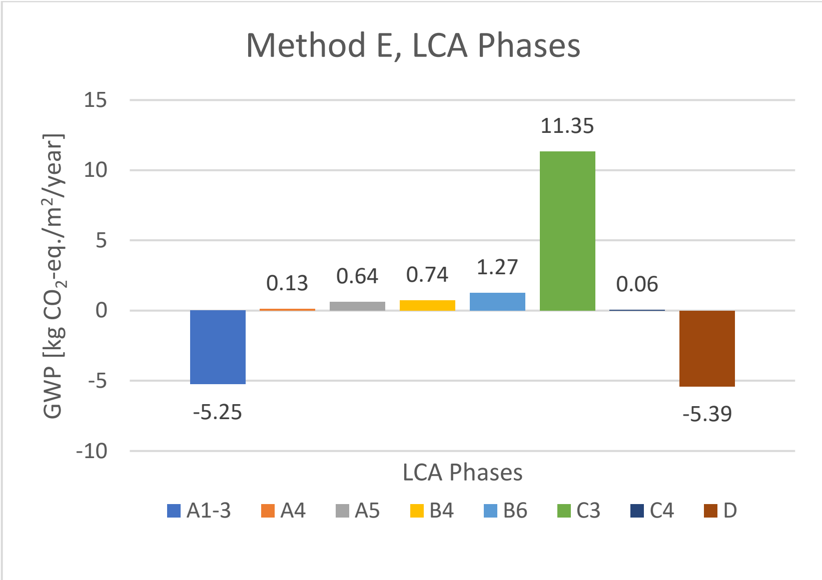


Figure 58 Method E, distribution between phases

Phase D, which is out of GWP calculation scope, has slightly higher recycling potential compared to previous methods due to the waste-to-energy incineration and even higher share of wood-based materials. This generally shows that wood has greater recycling potential, and so does Method E.

External walls, internal walls, floor, foundation, and roof construction

Phase A4 and A5 are calculated identically as Method A, Chapter 4.1.3. The average transport to building site for materials (phase A4) has been calculated. The GWP emissions for the three buildings ranges from 0.11 to 0.14 CO_2-eq./m^2/year. Meanwhile building process (A5) ranges from 0.01-0.04 CO_2-eq./m^2/year which could be considered negligible.

4.6. Energy performance

Energy performance is adjusted to match boundaries of 24.3-27.0 kWh/m^2/year from the functional unit. All methods fit within the boundaries with realistic dimensions for insulation layer thickness. The deviation is maximum of 1.1 kWh/m^2/year (building-specific) and is a result of decision to choose standard dimension structural and insulation materials that have influenced the precision to match equal consumption. The methods can perform equally good. The graph below shows the average energy consumption for all three buildings for each method and detailed calculation Be18 report can be found in Appendix 09a, 09b and 09c as an example of input data Building 1a, 2a and 3a.

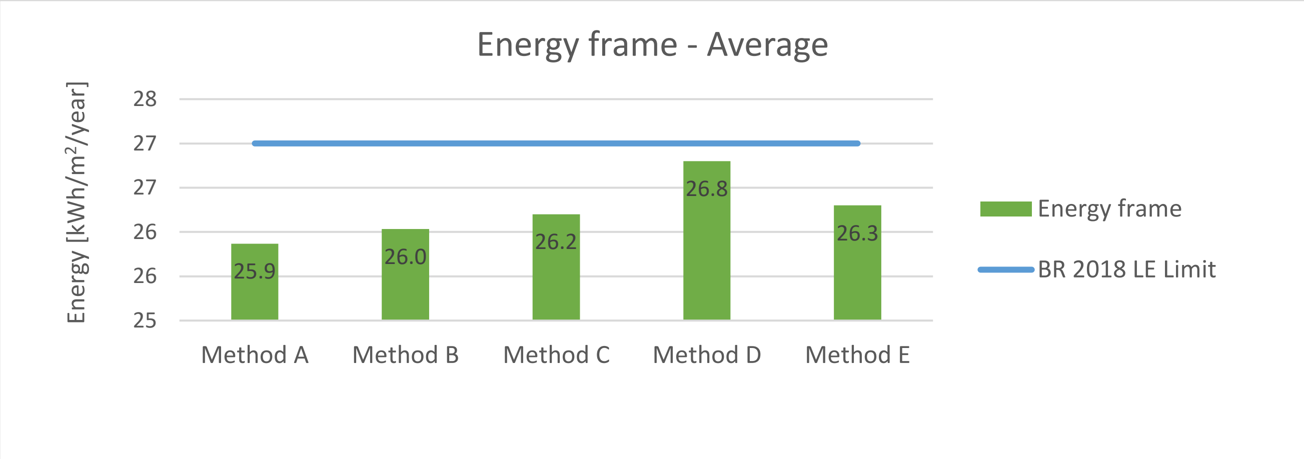


Figure 59 Energy frame results, average of three buildings

Methods C, D and E have gradually lower heat capacity, which is proportional to share of lightweight structural materials. The lower heat capacity, the higher the heating energy consumption is due to decreased ability to store solar gains in the heating season. Following methods therefore need to slightly compensate the additional energy consumption, and this is achieved by increasing insulation layer thickness to achieve lower U-values. The correlation can be seen for all three buildings as average on Table 12, where it ranges from 0.088 to 0.105 Wh/K·m^2.

	Heat Capacity [Wh/K·m^2]	**Average U-Value [W/m^2·K]**
Method A/B	105-140	0.105
Method C	51-55	0.096
Method D	34-40	0.091
Method E	34-40	0.088

Table 12 Correlation between heat capacity and U-Values

The trend in average U-values shows that lower U-value is required when using lightweight materials and thus building with lower heat capacity. There is no correlation for Method E compared to D, the change in U-values is caused by standard building material dimension change.

Another parameter to consider is increased heat loss through floor using wood framed floor deck on screw pile foundation (1) vs. traditional strip foundation (2). The main change is increased temperature difference between internal and external surfaces. Instead of 10 °C ground temperature, -12°C external temperature is used. This example will show impact based on floor heating construction and equivalent U-value for both situations. Internal temperature is set to 30 °C instead of 20°C due to floor heating. Energy frame is based on 185 m^2 example (Building 1, Method A) with same U-value for both situations for comparison reasons.

Floor with floor heating, 185 m^2 *U: 0.094 W/m^{2}K*	**Internal/external [°C]**	**$\Delta t_{emp.}$ [K]**	**Heat loss [W]**	**Energy frame [kWh/m^2/year]**
(1) Floor deck, screw pile	30 /-12	42	730	27.3
(2) Concrete slab, strip foundation	30 / 10	20	348	25.9
		Difference:	+109%	+5%

Table 13 Difference in heat loss and energy frame between (1) Floor deck, screw pile and (2) Concrete slab with strip foundation with Building 1 as a reference point. Heat loss is at floor construction level, and energy frame at building level. Temperature set according to DS 418 (Dansk Standard , p. 12)

From Table 13 it is evident that screw pile foundation has impact of 109% higher heat loss than concrete slab at floor construction level, if calculated with same U-value. Increased heat loss influences total energy frame of the building, leading to 1.4 kWh/m^2/year or 5% difference. The increased heat loss can be compensated by lowering U-value, which is done in Method D and Method E with different approaches.

4.7. Comparison of methods

Results of the previous chapter shows GWP emissions ranging from 7.2 to 12.7 kg CO_2-eq./m^2/year, depending on building method, location, and typology. Operational energy accounts for 12-17% of total GWP, which means that the embodied emissions in the constructions, in general have 5-7 times higher emissions than operational energy.

Reference construction Method A, mainly consisting of high-density materials such as brick and concrete has the highest GWP. For this method, buildings range from 10.3 to 12.7 kg CO_2-eq./m^2/year which can be seen on Figure 60. The highest GWP is achieved by Building 2, where soil conditions require very high level of excavation to construct foundation and floor slab, as well as concrete inner and outer leaf external walls. Comparing Method A to BR 2025 threshold limit values, only Building 1 fulfills the requirements. Method B does not fulfill any VSC or BR threshold limit values. Method C, which only involves external wall substitution to wood framing, fulfills BR 2025 for 2 out of 3 buildings. Building fulfills BR 2027 requirement as well.

Comparing Method D to VSC 2023 and BR 2029 threshold limit values only Building 3 fulfills the requirements with lowest of all value of 7.2 kg CO_2-eq./m^2/year. Building 1 and 2 with Method D are close to fulfill the limit with 8.05 and 8.28 kg CO_2-eq./m^2/year respectively. None of the methods comply with the ambitious VSC 2029 requirements on calculated buildings.

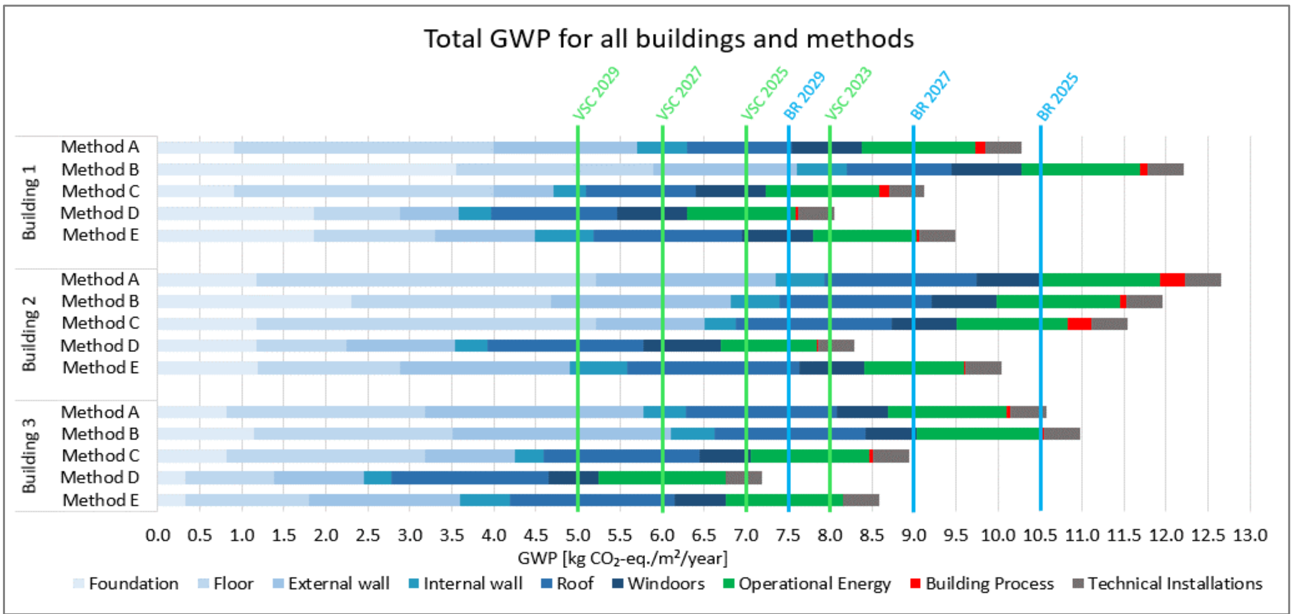


Figure 60 Total GWP of three buildings for five different methods (A-E). The numbers include more LCA-phases than BR requires. The limits for BR and VSC can been seen for different years .

Figure 60 shows Total GWP of three buildings for five different methods (A-E). The numbers include more LCA-phases than BR requires. The limits for BR and VSC can been seen for different years.

When comparing methods to each other, it is important to note that one method can be more advantageous than another and vice versa, all depending on soil conditions, building shape, window sizes and orientation which all impacts emissions from operation and constructions. For example, Method A, despite having highest maximum value, can in some cases as Building 1, result in as low GWP as 10.3 kg CO_2-eq./m^2/year, which is lower than any buildings built with Method B, and lower than Building 2 built with Method C. This indicates that it is very building-and location-specific, which building method is the most suitable and therefore sustainable. All buildings have lower GWP results when Method C, D or E with wood framing is chosen instead of Method A/B with masonry and concrete constructions. This shows that both traditional framing and advanced ACERA framing systems have less environmental impact than any of the calculated buildings built with masonry and concrete constructions. Generally, Method B is only advantageous for Building 2 with very complex soil conditions. Method C has for all buildings lower GWP than Method A or B. Method D has lowest overall GWP out of all methods ranging from 7.2 to 8.28 kg CO_2-eq./m^2/year, and Method E has lower, but very similar GWP to Method C, except for Building 1, which has lower GWP built with Method C, and lowest with Method D.

LCA results shows that biggest impact originates from embodied GWP in building constructions of about roughly 80%, which leads to detailed look at distribution between each construction (foundation, floor, external and internal wall, roof and windoors) on Figure 60. Floor and foundation in nearly all methods are largest contributors of up to 5.9 kg CO_2-eq./m^2/year, except D and E with wood framed floor deck on screw pile foundations. If external wall construction is substituted with wood framing, it also provides significant savings in GWP of up to 59% if Method C is used. Method D followed by Method E combines both sustainable building methods, wood framing and screw pile foundation, which results in lowest overall GWP for building constructions. The two methods have energy consumption of max 27 kWh/m^2/year complying with BR 2018 LE requirements and thus provides as equivalent energy performance as reference Method A.

4.8. Recyclability potential

Previously described results regarding BR and VSC threshold limit values, does not include phase D (recycling potential), as it is considered to be outside the project scope, and thus is not included in the total GWP emissions. The recycling potential between the five methods analyzed can vary significantly. Recycling potential is a future scenario, where materials in end-of-life gets either reused or incinerated for energy production processes. All upcoming calculation results for structural wood are based on waste incineration scenario, which is decided to be the most conservative, realistic, and least optimistic option. The comparison between methods on Figure 61 shows potential as an average of three case buildings for the different building methods, for phase D only.

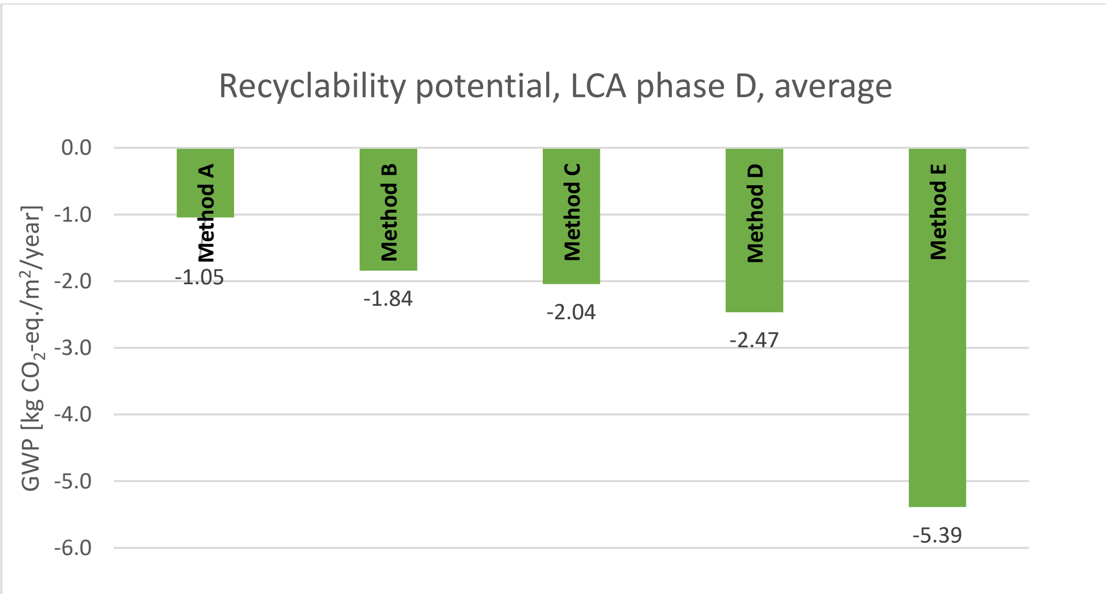


Figure 61 Recyclability potential, LCA results as an average for the three buildings of Phase D

Method E has by far the highest recycling potential of -5.4 kg CO_2-eq./m^2/year, followed by Method D with -2.5 kg CO_2-eq./m^2/year. The trend is similar when continuing, where more masonry and concrete materials result in lower recycling potential. Methods with highest share of wood and even metal, has the highest recyclability potential.

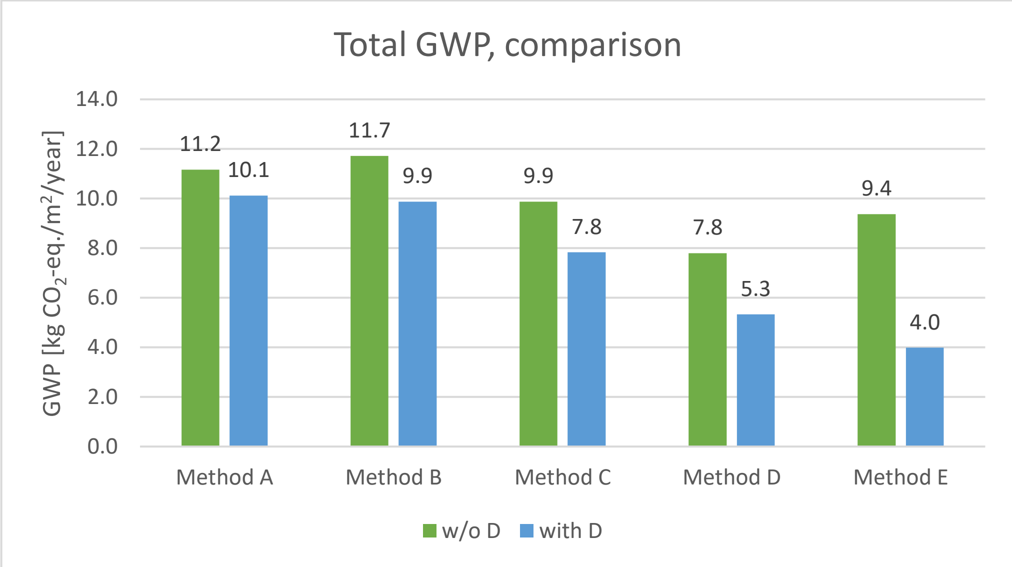


Figure 62 Total GWP LCA calculation comparison as an average for all three buildings, without and with Phase D

Since the Phase D cannot be included in the BR/VSC calculation, this cannot benefit any of the methods calculation wise. On the other hand, an example for Method E would result in performing as the best out of all methods, if Phase D would be taken into account, as presented on Figure 62, resulting in as low as 4 kg CO_2-eq./m^2/year, versus 10.1 kg CO_2-eq./m^2/year, for Method A. Method E would otherwise result in 20% higher GWP than Method D if phase D is not taken into account, despite more wood-based materials is used in Method E, such as wood-fiber insulation and wood-fiber insulation boards. Looking at the material level, materials with most recyclability potential in Method A are as following, for Building 1 as an example:

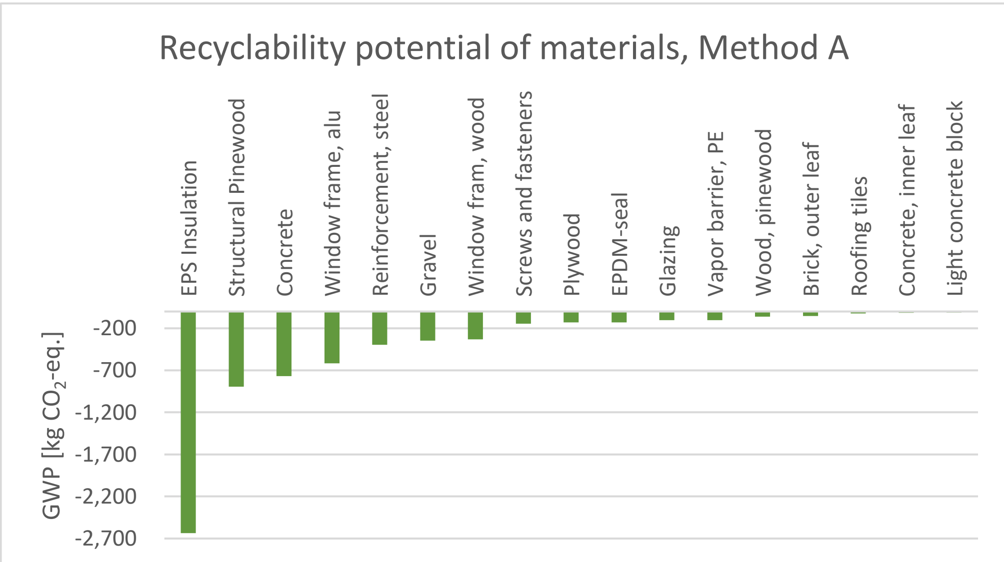


Figure 63 Recyclability potential of materials, sorted by highest potential in Phase D, Method A (Building 1 example)

Method A features EPS insulation, structural pinewood, and concrete as the three materials with highest recycling potential of phase D. The materials (except wood) in general have low recyclability factor. For example, it can be seen on Table 14 that concrete only has 10% recycling potential, when comparing GWP of D phase and A, B, C phases, while structural wood has 640% recyclability, due to energy incineration.

Material	D [kg CO_2-eq.]	A, B, C [kg CO_2-eq.]	Recyclability [%]
EPS Insulation	- 2,637	9,051	29%
Structural Pinewood	- 892	139	640%
Concrete	- 767	7,923	10%

Table 14 Method A, three materials with highest D phase. % Of GWP that can be recycled (Building 1)

Method E in the upcoming Figure 64 with much larger D-phase potential for materials and indicates significantly higher recycling potential. On Figure 64, wood fiber insulation, followed by galvanized steel and structural pinewood are the three materials with highest recycling potential of phase D.

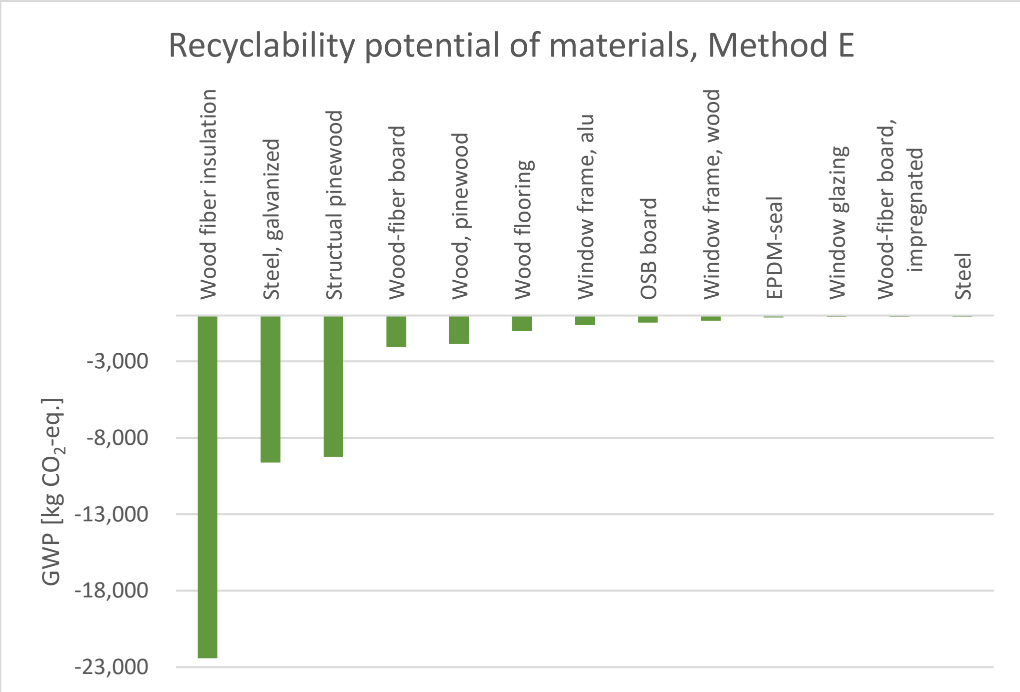


Figure 64 Recyclability potential of materials, sorted by highest potential in Phase D, Method E (Building 1 example)

The materials used in Method E have very high recycling potential, and in general quantities are 8-9 times higher. Wood fiber insulation and structural pinewood can be recycled with up to 151-640% respectively, which result in a surplus energy balance due to energy incineration. Steel features very high recyclability, of 63%. In direct comparison to concrete slab, steel screws after end-of-life can be removed by unscrewing them from the ground and recycling a high share of metal.

Material	D [kg CO_2-eq.]	A, B, C [kg CO_2-eq.]	Recyclability [%]
Wood fiber insulation	- 22,415	14,805	151%
Steel, galvanized	- 9,620	15,227	63%
Structural pinewood	- 9,238	1,444	640%

Table 15 Method E, three materials with highest D phase. Percentage (%) of GWP that can be recycled (Building 1)

Considering the high negative GWP balance of wood-based materials, it is uncertain to predict if the energy incineration scenario will provide same savings in energy mix throughout buildings lifetime, described in Chapter 6.3. The energy mix (share of renewable energy) projections are not considered in LCAbyg calculation at material level, as it is otherwise is done for building operational level.

It can be concluded that D phase is significant, especially for wood-based materials, and should be considered as an additional sustainability indicator. This indicator can be mostly used in long-term projections, which can be difficult to predict. Nevertheless, all buildings and their construction parts at some point reaches end-of-life point, hence why it is still relevant to consider, despite not being included in upcoming BR/VSC CO_2-eq. requirements and could be future research area for circular economy purpose.

5. Screw pile foundation analysis

From the sub-chapter regarding screw pile foundations, Chapter 1.1.2, it could be read that multiple articles have documented a possibility of CO_2-savings (not CO_2-eq.) being as much as 85-87% for single-family houses, without including Phase A5 of LCA. The main area of CO_2-savings is the direct substitution of concrete needed in the building, but also savings related to the construction phase because of no need for soil excavation and sand/gravel-fill for a stable subbase - this will furthermore reduce associated heavy transport to the construction site, prior to the construction phase. The screw pile foundation method can affect other parameters than GWP, due to the fact that construction sand and gravel will be in serious shortage within the next 10 years, (Andersen 2021), (Pedersen and Møller 2018). Through the previous analysis of the five different methods, and the respective LCA-calculations, it is possible to isolate floor and foundation constructions and investigate and compare the two methods at construction-level. Comparison is based on two parameters: CO_2 and GWP (CO_2-eq.).

Analyzed results from the three case buildings show saving potentials from 29% to 57% for foundation, floor and buildings process combined as per Chapter 4.4.1. However, investigating foundation only, showed from 0% to 61% savings compared to the concrete strip foundation. Figure 65 shows that specified savings with Method D can be achieved using screw piles with wood framed floor deck instead of concrete slab.

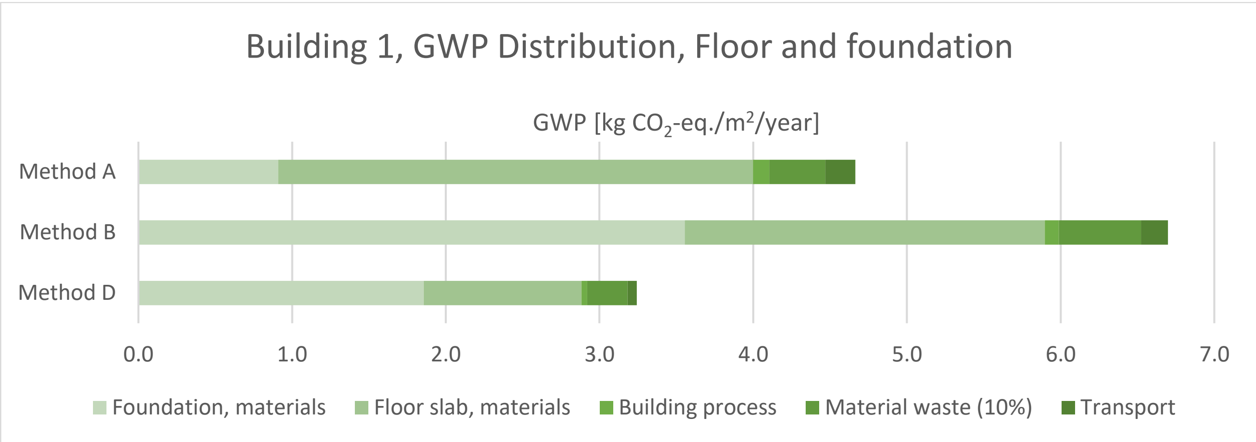


Figure 65 Building 1 GWP Distribution results from Floor and Foundation in worst case scenario with digging depth of 1.3 m. Material waste and transport is combined for floor and slab. Building process consists of soil removal for Method A, and screw installation for Method B and D.

Savings mainly originate from substitution of concrete in the floor slab. Concrete substitution in the foundation itself does not necessarily provide savings compared to steel screws, especially for Building 1, where the screws are 11 meters long, and a total of 68 screws for Method B and 47 screws for Method D due to the decreased bearing load. Emissions are estimated using generic data from LCAbyg/ÖKOBAUDAT EPD for galvanized steel plates. Building process and transport emissions are greatly reduced with both methods. The estimated lifetime of screw pile foundations is 80-100 years, which is more than the investigated building lifetime period of 50 years.

Varying results indicates that soil conditions have a relatively large impact on material consumption and thus environmental impact. The following table shows the relationship between depth of bearing soil layer, removed soil, and required screw length, where Building 1 has been additionally modelled with different soil conditions as an example.

Soil conditions	Digging depth to solid ground	Soil removed/soil deposited in the property	Screw pile length	Screw pile quantity	
Building 1	Method A		Method B and D	Method B	Method D
Worst case (reference)	1.28 m	220.3 / 69.4 m^3	11 m	68 pcs.	47 pcs.
Best case	0.40 m	114.4 / 87 m^3	4 m		

Table 16 Description of soil conditions and screw pile properties for Building 1

The soil that has not been deposited on the property is deposited to waste facilities requiring 100 km of transport with truck in this scenario. Upper 0.15 m of topsoil layer is deposited on the property due to various contents (roots etc.) which would not be suitable for property fill is always removed from the property according to site conditions on Appendix 02a and average industry findings (Designing Buildings 2020).The total amount of soil moved is input parameter representing fuel consumption during excavation, calculated by LCAbyg. GWP for the two different soil conditions are plotted in the graph for three methods, where Method A is the reference method with concrete strip foundation, Method B is the screw pile foundation method (w/Sundolitt F-element) and concrete slab, and Method D is screw pile foundation with wood framed floor deck.

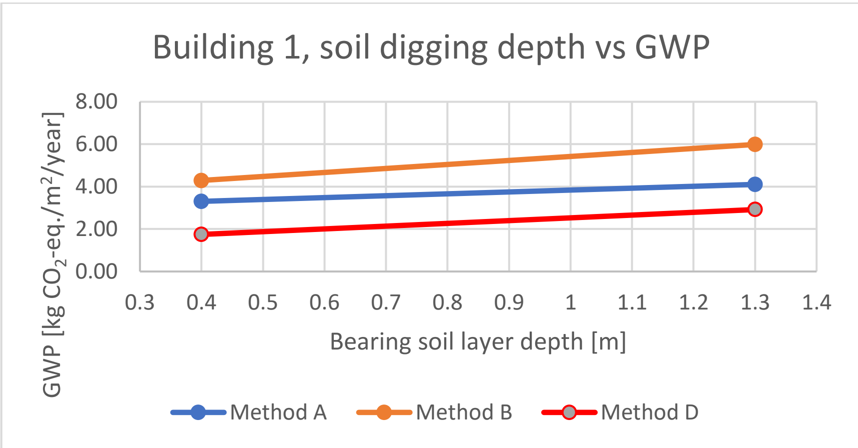


Figure 66 Building 1 bearing soil layer digging depth compared to GWP for Method A, B and D. Floor, foundation

Figure 66 shows that methods have linearly higher GWP as the bearing soil layer increases, as consumption of gravel and steel increases depending on the depth. Method D, wood framed floor on screw pile foundation has lower GWP than the other two methods. Results indicate that screw pile foundation in masonry build with concrete floor slab did not have potential of reducing GWP, except from Building 2. However, considering recycling potential phase D, screw pile foundation used as Method B, has very similar GWP emissions to the traditional Method A, as per Chapter 4.8 due to higher recyclability for steel in general. Screw pile foundation can provide advantages in other indicators than GWP. For example, end-of-life phase when simply unscrewing piles from the ground is very different compared to excavation of up to several meters of soil and in some cases will matter more than others.

6. Sensitivity analysis

Results in previous chapters represent the functional unit and are based on assumptions and fixed values. There is a possibility that these results might be sensitive to some prerequisites that might have been delimited or unexpected. The results should represent typical building methods in the best possible way, but there could be some deviations that might affect results more than others The chapter will also explain and clarify some of the excluded calculations due to certain level of insignificance or for fair comparison reasons.

6.1. Transport distances for building materials and soil removal

Transport of buildings materials of 100 km in all previous calculations for all products using generic EPD's, except for structural pinewood and screw pile foundations. The argument for choosing 100 km of transport, is the assumption, that most of the materials (brick, tile, mortar, concrete etc.) can be delivered from local production plants that does not involve relatively long transport distances and if potentially different materials are averaged out it is assumed that 100 km is conservative number. This approach resulted in maximum share of 3.1% in Method C out of total GWP for building. Method A has second highest share of 2.7%.

However, this distance will be varied to 50 km and 500 km to investigated how sensitive the total building GWP is. Method A (with example in Building 1) is chosen because the method contains the largest quantities of building materials that are using the 100 km average transport distance, rather than product specific distance (structural wood and screw piles), and highest overall building GWP emissions.

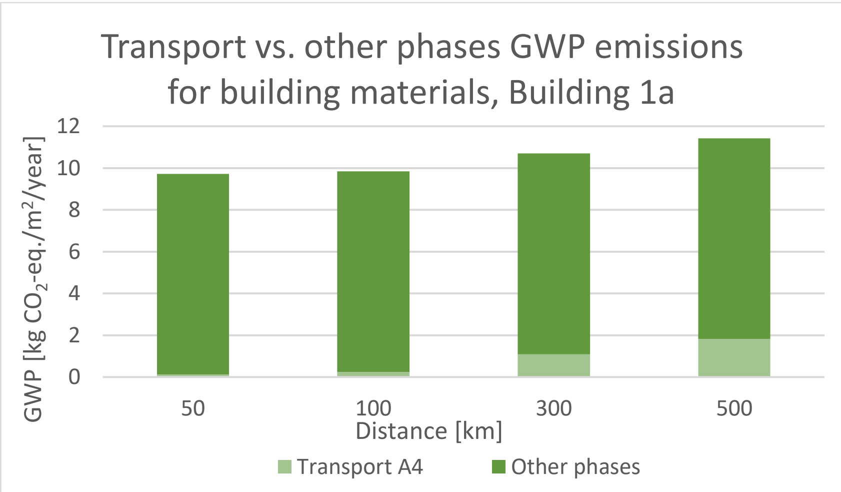


Figure 67 Transport (A4 phase) vs other phases, comparison in GWP emissions with varying transport distance, Building 1, Method A

Estimated transport GWP emissions from LCAbyg shows 0.0037 kg CO_2-eq./m^2/year per driven km with truck, or in other units 33.4 kg CO_2-eq. per km as linear correlation.

From Figure 67 it can be observed that total GWP is relatively small with 0.12, 0.25, 1.10 and 1.83 kg CO_2-eq./m^2/year for 50, 100, 300 and 500 km distances respectively. Expected distances from producer can in most cases realistically range from 50-300 km, and therefore have a share of 1% to 10%. Deviation this from project's 100 km distance is therefore 1.5%, if distance is reduced to 50 km, and 7.5% if distance is increased to 300 km. This deviation is considered to be relatively small compared to other inaccuracies in LCA calculation. But if it is known that distance is very long, it should be adjusted accordingly, e.g., if it exceeds 100 or 200 km.

Removal of soil has been set to 100 km distance on Table 17, same as for building materials. Linear correlation is estimated by LCAbyg to 6.7 kg CO_2-eq. pr. km truck transport[1] for 104.059 kg of soil removal in Building 1 with Method A. The impact is expected proportionally to be similar for Method C using same traditional building method for floor and foundation.

Distance	Transport A5, GWP	Other phases	Total	Share of total
[km]	[kg CO_2-eq./m^2/year]			[%]
50	0.04	**9.77**	9.81	0.4%
100	**0.07**		**9.84**	**0.7%**
300	0.22		9.99	2.2%
500	0.36		10.13	3.6%

Table 17 Soil removal transport (A5 phase) vs other phases, comparison in GWP emissions with varying transport distance, Building 1, Method A. (100 km used in this project)

It can be concluded in Table 17 that the distance of soil removal has a little impact (maximum 4%) for transport of 500 km, which in most cases would be normal of 20-100 km. Therefore, this deviation can be considered as a very insignificant error and assumed 100 km distance is suitable.

6.2. Energy consumption during building process

During the constructions process, electricity is used for tools and various machinery, prior to operational phase. District heating in this case is used for drying process in winter period build. On other buildings sites without district heating, fossil fuel might be used for heating in building process. The energy consumption for the two energy sources during construction has been excluded from this project, as information about consumption was only found for traditional building methods, with concrete slab and masonry walls. Therefore, it was not possible to include them, as if included it could result in disadvantageous/ incomparable calculation for Method A. Nevertheless, investigation is about what impact it could have on Method A, Building 1, as data was available for actual electricity consumption for the reference case building (H-Hus). Table 18 below shows that electricity consumption can vary depending on season. In best case it results in 1% out of total building GWP, and in worst case 1.6%, which is relatively small proportion, but might be taken into consideration.

	Electrical Energy	GWP CO_2-eq.	Share of total
	[kWh]	[kg/m^2/year]	[%]
Winter	11,364	0.16	1.6%
Summer	7,273	0.10	1.0%

Table 18 Electricity consumption and GWP during building process for Building 1 Method A

Table 19 shows that district heating consumption is significantly higher of 0.53 kg CO_2-eq./m^2/year emissions, which could potentially represent 5.1% of total building emissions. Reference data of 100 kWh/m2 is used from literature screening (6 sources) from a report made by Danish Technological Institute (Teknologisk Institut 2013). Calculation can be found in Appendix 10.

District heating	GWP CO_2-eq.	Share of total
[kWh]	[kg/m^2/year]	[%]
18,685	0.53	5.1%

Table 19 District heating consumption and GWP during building process for Building 1 Method A

[1] Truck with loading capacity of over 25 tons

Taking both electricity and district heating (during building process) into consideration, results of Method A, total building GWP could have been 7% higher, and in fact would have more impact than transport or technical installations. This should be included in a calculation, if data for all compared methods is available, so that they are compared with valid calculation prerequisites. Unfortunately, it was not possible to investigate if other methods result in lower emissions from building process, due to insufficient data available. If properties of masonry and concrete materials are considered, it can be hypothetically expected that wood framed building methods might have advantage from faster drying and assembly process, resulting in lower overall energy intensity from building process.

6.3. Generic vs. product or industry specific EPD

Structural Wood EPD differentiation and end-of-life scenario

Whenever using specific rather than generic EPD from LCAbyg, which is based on ÖKOBAUDAT, there might be a difference. Results on Figure 68 compare two EPD's, which are industry specific (not product specific) per m^3 structural pinewood. In this project, specific EPD developed by træ.dk (Appendix 08a) has been used with energy incineration scenario. Investigation will compare how the results could differ if either generic EPD or same specific EPD with reuse scenario would have been used. Firstly, impact at material level, later at building level. Note: generic EPD only includes energy incineration available, and only Building 1 is used as an example.

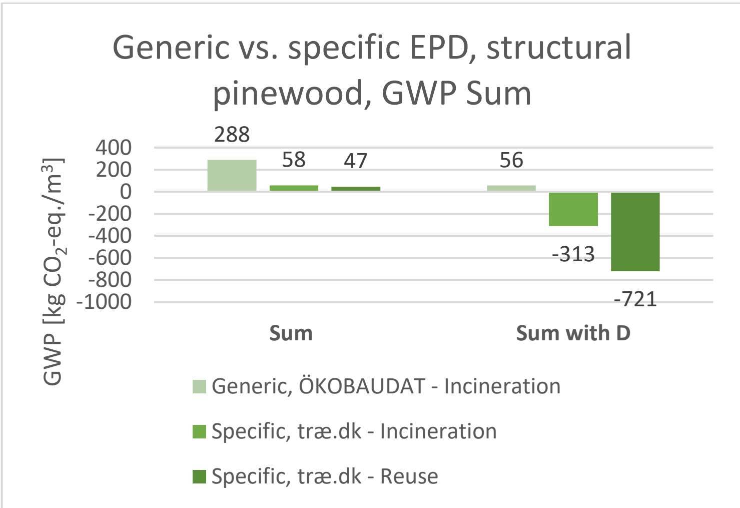


Figure 68 Structural pinewood GWP sum differentiation for generic vs specific EPD

Sum on the figure is A1-3 and C3 phases, and the difference of using the specific EPD rather than generic differs by almost -80% in GWP. If energy incineration scenario is chosen for the specific EPD, it results in -84% difference. However main difference can be seen on *Sum with D* phase included[2] (on the right), as the specific EPD has much higher recycling potential both from incineration and reuse scenario, deviating by 209% and 350% respectively.

[2] Note: D-phase is not considered in upcoming VSC/BR requirements and is out of current building lifetime scope.

Impact of EPD on building level depends on quantities used of the building product. Building level comparison includes all building constructions (excluding operation, technical installations and building process). In this case on Figure 69, Method A where only roof uses structural wood product, the impact is very minimal, both to sum and D-phase, maximum being -2% (D-phase) for specific EPD reuse scenario vs. generic EPD incineration.

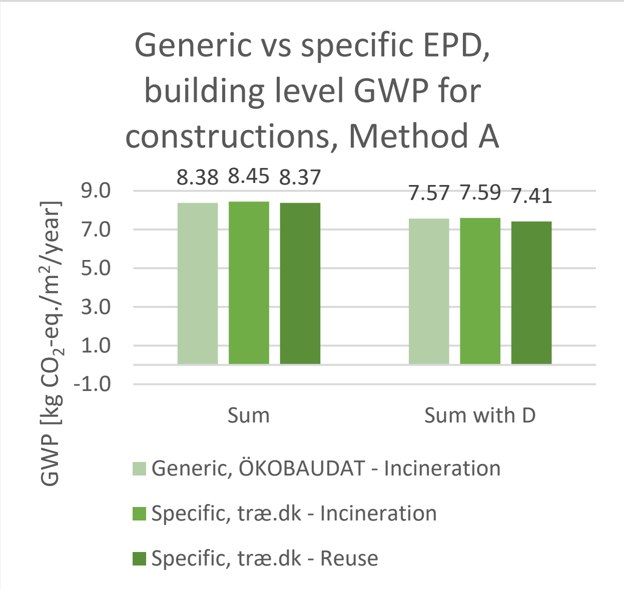


Figure 69 Structural pinewood GWP differentiation of EPD impact at building constructions level, Method A, Building 1

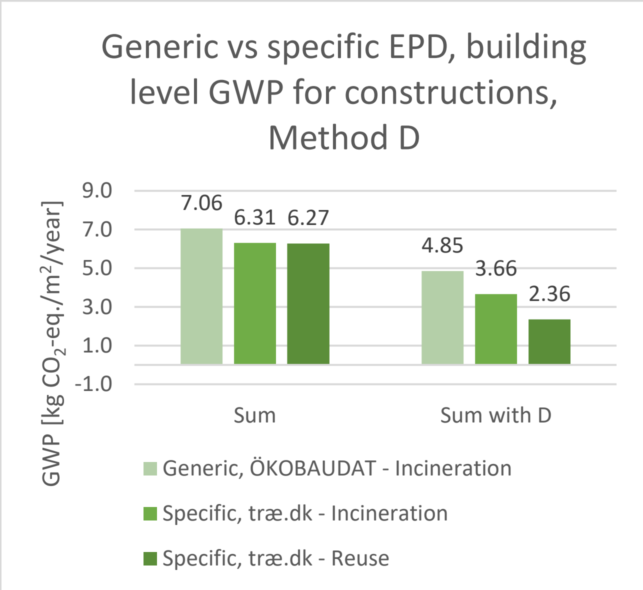


Figure 70 Structural pinewood GWP differentiation of EPD impact at building constructions level, Method D Building 1

Impact is higher when building Method D with high share of wood is considered on Figure 70. For sum including A1-A3 and C3 phases, deviation is -10% and -11% depending on whether incineration or reuse scenario is chosen for specific EPD. Significant difference for D phase can be observed of 25% or 52% if incineration or reuse EPD scenario is chosen respectively.

Concluding the building level sensitivity, if not considering D phase, there could have been less than -1% in difference if reuse scenario was used (with same EPD), and if generic data would have been used instead, +11% for Method D. Recycling potential differs significantly in the other hand, up to 36% higher if reuse scenario is used instead of energy incineration. Regardless some deviations in EPD or scenario, structural wood will still remain as one of the materials with highest recycling potential compared to other materials in the building.

Method A does not provide sufficient differentiation due to low share of wood and thus can be considered negligibly small impact. However other specific EPD's than wood could have been used for building products with high share in Method A or any other methods and could have potentially provided different outcome.

Difference in energy incineration scenario between generic EPD (German) and actual Danish CO_2 intensity

In the project, generic EPD is used for wood fiber insulation, as one of the materials with biggest recycling potential in D phase among all building methods analyzed. Energy recovery benefits are calculated from German energy mix background, which provides significantly higher recycling potential than with actual Danish conditions.

Danish energy mix with CO_2 intensity of 264 g CO_2-eq./kWh for district heating and 131 g CO_2-eq./kWh for electricity is cleaner than Germany's 311 g CO_2-eq./kWh (European Environmental Agency 2021) for electricity 390 g CO_2-eq./kWh for both electricity and heating combined. (IEA 2020). District heating consumption CO_2 intensity data was determined unable to obtain for Germany, therefore combined intensity is used.

Energy Type	Share of utilization[3]	CO_2 intensity Denmark [g CO_2/kWh]	CO_2 intensity Germany [g CO_2/kWh]	Factor in difference (DK vs. DE)
Electricity	33%	131	390	**1.8**
District heating	66%	264		

Table 20 Difference in emissions from energy sources for waste incineration in Denmark and Germany, for D phase

Considering 1.8 times difference in emissions from the energy mix, the recycling potential of -22,415 kg for wood fiber insulation is overestimated, as in Danish energy mix that would equal to -12,453 kg instead. The same can be applied for wood fiber insulation boards, where product specific EPD has been used from *Hunton* (Appendix 08a) underestimated recycling potential due to the energy mix in Norway being 22 g CO_2/kWh or 10 times lower than in Denmark.

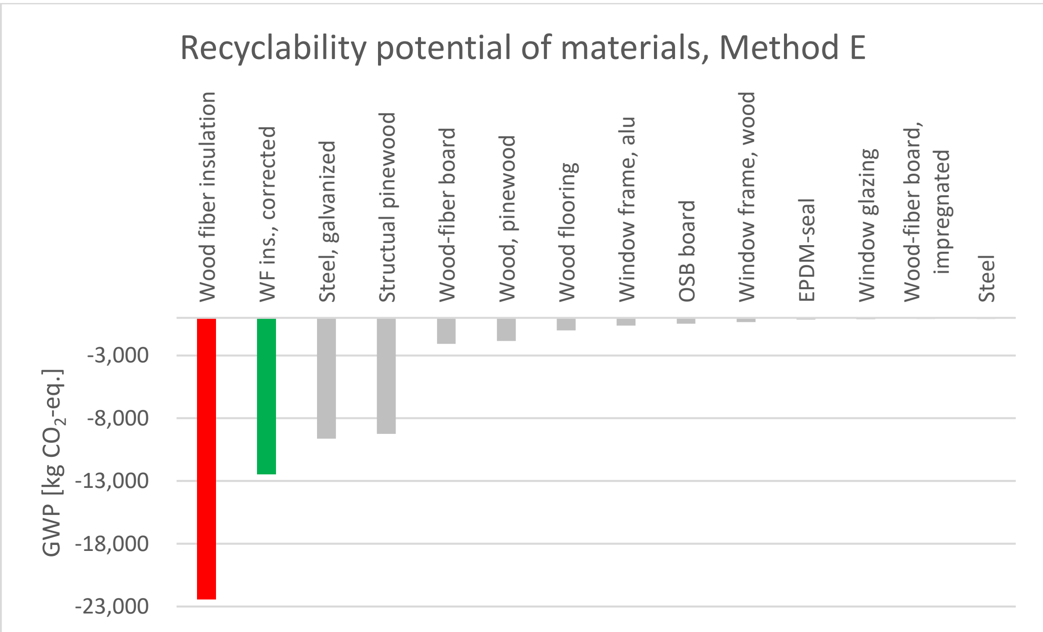


Figure 71 Wood fiber recycling potential after correction to Danish energy incineration (green) vs. German energy incineration (red)

Looking at wood fiber insulation compared to other materials on Figure 71, it remains the material with most recycling potential despite correction for local CO_2 intensity rather than German conditions. Note: other materials using ÖKOBAUDAT data have not been corrected, this figure shows worst-case impact of wood fiber insulation only. Structural pinewood used with industry specific EPD, already has Danish energy incineration scenario.

[3] Wood fiber estimated share of process for electric and thermal energy recovery based on wood fiber insulation board EPD (STEICO and Institut Bauen und Umwelt e.V., (IBU) 2020)

Remaining materials use generic EPD's originate from the ÖKOBAUDAT database, which uses German energy mix. Another possible sensitivity consideration for future research would be accounting for projection in reduced energy mix emissions (which is not modelled or standardized currently) into account during building lifetime, as D-phase is rather sensitive to deviations in energy mix.

6.4. Type of pitched roof waterproofing underlayment

Pitched roof lifespan can be chosen to be calculated differently and thus affects overall GWP. Mainly, the roofing part, above joists is one that needs replacements in building lifetime, e.g., roof tiles, metal roofing, fiber cement or other material. However, despite finishing materials that can have up to 120-year lifetime like tile in this project, they still require additional waterproofing measures. Conventional tiles are not completely waterproof and in windy/rainy or harsh snow conditions leak certain amount of water, and therefore additional waterproofing layer is used.

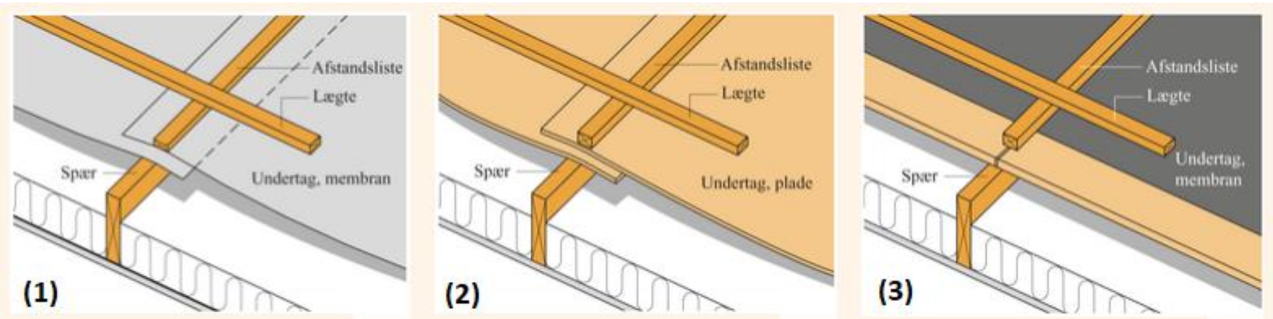


Figure 72 Types of roof underlayment. (1) membrane only, (2) board sheathing (3) board sheathing and membrane (Praxis 2014)

Most often waterproofing layer consists of a membrane made from textile/foil (1), board based (2) or membrane and sheathing combination (3). Most conventional foil type roofing membrane is made of PE, PP, textile, or combination of them, and allow vapor diffusion from interior to exterior. Common for those membranes is that some membranes do not necessarily require underlayment in form of sheathing board. There is a difference in expected lifespan, depending on whether or not sheathing is used. The membrane deteriorates faster without sheathing from wear and mounting in general, resulting in only maximum 20-year lifespan. Roofing is then expected to last only as long as the weakest link, which is the waterproofing membrane, thus overall lifetime for roofing layer is reduced. If membrane is backed up by underlayment sheathing board, lifespan can be extended above 50 years.

<table>
<tr><th rowspan="4">Roofing</th><th>Underlayment</th><th>Lifespan[4]</th><th>Replacements</th><th>GWP Roof</th><th>GWP building</th></tr>
<tr><td></td><td>years</td><td>times</td><td colspan="2">[kg CO_2-eq./m^2/year]</td></tr>
<tr><td>Membrane only</td><td>20</td><td>2</td><td>2.00</td><td>10.60</td></tr>
<tr><td>Membrane + board</td><td>50</td><td>0</td><td>1.24</td><td>9.84</td></tr>
</table>

Table 21 Roofing underlayment lifespan, replacements, and GWP results in roof construction and building level

[4] Expected lifetime of 5-20 years for conventional foil type only or average 50 years for underlayment of sheathing material (plywood, OSB, pinewood) Note*: reinforced foil can last 10-30 years, but still generally shorter than 50 years and 2 replacements are to be expected.* (Træguiden)

Table 21 shows GWP differences of up to 38% depending on if sheathing is used or not at roof construction level, or 7% in building level (incl. operating energy) considering the difference of two replacements for the two types of underlayment. This project has used 50-year lifespan with membrane and board underlayment, in all buildings with pitched roof.

6.5. External wall dimension impact on net living area

Buildings in the functional unit have been declared in terms of gross area of 185, 150 and 169 m^2. In the calculation it is assumed that net living area does not vary significantly for the different building methods A-E, due to external wall thickness being very similar. For Building 1 and 3, range is 450 to 470 mm. Exception is Building 2, where wall dimension of 563 mm thickness was required to meet energy frame. The difference for Building 2 is clearly seen on Figure 73, where 9 m^2 are lost in net living area, comparing Methods C/D to Method A/B. Method E performs well of only 1 m^2 lost. Method E benefits from more homogenous insulation layer due to the cold bridge interrupted joists in this situation, where very low U-Value is needed due to building typology in terms of window orientation sizes and external wall shape with many corners.

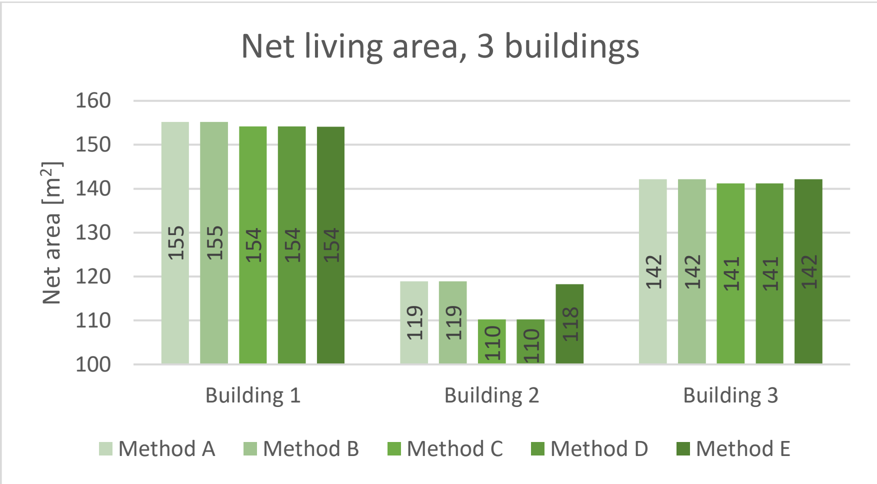


Figure 73 Net living area, comparison across different methods for 3 buildings

7. Journal Article

A Life Cycle Assessment (LCA) research on potential of future CO_2-demands from lightweight wood constructions and screw pile foundations

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07-January-2022

ABSTRACT

Currently the building regulation, BR18, do not have specific rules of environmental focus, only voluntary sustainability class and third-party sustainability certifications. From 2025 the building regulation has set limits, 10.5 kg CO_2-eq./m^2/year, through its lifetime, making a need to rethink the design of new built single-family houses. These CO_2-eq. limits can be reached by e.g., using more wood-based materials and avoid high-density construction materials like concrete, steel, and brick/tile, as these are energy heavy to produce. This report researches the possibilities of meeting these limits by substituting concrete, brick, EPS and mineral wool to wood-based materials and alternative lightweight screw pile foundation. The results conclude that the emissions are affected by the architectural design and soil conditions, but it is possible to construct buildings with as little as 7.2 kg CO_2-eq. per year for a 50-year lifetime.

INTRODUCTION

The newest research from IPCC and UN shows that there is an urgent demand for CO_2-reductions, to prevent the forecasted 1.5 °C temperature increase, due to a tipping point of ecological systems in our environment [1]. To prevent this from happening, drastic measured needs to be taken, why the EU aims for a 70% carbon reduction in 2030 and carbon neutrality in 2050. To fulfill these goals, it has been identified that 30% of the total carbon emissions comes from the construction industry [2, p. 9] and 35% of all waste [3, pp. 4-5] . Making this one of largest single contributor of carbon emissions. To counteract and reduce the emissions, one of the strategies is in the future national building regulations of Denmark, which limits the total emissions of buildings for its lifetime. This can be done by reducing the use of concrete, steel, and brick/tile and use wood-based materials instead. The environmental impact of a building throughout its lifetime, can be calculated through the LCA (Life Cycle Assessment) method with the LCAbyg tool. The LCA relies on a strong dataset and EPD´s (Environmental Product Declaration) from thousands of specific products and product groups. Worldwide there is multiple EPD-databases and the one used in Denmark is the German Ökobaudat that is well-known in the industry due to the use of it by making DGNB-certified buildings. The LCAbyg and the BR requirements do not include all phases of the LCA, why the potential saving can be biased, why the goal of this report is to show, that the Danish Government could set a more ambitious goals for the new built single-family houses, with stricter CO_2-eq. limits, to intensify the effort towards the goal of reduced CO_2-emissions.

A manufacturer of screw piles, state that there is a saving potential by 85%, using screw pile foundation instead of traditional strip-foundation, [4]. This is due to the ease of installation, and a considerable reduced volume needed compared to concrete. Other benefits can be avoiding the need of soil excavation and deposit, and a fast installation time, not effected by weather or drying time, like concrete.

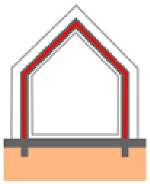
METHODOLOGY

The methodology is based on a result-orientated approach, but with the possibility of being used in a larger holistic view, where indoor climate, economy and time can be other parameters to consider. The method used in this project is to test the impact of substituting CO_2-eq.-heavy materials to materials that have a lower carbon footprint, like wood. Three single-family houses of different sizes, materials, and geographical locations have been chosen. All houses are one story and secondary buildings are excluded. Building 1 is located in Klarup, 185 m^2, H-shaped and built with brick and lightweight concrete cavity wall and with pitched roof. Building 2 is located in Klitmøller, 150 m^2, H-shaped and build in in-situ casted concrete cavity walls and flat roof. Building 3, is located in Solrød Strand, 169 m^2, box-shaped and built with lightweight wood framed walls, flat roof, and screw pile foundations. Despite 3 houses being built differently in the starting point, all five building methods are applied for each house, so that methods, location and building typology impacts can be assessed.

The three buildings will be modified to fulfill the set functional unit, being BR18 LE (Low Energy Class) with a maximum deviation of -10%, making the range for total energy consumption 24.3-27.0 kWh/m^2/year. An important consideration when changing constructions is to avoid unreasonably thick walls, as that would have negative effect in terms of reduced net area and reduced daylight. The buildings have been modified to fit and undergo the following five methods (A to E).

Method A:

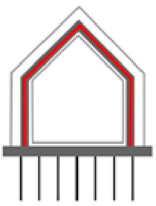
Method A



The three buildings are designed to fit the functional unit. The buildings are constructed with traditional CO_2-eq.-heavy materials like brick cavity walls, and concrete slabs built on a subbase. The insulation layer and the respective u-values is designed to fit a traditional single-family house.

Method B:

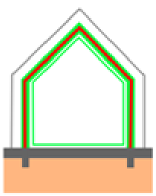
Method B



The three building is substitution on the traditional foundation and built on screw piles, casted into the concrete floor slab. The changes in GWP (Global Warming Potential) are calculated using LCAbyg and compared. Regarding screw pile installation, it is important to know the geotechnical conditions and, why these are considered with respect to the statics and weight of the building.

Method C:

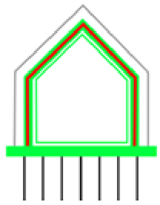
Method C



The three building undergoes yet another substitution, but at Method C it is a substitution of the bearing construction in the external wall. The buildings will have the same foundation and concrete floor slab as Method A, to compare the effects of the substitution of the wall, to a lightweight wood framed wall. The changes in GWP will be calculated using LCAbyg and be compared. This change requires a new calculation of roof u-value, due to the change in rafter's placement form cc 1000 to cc 600.

Method D:

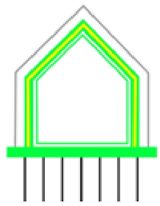
Method D



With method the floor slab is substituted with a wooden floor deck on screw pile foundation. This change makes the building a wood framed building with mineral wool insulation. This change especially affects the thermal capacity of the building as the constructions are modified to keep fulfilling the functional unit in order to be comparable with the other scenarios. The dimensioning of the screw piles changes, because of the reduced weight of the building. This affects the GWP, due to the reduced screw pile length. The changes in GWP will be calculated using LCAbyg and be compared.

Method E:

Method E



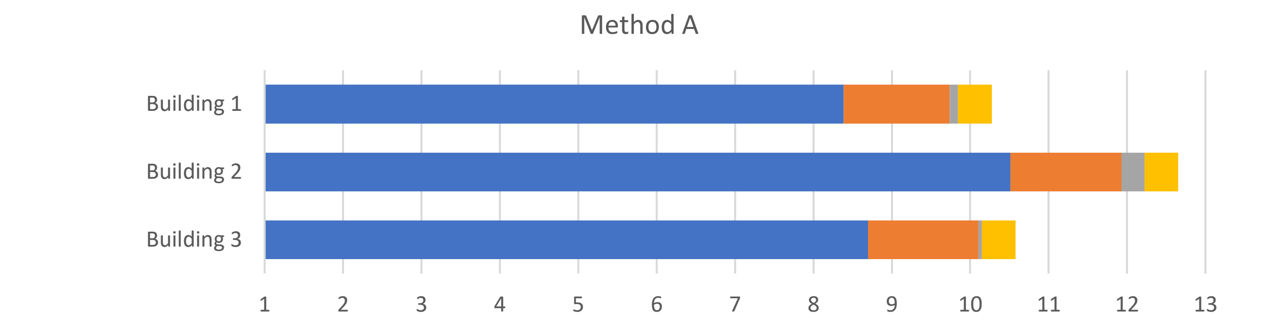
Method E is the fifth and last method and is based on ACERA building system. It is a wood framed building, built on screw pile foundations and insulated with wood fiber insulation. This building system has special thermal bridge break, which makes the construction slimmer than Method D. It is furthermore designed to be disassembled and focusses on a high rate of recyclability. This affects the GWP and will be investigated further in a separate section.

These five methods make it possible to identify the most CO_2-eq.-heavy materials and measure the effect of the substitution by using the LCAbyg software. The included phases of the LCA are,

- Phase A1-A3: Product Phase
- Phase A4-A5: Building Process
- Phase B4, B6: Use Phase
- Phase C3-C4: End of lifetime
- Phase D: Beyond system

To compare the results of this substitution method, the phases above are taken into consideration. The following phases are included with respect to VSC (Voluntary Sustainability Class) and is covering the same phases except Phase D, but it is chosen to showcase the phase to evaluate the potential of recycling, due to the fact of the building and construction industry is accountable for 35% of all waste generated [3]. The results are compared with each other in relation to the individual methods, but also buildings are compared to each other. The purpose is to analyze the sustainability potential, and not just for instance reduce the embodied CO_2-eq. only to have higher emissions at another phase. This allows for decision making that gives the best overall CO_2-eq.-reduction for the building in all its phases for the whole lifetime. The technical installations are not a prioritized parameter to investigate in this project, which is why all buildings for all methods will use a fixed standard value for GWP of 0.4 kg CO_2-eq./m²/year [5].

The results of the environmental impact will be calculated using LCAbyg and shown for each building, an example of this could be Figure 74.



	Building 3	Building 2	Building 1
Building Constructions	8.69	10.51	8.38
Operational Energy	1.41	1.42	1.35
Building Process	0.04	0.29	0.11
Technical Installations	0.43	0.43	0.43
Total	10.58	12.65	10.27

GWP [kg CO_2-eq./m²/year]

Figure 74 Method A. Total GWP of buildings

Looking at the figure it is evident that the building constructions have the largest impact, why further results will focus on the substitution of the building materials and the respective change and distribution of GWP from the building materials. The distribution of GWP for specific construction parts is shown as on Figure 75.

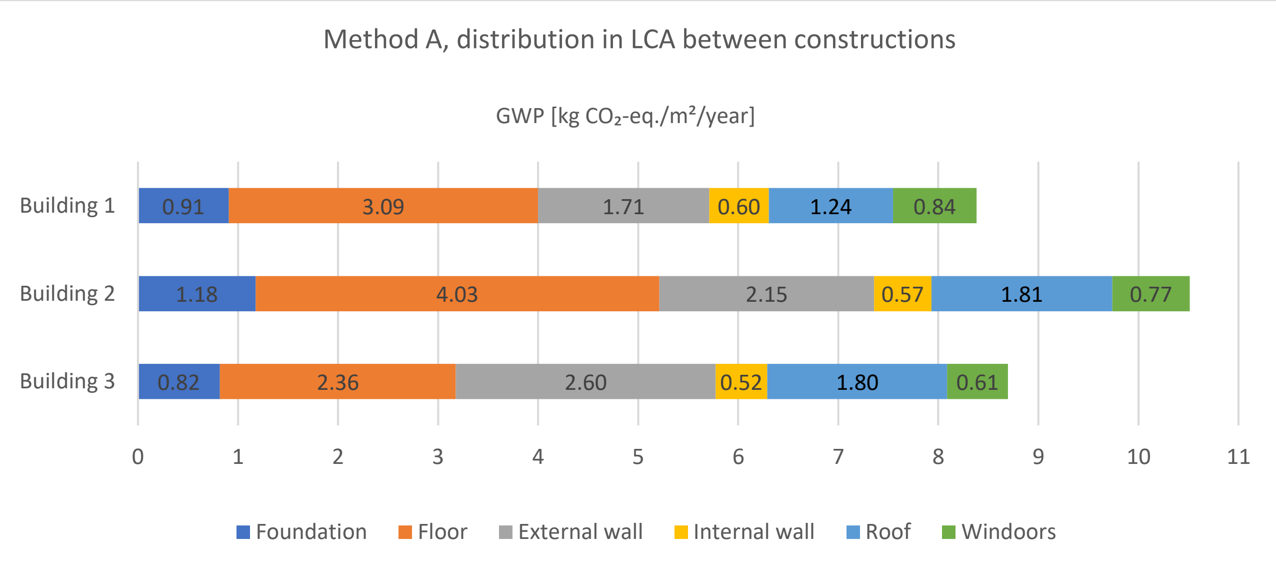


Figure 75 Distribution of GWP for different construction parts

The environmental impact of each building will be showcased using the different phases of LCA. The phases show where in the building's lifetime the largest CO_2-eq. appears. The distribution between different phases for e.g., building 1, for construction materials is as follow on Figure 76. The graph shows the largest environmental impact is the embodied CO_2-eq. from the A1-3 phase, which accounts for the building materials.

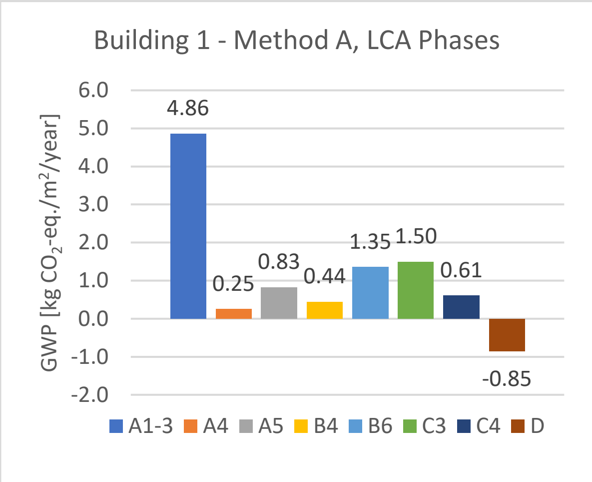


Figure 76 Building 1, Method A - distribution of GWP for different LCA phases

RESULTS

The five methods (A-E) are compared, and the three buildings are constructed to follow the same functional unit. The total GWP result for the specific buildings for different methods can be seen at Figure 77. The findings are similar to the results of the SBi report published in 2020 [5]. The result of the report for 11 measured single-family houses was a total GWP of 6.45-12.2 kg CO_2-eq./m^2/year, where the results at Figure 77 range from 7.2-12.7 kg CO_2-eq./m^2/year. This result however includes the VSC-phases of LCA (Phase A4-5), whereas the comparable results to the SBi report are when corrected 6.7-11.05 kg CO_2-eq./m^2/year. The tendences are similar, where wood framed houses have the lowest GWP. As it can be seen on the graph, close to all building methods for the three buildings, fulfill the minimum BR-requirements of the CO_2-eq.-limit for single-family houses starting at 2025. These requirements are set to be tightened by 1.5 kg in 2027 and 1.5 kg in 2029, ringing it down to only 7.5 kg CO_2-eq./m^2/year. The same tendency can be seen for VSC, starting at 8 kg CO_2-eq./m^2/year in 2023, and tightened to 5 kg CO_2-eq./m^2/year in 2029. The graph clearly demonstrates that few or none of the current buildings at different methods, are suitable to fulfill these requirements. The lowest GWP´s are seen for Method D (wood framing with mineral wool insulation). Taking a detailed look at the graph it can, for example, be seen that the roof accounts for a large share of the total GWP, whereas it is assessed that there is a great potential in optimizing the roofing, which primarily comes from the roof-tiles. Another perspective of these results is that the recyclability potential is not included, therefore the result might change drastically, if the design and use of materials is to be recycled after use.

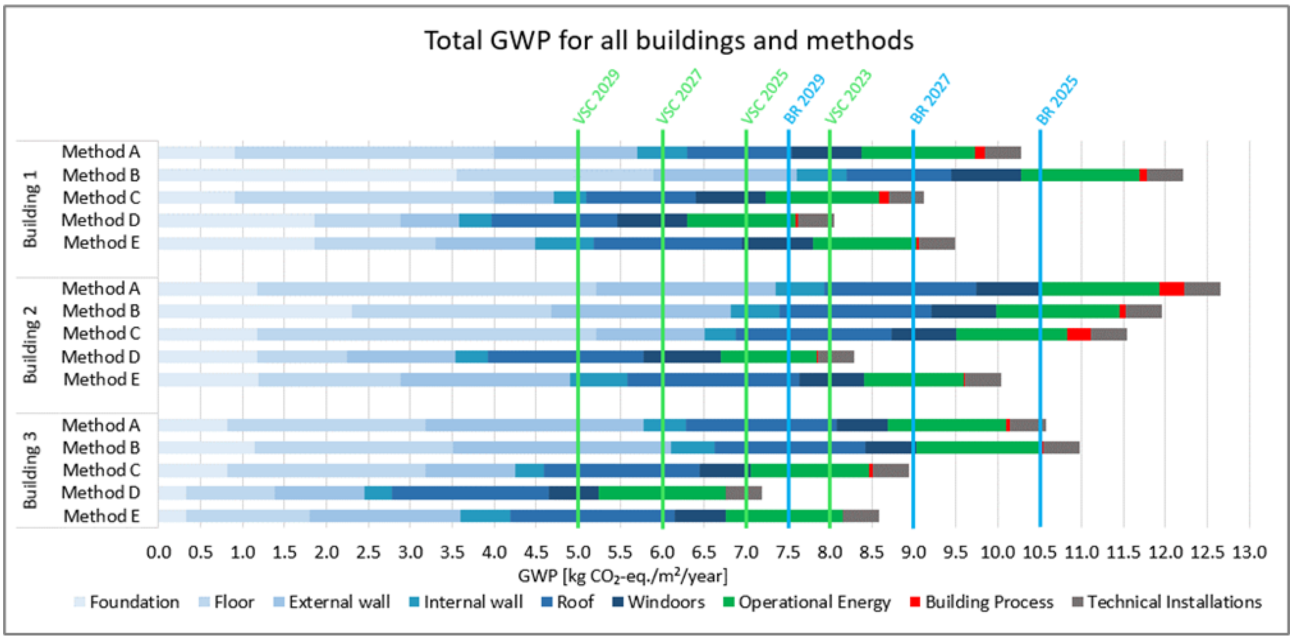


Figure 77 Total GWP of three buildings for five different methods (A-E). The numbers include more LCA-phases than BR requires. The limits for BR and VSC can been seen for different years

A Screw pile foundation is based on findings relevant solution to in general lower environmental impact of floor and foundation constructions when compared to traditional concrete strip foundation and slab. Solution called Method B where concrete slab is still used and supported by screw pile foundation did not provide any savings in Building 1 and 3 as seen on Figure 78, but in very complex soil conditions like in Building 2 resulted in 14% saving. Building Method D, where screw pile foundation allows to build floor deck with wood framing results in the biggest savings ranging from 29% to 59%. Method E built with identical screw piles, results in slightly lower savings, due to additional board-based materials used in floor construction.

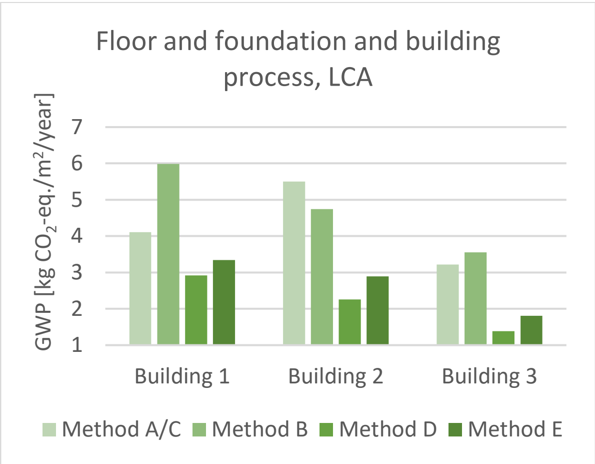


Figure 78 Traditional concrete strip foundation and slab (Method A/C) vs. screw pile foundation and concrete slab, vs. screw pile foundation and wood framed floor deck (Method D, E)

Screw pile foundation can in fact result in rather high GWP due to high use of steel, as quantities are depending on soil conditions, affecting the length. Looking at Building 1 as an example, Figure 79, it can be observed that for example Method B and D, approx. 50 and 60% of GWP respectively is originating from screw pile material consumption, higher than in Method A. GWP from building processes are mainly reduced in Method D, and main savings as previously described are caused by wood framed floor deck which in overall results in lighter construction and less weight that screw piles needs to support. Building 2 and 3 might results in different results, but in general showing similar trends in terms of distribution.

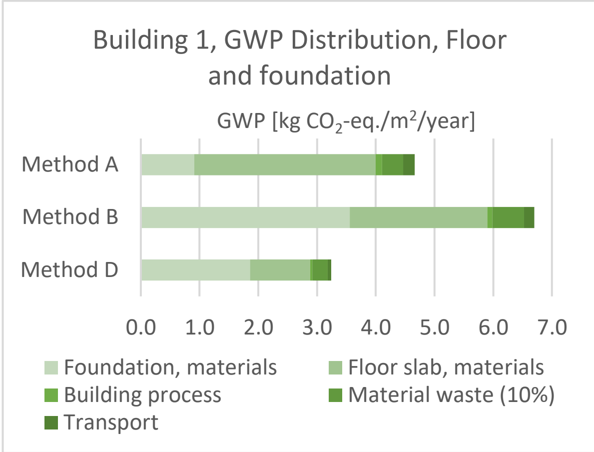


Figure 79 Building 1 GWP Distribution results from Floor and Foundation in worst case scenario with digging depth of 1.3 m. Material waste and transport is combined for floor and slab. Building process consists of soil removal for Method A, and screw installation

Discussion on 85% savings in foundation construction itself have been discovered in reports, [6], which compared to findings of this report are overestimated. Maximum saving of 61% is found in Building 3, a situation with soil bearing layer very good and close to the surface, and a simple box-shaped architecture. Otherwise, savings were 0% in Building 2, and in fact +350% increase in GWP for Building 1, as previously mentioned, and seen on Figure 79. This leads to conclusion that foundation cannot be considered as standalone construction substitution, and main savings should be considered holistically combining it with floor deck substitution to provide full and representative picture. If only foundation is considered, GWP for some buildings can in fact therefore be higher for screw pile foundation but considering advantages of wood framed floor deck screw pile solution provides overall lower GWP results and long lifetime of over 80 years. Furthermore, comparison of 85% saving of previous research shows that different calculation prerequisites such as EPD and quantities can overestimate and underestimate LCA results by a relatively big margin.

DISCUSSION

The results presented in Figure 77, show the total GWP for the three buildings for all five respective phases, including both the traditional buildings (Method A) and the analyzed ones. The graph also shows the intended limits of BR and VSC, and it is clear that multiple buildings fulfill the limits of BR 2025, but only one (or two) fits the VSC 2023. The results of this report have shown that a substitution of CO_2-eq.-heavy materials is not enough to fulfill the requirements, but there is a need to extend and develop the way LCA is used, and what phases are included. For this project, Phase D is not included because it is not a part of the regular LCA used for BR nor for the LCA used for VSC, but phase D is showcased by examples on the unutilized recyclability potential.

Method E (ACERA) is designed for disassembly and the building system is also designed to use standard materials in standard dimensions with wood fiber insulation, which makes the recyclability potential of this method higher than Method D, even though both methods cover a wood framed house. This difference in recyclability potential is taken into perspective and investigated. Recycling potential is a future scenario, where materials in the end-of-life phase gets either reused or incinerated for energy production processes. All upcoming calculation results for structural wood are based on waste incineration scenario, which is decided to be the most conservative, realistic, and least optimistic option. A future development of the method to calculate the D-phase can result in a substantially higher potential, due to the direct reuse of products and not only for energy production.

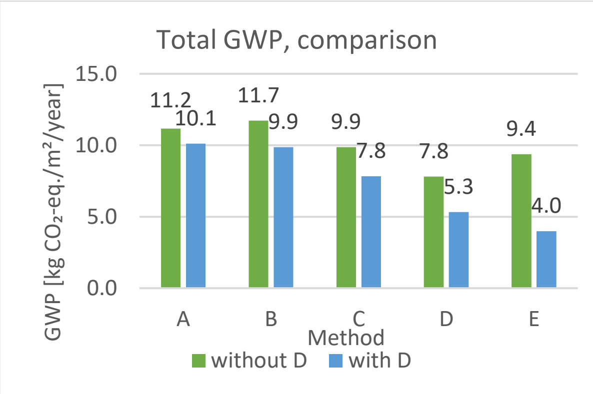


Figure 80 Comparison of total GWP with and without LCA Phase D (Recyclability)

Figure 80 shows when the D-phase of LCA is included, the estimated total-GWP, is heavily reduced with buildings made of wood-based materials. This is due to the fact that wood can be used as fuel when waste incinerated compared to concrete and brick that do not provide the option of easy demolition and no energy at an incineration plant. These estimated recyclability potentials are all based on the energy mix of today, therefore the savings are estimated to have smaller impact within the next 50-60 year, at end-of-life phase. This is due to increased share of renewable energy sources in the energy mix. Another thing that can be considered, is that building-systems like ACERA are designed for disassembling, which is also a LCA phase (Phase C1) and not included in the LCA calculation. For future LCA-calculations of buildings, Phase C1 might be a parameter to include, in order to make an incentive for building in a sustainable way. this will have an effect on the total GWP, and constructions like concrete will not benefit from it, due to the difficulty of separating the materials and recycling them.

Another questionable result is the GWP of using screw piles instead of a traditional foundation. The screw piles are heavily impacted by the soil conditions, why in some cases a subbase is more sustainable. This result is questionable because the analysis only covers one of the sustainability parameters, GWP. There are multiple other parameters, one of which is ADPe, is an indication of a high consumption of abiotic resources, that can contribute to the depletion of available elements e.g., metals or minerals. It is known, and a fact, that there will be a serious shortage on construction sand and gravel within 10 years, and so a parameter like ADPe can have an impact on decision making of future construction projects, [7], [8]. The shortage of sand and gravel creates a need to find more sand, reuse existing sand and gravel from subbases or find alternative solutions with a reduced consumption of sand and gravel. One solution could be screw pile foundation. These are made of steel, and it is possible to un-screw them from the ground, after end-of-life (50 years). This way, the metal-resource can be melted and reused for new products. This will also lead to a reduction of heavy transport to the construction site because there is no need for excavation of soil, to create a stable subbase. In the report it is evident that the transport of soil does not have a high impact on the total GWP. The results being less than 1% for distances of 100 km, and approx. 3.6% for 500 km. A 500 km distance would result in a travel across Denmark, which is highly unlikely to happen. Two products with specific EPD are used regarding the transport; one being 1100 km with truck for screw piles, as they are produced in the Czech Republic, and the second being Swedish construction wood with boat and truck transport. The use of specific numbers does only have a small impact on the total GWP.

To decide what is the most sustainable solution for a specific case, a local geotechnical investigation needs to be conducted in order to determine the soil conditions and depth of a load bearing layer. Therefore, considering end-of-life and site disturbance, screw pile foundation is far superior to concrete strip foundation. Installation time is very fast and weather independent and the load carrying capability is immediate. Disadvantages and concerns associated with screw pile foundation could mainly be regarding insufficient corrosion protection, incorrect installation (e.g., insufficient torque) or if used with wood framed deck or, damage from pests due to exposed underside cladding. In general risks consist of design flaws or installation errors and these risks are not necessarily higher than those in relation to concrete strip foundation, as these can be more sensitive to settlement and water damage. There are limitations where screw pile foundation is unsuitable or problematic for certain soil types, with a few examples being very rocky soil with few fines, compacted and frozen saturated soil [9].

PERSPECTIVE

A limitation of this study is the holistic view, that does not consider the IEQ (Indoor Environmental Quality), economy (LCC) and time. Future studies should take a full holistic view in order to determine and cover all parameters in determining the decision-making framework of what a sustainable building is. The IEQ could be an important parameter when using building methods like Method E, ACERA. This type of construction uses vapor retardant and organic (non-plastic based) paint, why this construction type is open to diffusivity, and have the potential of a healthier indoor environment, and a more stable humidity, possible with lower operational cost for ventilation systems.

Finances and time are both relevant factors to consider, in order to be able to build efficient and sustainable. It can be investigated if a prefabricated construction part comes with a smaller waste than 10%, because of a lean and efficient production line, where it is cost-effective and easy to use surplus products elsewhere in the production. As the EU have indoor air quality as one of their Level(s), the IEQ is also an important parameter to investigate for future studies. The IEQ can be affected by the change in design and materials, by architectural design and a changed thermal capacity, all of which can cause IEQ changes. Through a design process it should be considered what the net living-area is and optimize the effective use of sq. meters. In a future design process a holistic view of the whole building should be considered, as the effect of single product on the GWP might be neglected, and so a framework which takes into consideration all building materials as a whole, can reveal a better potential for sustainable building methods. For example, screw piles and wooden floor deck in combination.

LCAbyg and the EPD´s used by the software has a limitation. There is little to no standard possibilities of declaring reuse of a product. As an example, and considering the buildings in Method A, where bricks make up a large share of the total GWP. In the future, a brick with a lifetime of 120 years could potentially be re-used in multiple buildings during its lifetime - this will create a need for development of mortar to create incentive for reuse. A way of achieving this is, to develop predicted forecast, in same manner as for energy-mix.

CONCLUSION

This study and project conclude that there is no single method that is suitable for every situation making single-family houses sustainable, but there are existing technologies and materials that can be a part of the solution. Wood, wood-based boards, and wood fiber insulation have shown a substantial potential of reducing the GWP. There is a need for more research and development to achieve a full holistic solution that is sustainable for the industry, the economy, time/labor, materials, and the people who are going to live in the buildings. This conclusion is in affected by assumptions and invalid data or no data availability due to the industry being in a transition phase. The LCA phases and the LCAbyg software is also in constant development, and a note related to the future BR and VSC, calls that the limits will be revised based on previous studies and possibilities. This report is to challenge the ambitions of the future CO_2-demands through BR and VSC. It can be concluded that the possibilities are there, but the industries are not utilizing the full potential, which is why the transition towards a CO_2-limit is needed, as seen in the regulations.

Determining the potential of (possible) CO_2-eq.-savings in perspective, the approximate saving is 30% from Method A to Method D. On a yearly average between 2009 and 2019, 93% of the buildings are constructed without wood façade. The average size of a single-family house was 196 m^2 in the same period and this adds up to a total of around 960,000 m^2 is built [10, pp. 128-132]. To mention an example, it is set as an expectation that from 2022, 2% of all new sq. meters will be built to follow the principles of Method D. From 2025 the share will increase to 4% due to the new BR. Adding up the numbers in 2032, meaning that 36% of all new builds will be with wood façade. If this is compared to a situation following the current traditional methods, the savings will be around 294,000 ton of CO_2-eq (Appendix 11). This equals the same emissions as that of 15,000 people's emissions per year [11], 172,000 cars per year driving 15,000 km [12] or same emissions as 15 million ton of beef [13].

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8. Conclusion

The goal of this report was to compare the environmental impact of the currently most used building methods to LCA threshold limit values of BR and VSC and determine constructions with highest potential. The potential is determined by comparing current building methods with other methods that shall hypothetically result in lower GWP emissions for a 50-year building investigation period in kg CO_2-eq. Research in LCAbyg shows that a substitution of traditional floor slab construction, to a wood framed construction provides the biggest saving potential of 2.21 kg CO_2-eq./m^2/year in average (±46% deviation) or 50% in single-construction level. The floor savings, equals to 19% of the total building level. The construction with the second biggest saving potential, is the substitution of the bearing construction in the external wall with potential of savings of 1.1 kg CO_2-eq./m^2/year in average (± 28% deviation) or 52% in single-construction level. External wall savings equals to 9% of total building level. Generally, the largest potential in terms of CO_2-eq. savings are achieved by substitution with bio-based materials that are produced with minimal processing and additional substances in production. Floor concrete slab supplement with screw pile foundation is only environmentally feasible for very complex soil conditions such as Building 2, and the respective location. Biggest recycling potential in terms of end-of-life scenario is provided by structural wood, wood fiber insulation and screw pile foundations of galvanized steel.

A sustainable building method is achieved by combining methods that provides large savings. For example, screw pile foundations are providing biggest savings with wood framed floor deck, and wood framed floor deck has biggest savings when built with wood framed walls. Therefore, building methods should represent a combination of several material substitutions to achieve biggest possible savings.

In general, single family house typologies are suitable for wood framing, including external wall, floor deck and screw pile foundation solutions providing significant carbon emission savings and biggest recycling potential after end-of-life. Wood framing and screw pile foundation solutions perform equivalent in terms of energy performance compared to traditional building solutions if insulation level is corrected for lower heat capacity accordingly and higher internal/external temperature difference for floor. Adjustment increases insulation layer thickness in some cases but does not offset total building environmental impact in significant matter compared to traditional building Method A. The ACERA-solutions with cold bridge interruption strategies, requires no or very minimal change in dimension of construction thickness. Wood fiber insulation has higher λ-value class 37, than lowest class 34 mineral wool and therefore wood fiber insulation could only realistically be used with framing system with cold bridge interruption to avoid walls exceeding surplus of 600 mm thickness because of energy frame requirements in BR18 LE. The lifespan of building materials in structural constructions, for all material substitutions, is well above the 50-year investigation period and therefore only finishes are requiring one or two replacements in the investigation period. Replacements of finish, such as exterior or interior wall paint does not offset the total environmental impact of the buildings in significant matter compared to traditional Method A.

Comparing all building methods, Method D where both external wall and floor deck is substituted, has the largest saving potential in terms of total building environmental impact. Savings can be achieved in average of 30% or 3.37 kg CO_2-eq./m^2/year resulting in a building total of 7.8 kg CO_2-eq./m^2/year, including operational energy, building process, transport to building site, and technical installations. Reference Method A provides 11.72 CO_2-eq./m^2/year for the buildings total GWP.

Building regulation (BR) will establish CO_2-limits in 2025. BR 2025-2026 estimated threshold limits of 10.5 kg CO_2-eq./m^2/year (excluding A4-5 phases) can be met without any additional measures using traditional building methods with masonry and concrete structural constructions that are the most used currently. Revised requirements in 2027 of 9.0 kg and 7.5 kg in 2029 cannot be met with traditional Method A.

Voluntary Sustainability Class (VSC) is already available and can be voluntarily used. VSC 2021-24 threshold limit values of 8.0 kg CO_2-eq./m^2/year cannot be met with traditional building method Method A or even B/C but can be met using method (Method D) with wood framed external walls and floor deck with screw pile foundations, but not with single-construction substitution.

VSC 2025-2026 threshold limits of 7.0 kg CO_2-eq./m^2/year cannot be met using any of analyzed methods or calculation methods for single-family housing. Future reduction of threshold limits in every 2-years with 1 kg CO_2-eq./m^2/year up to 2030 would require future research for even more sustainable methods than analyzed in this report. Solutions have shown to require a holistic approach to achieve overall sustainable buildings during the building's life cycle, from production of building materials to end-of-life recyclability potential.

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