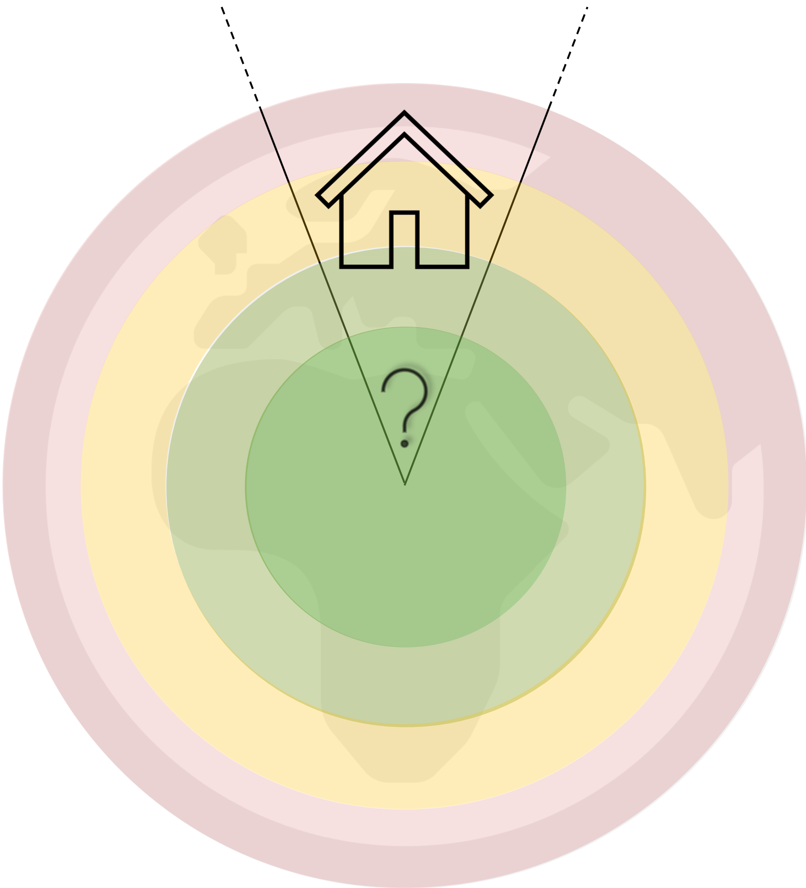
Buildings Within the Planetary Boundary for Climate Change

Investigation of the environmental impact of Danish single-family houses



Master Thesis

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Synopsis:

The work of this thesis concerns an exploration of low-emission building combinations of single-family houses in Denmark. The aim is to reach a GWP within the planetary boundary for climate change of $0.4\,\mathrm{kgCO_2/m^2}$ year. First, the current state of the industry is investigated through a case study of LCA calculations of six building concepts. The results are compared mutually and afterwards related to the proposed GWP-limits of the Danish Building Regulations and other limits towards staying within the planetary boundary.
As a means to reduce the GWP of the building industry, alternatives to the current unit $\mathrm{kgCO_2/m^2}$ year are investigated. The aim is to find a unit that promotes smaller single-family houses to ensure a reduction of the total GWP, not only per square meter. As a result, alternative methods to assess the environmental impact of buildings are presented.
As the case studies did not meet the GWP-limit of the planetary boundary, a low-emission design variation is performed to investigate if and how the GWP of one of the case buildings can be reduced. The design variation is based on an EPD Database and a variety of building elements applicable to the building design of the case study in the Danish context.
The design variation concluded that it is not yet possible to stay within the planetary boundary. Concluding the thesis, the results of the design variation shed light on areas where a focus can help reduce the GWP of buildings and building materials further.

Resumé

Dette speciale har til formål at afdække mulighederne for at bygge enfamiliehuse i Danmark, hvis CO_2-udledning ligger inden for den planetære grænse for klimaforandringer. Dette indebærer en reduktion fra 9.6 $kgCO_2/m^2$ år til 0.4 $kgCO_2/m^2$ år. For at overholde målsætningen i Paris Aftalen om at begrænse den globale opvarmning til 1.5 °C skal denne reduktion finde sted senest i 2036.

Afhandlingen undersøger derfor, hvad tilgængelige enfamiliehuse på det danske marked udleder i dag, først gennem et case studie, hvor der gennemføres LCA-beregninger på seks forskellige bygningskoncepter. Resultaterne heraf sammenlignes og sættes i relation til de fremsatte krav i Bygningsreglementet, samt øvrige krav frem mod den planetære grænse.

Alternativer til den nuværende enhed, $kgCO_2/m^2$ år, fremsættes og testes på case bygningerne med henblik på at undersøge, om der findes et alternativ, som vil fordre mindre enfamiliehuse. Baggrunden herfor er nødvendigheden af, at den totale CO_2-udledning reduceres, ikke blot per m^2. I forbindelse hermed opsættes alternative bedømmelsesmetoder, som bygger på de enheder der fremmer mindre huse.

Endeligt gennemføres en lav-emissions design variation på baggrund af en EPD Database, der indsamles til formålet. Design variationen søger at finde den kombination af produkter med EPD'erne i og uden for Danmark, som kan resultere i den lavest mulige CO_2-udledning frem mod overholdelse af den planetære grænse. Design variationen viser, at det endnu ikke er muligt at opnå en reduktion tilstrækkeligt stor til at udlede mindre end 0.4 $kgCO_2/m^2$ år.

Afslutningsvist sætter design variationen fokus på områder, hvor der med fordel kan sættes ind for at opnå netop dette mål. Et område indebærer nye bygningsmaterialer og koncepter, herunder biogene bygningsmaterialer og en generelt bredere mangfoldighed af materialer tilgængeligt i det danske marked. Et andet område er indførelse af produktspecifikke EPD'er for bygningsinstallationer, og desuden forelås det at introducere flere lav-emissions energikilder i det danske energi mix.

Preface

The Master Thesis is completed from February 1st 2023 and finished on June 9th 2023 by Brian Saya & Esther Laugesen Nygaard on the 4th semester of the Master's Programme *Indoor Environmental and Energy Engineering* at Aalborg University.

The authors of the thesis want to express gratitude to the companies that have contributed information on case buildings. This has allowed the authors to investigate the current state of the single-family housing market in Denmark. Contributing companies include DC-System Insulation A/S, Helios Huse A/S, ACERA and Holm Huse.

Reading Guide

Reference to sources is made using the Harvard method. Sources are referenced as "[Surname, Year]" in the text when citing a source at the end of a sentence. In-text citations are used as well, appearing as "Surname [Year]". The associated reference in the bibliography will appear as "Surname, Year" shown in alphabetical order.

References from Danish Standards, SBi and the Danish Building Regulations are exempt from this, instead, they are referred to as [Standard/Regulation, Year].

The thesis consists of 4 parts in the main report. First, the problem dealt with in the thesis is described followed by the thesis statement and research questions. Finally, the methodology of the thesis is described.

The first part of the thesis then follows, concerning life cycle assessments of the case buildings included in the thesis. The second part is formatted as an article, concerning the design variation of low-emission buildings. The thesis is concluded with a third part consisting of a discussion and conclusion.

In addition to the main report, an appendix report supports the findings of the main report. Finally, a separate appendix folder is supplied with additional information to support the thesis.

Abbreviations

A1-3	Product Stage
B4	Replacement
B6	Operational Energy Use
BR18	Danish Building Regulations
C3	Waste Processing
C4	Disposal
D	Reuse, Recovery, Recycling Potential
EPD	Environmental Product Declaration
GenDK	Generic Data from LCAByg 2023 (5.3.1.0)
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LowE	Low Emission Class
PIR	Polyisocyanurate
PV	Photovoltaic
OSB	Oriented Strand Board
RSL	Reference service life
SOS	Safe Operating Space

Contents

1 Problem Description

In 2015, the Paris Agreement was adopted by 196 parties, stating that measures should be taken to limit greenhouse gas emissions to reduce global warming to 1.5 °C [United Nations, 2015]. The building industry is central towards reaching this goal as it accounts for 37 % of global emissions, with a recent increase in emissions of 5 % from 2020 to 2021, exceeding the pre-pandemic increase of 2019 [United Nations Environment Programme, 2022], bearing in mind the rebound effect following the pandemic.

These new numbers demand action to reduce emissions in the building sector. In 2021, the Danish Government announced a *National Strategy for Sustainable Constructions* containing a gradual implementation and intensification of CO_2-emissions demands for new buildings [Indenrigs- og Boligministeriet, 2021]. The planned scheme for gradual implementation is presented in Figure 1.1, containing expected Global Warming Potential (GWP) ceilings through 2029.

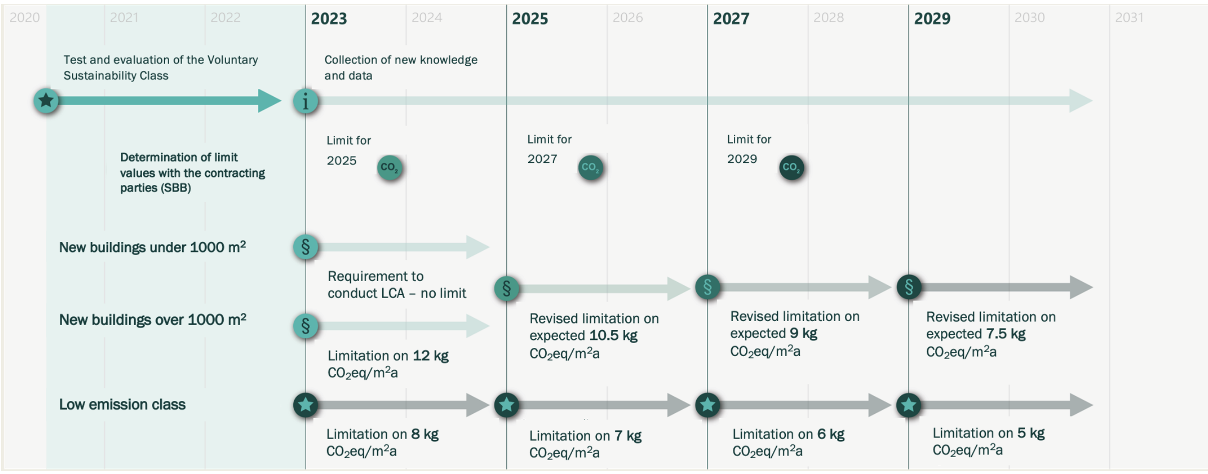


Figure 1.1: Gradual implementation of CO_2 demands for new buildings in Denmark [Indenrigs- og Boligministeriet, 2021].

The first step has been implemented in the Danish Building Regulations (BR18) in 2023, with an upper limit of 12 $kgCO_2eq/m^2$ year in effect for buildings above 1000 m^2 and a requirement to conduct a life cycle assessment (LCA) for buildings below 1000 m^2 [BR18, 2023,§297-§298]. The future demands in Figure 1.1 represent what the building industry should expect and prepare for but can change pending incoming experience and advice from the industry [Indenrigs- og Boligministeriet, 2021][Bolig- og Planstyrelsen, 2022].

The preliminary road map entails GWP ceilings through 2029, going down to 7.5 $kgCO_2{-}eq/m^2$ year. However, further steps must be taken going forward towards reaching the aforementioned climate goal for Denmark, along with the goal of being a climate-neutral society in 2050 [MINISTRY OF FOREIGN AFFAIRS OF DENMARK, 2023]. In addition, the preliminary road map has been criticised for not being ambitious enough [Strateginetværket for Bæredygtigt Byggeri, 2023].

Various approaches have been taken by interest groups in defining future reduction goals for buildings. One example is Realdania, a non-profit association in Denmark, that in collaboration with the VILLUM FONDEN, has launched the project *"Boligbyggeri 4 til 1 Planet"* (Dwellings 4 to 1 Planet), intending to reduce the GWP of new houses in Denmark by 75 % in 2030 compared to 2022 [Realdania, 2023][4 TIL 1 PLANET, 2023a]. The goal of the project is based on Denmark's Earth Overshoot Day, which fell on March 28 in 2023 this year, meaning that Denmark within the first quarter of 2023 used all its resources. [Earth Overshoot Day, 2023]. This means that Denmark uses four times its share of the earth's resources, so the consumption should be reduced with 75 % [4 TIL 1 PLANET, 2023b].

If the goal of the project is met, the greenhouse gas emissions will still exceed the level of which it is ensured that the housing industry stays within the planetary boundary, also called the *Safe Operating Space* (SOS) for climate change [Reduction Roadmap, 2023]. According to Petersen et al. [2022], the global emissions must be scaled by 96 %, to be within the SOS. To stay within the 1.5 °C scenario from the Paris Agreement, this reduction of global emissions must happen within the next 7-14 years [Reduction Roadmap, 2023]. By using the allocation principle from the Paris Agreement, the Danish building industry must reduce its GWP from a median in 2020 of $9.63\,\mathrm{kgCO_2{-}eq/m^2/year}$ to $0.4\,\mathrm{kgCO_2{-}eq/m^2/year}$ [Reduction Roadmap, 2023]. To ensure a 83 % likelihood of staying within the 1.5 °C scenario, this must be done before 2029, which calls for reductions 94.67 % lower than the proposed GWP ceiling in 2029 in the road map in Figure 1.1 [Reduction Roadmap, 2023]. Alternatively, the reduction can be postponed to 2036, ensuring a 50 % likelihood of staying within the 1.5 °C scenario [Reduction Roadmap, 2023].

Altogether, large reductions must be made within the coming years, offering a new challenge to the building industry, and demanding action in legislation and innovation of the players involved.

1.1 Thesis Statement

The urgent need for the reduction of the greenhouse gas emissions of the building industry poses a large challenge for the actors involved, both legislators and developers. While it is known that measures must be taken, it is yet unclear, what can be done today, and what is needed in the future to succeed with the reduction targets. This master thesis concerns the following thesis statement:

Do current technologies and available products allow standard single-family houses to be built within the planetary boundary for climate change? If not, what can be done to succeed?

Research Questions

The thesis statement is investigated through the following research questions:

- What is the current state of the single-family house industry in Denmark?
- Does the current state motivate a reassessment of the benchmark values of the environmental impact of buildings in the Danish Building Regulations?
- What are the alternatives to the proposed road map to stay within the planetary boundary for climate change?
- What is the availability of EPDs for single-family houses in Denmark and other markets, and is there any data missing towards staying within the planetary boundary?
- Using only EPDs, what is the possibility of building a single-family house while staying within the planetary boundary?

2 Methodology

The methodology of the thesis is shown in Figure 2.1. The thesis starts with assessing the current state of the industry of single-family houses in Denmark, concerning the level of environmental impact, expressed by the GWP. The current state is assessed by collecting data from companies. This includes various companies representing different building concepts, some conventional and some novel.

After collecting the data, LCAs are performed for each case study, the results of which are presented. The next step consists of comparing the case studies to assess the building concepts, first based on the standard unit for comparison used in Denmark, and second based on alternative units that are proposed and tested towards mitigating the GWP of the single-family house industry. The results are then compared to the proposed road map for mitigation of the GWP of buildings in the Danish Building Regulations, and alternative, more ambitious GWP limits suggested by actors in the industry. Following the comparison, it is attempted to reduce the GWP of a selected case study, to stay within the planetary boundary.

The reduction is attempted through a low-emission design variation, which entails the collection of an environmental product declaration (EPD) Database and typical construction methods of the main building elements in a one-storey single-family house. The EPDs collected are analysed in an EPD Study, based on which the database is filtered before proceeding to perform LCAs on the design variations.

The LCA on the design variations consists of combining the products in the EPD Database on the building elements. Then a filtration, with the aim to find the lowest GWP of building elements, is performed to subsequently combine the elements on the building level. After the combination on the building level, the energy performance of the building designs is calculated in order to include the operational emissions of the building in the LCA. The final step of the LCA of the low-emission design variation is then to add the remaining embodied emissions.

The LCA of the low-emission design variation is concluded with an analysis of the results, before proceeding with a presentation of possible building designs attempting to stay within the planetary boundary and the alternative road maps.

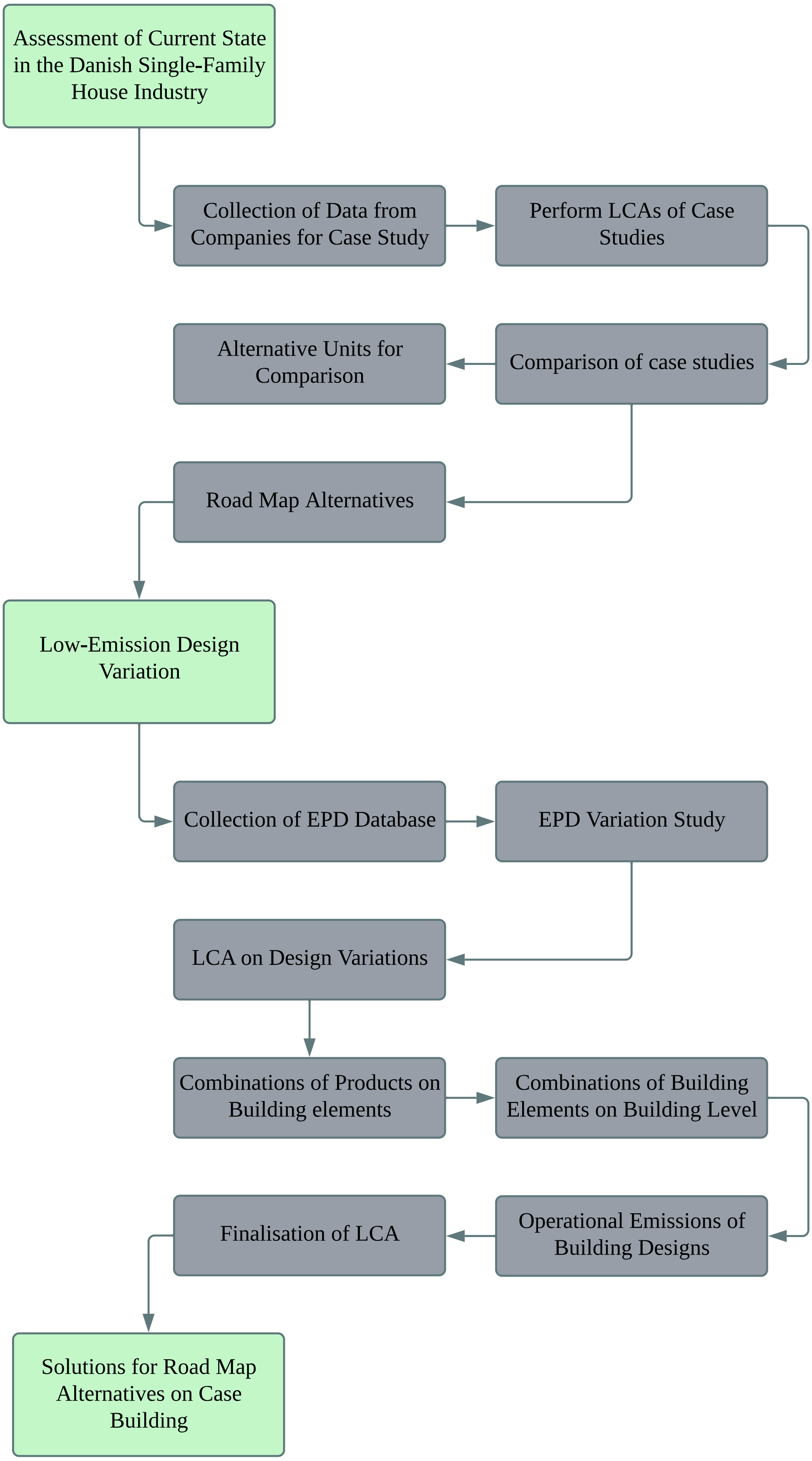


Figure 2.1: Flow chart representing the methodology of the thesis.

Part I

LCA of Case Buildings

3 LCA System Boundary

In the following, the stages of a building assessment are described, followed by an explanation of the requirements regarding life cycle assessments within BR18. Afterwards, the stages omitted in BR18 are discussed for the purpose of establishing the benefits and drawbacks of including these stages in the calculation.

The system boundary of a building's life cycle is defined in DS/EN15978. There are overall five stages that include all upstream and downstream processes, which are required in the establishment and maintenance of the functions in the building [DS/EN15978, 2012].

1. Product Stage
2. Construction Process Stage
3. Use Stage
4. End of Life Stage
5. Beyond the Building Life Cycle

Within each stage, several modules exist. These modules are visualized in Figure 3.2, where the stages are put in relation to the different life cycle models that exist. In total, there are three life cycle models; cradle-to-gate, cradle-to-grave, and cradle-to-cradle. These life cycle models are particularly important regarding EPDs and the extent of the declared modules for products.

Modules A4-5, B1-7, and C1-4 are marked with an asterisk as these modules are scenario based. As opposed to A1-3, where the production of a product is known based on the manufacturer, these stages are dependent on the conduct in the actual building, where a product is applied. It must therefore be disclosed in detail, which assumptions lay the base of the calculations, as it varies based on the building case.

Module D differs from the remaining stages, as it deals with components from the building that could potentially be used as resources in future projects. Thus, it is beyond the actual life cycle of the building in question.

If it is desired to depict the actual environmental impact of a building throughout the whole life cycle, all stages in Figure 3.2 should be included. However, current practices in Denmark are simplified calculations, where only select modules are included in an LCA calculation. As of January 2023, an addition to BR18 dictates that LCA should be performed for every new building in Denmark, as well as establishing an upper limit for buildings above $1000\,m^2$.
In BR18, however, not all stages are required to be included, when performing an LCA. The modules included are shown in Figure 3.1. Module D must be declared, but the environmental impact calculated should not be included when considering the upper limit for larger buildings [BR18, 2023,§250-§298]. 8 of 17 modules must be disclosed to meet the requirements in BR18.

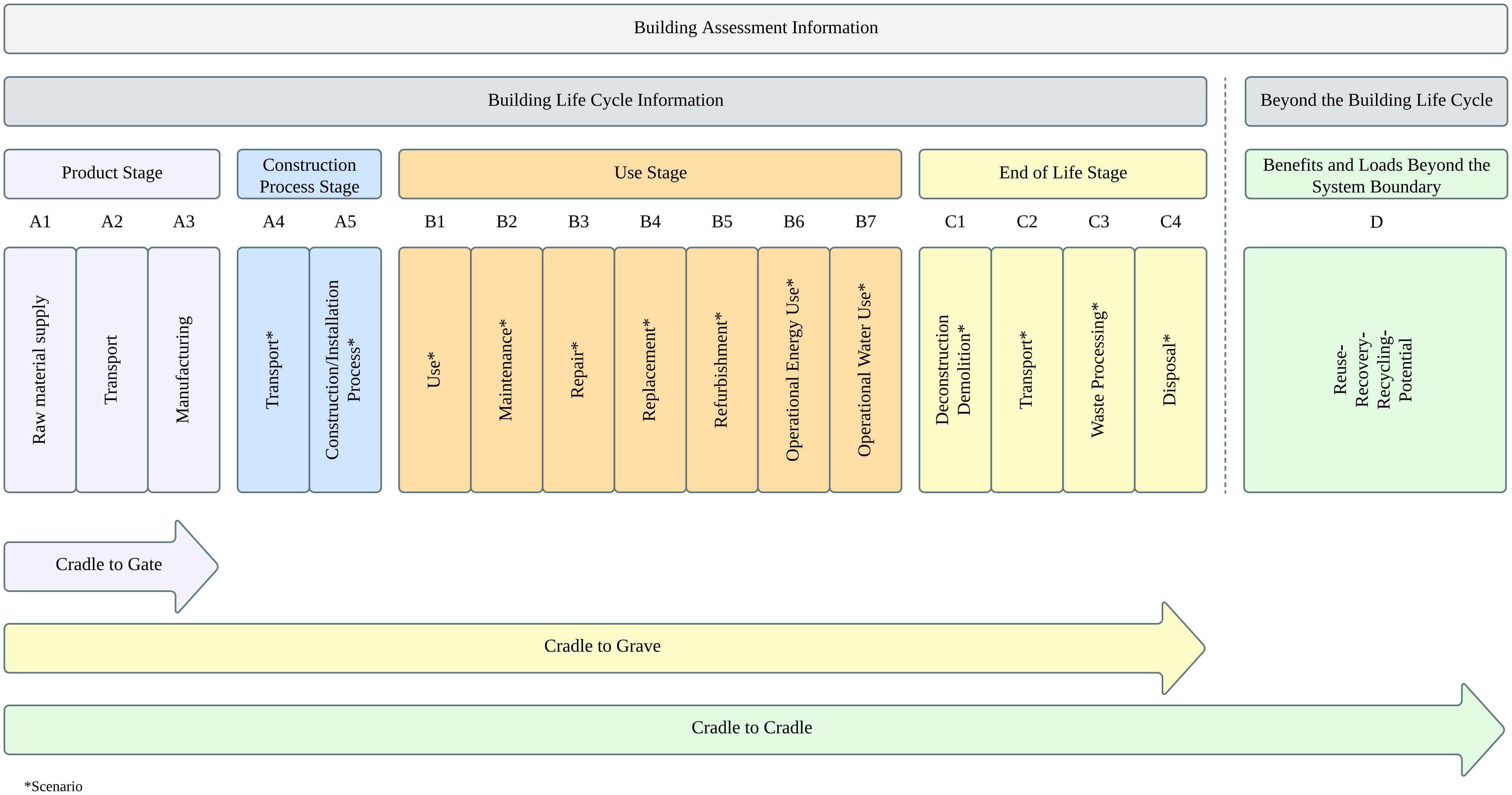


Figure 3.2: Building Assessment Information as defined in DS/EN15978 [2012], with definition of life cycle models. Scenario means that the modules are scenario-based, and can alter from project to project.

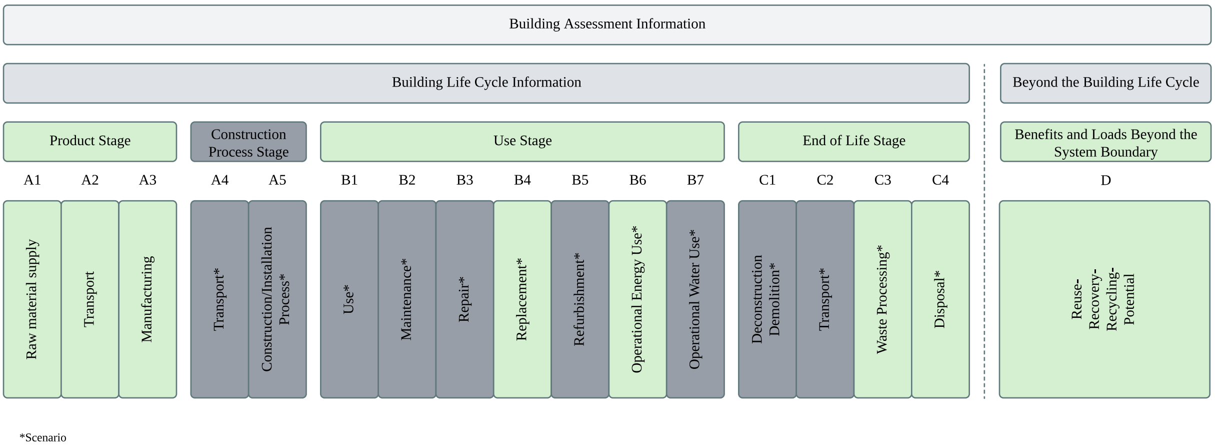


Figure 3.1: Modules included in the mandatory LCA calculations in the Danish Building Legislation, highlighted with green [BR18, 2023,§250-§298].

It is an accepted premise that something must be done to reduce greenhouse gas emissions, including those originating from the building industry. According to Earth Overshoot Day, Denmark consumes more than 4 times its share of the Earth's global resources [Earth Overshoot Day, 2023]. Based on this VILLUM FONDEN and Realdania have founded the non-profit organisation "Dwellings 4 to 1 planet", which calls for a reduction of 75 % of the environmental footprint from new dwellings in Denmark [4 TIL 1 PLANET, 2023b]. This reduction goal will leave Denmark with a 50 % of staying within the Paris Agreement aiming to limit global warming to 1.5 °C, while staying within the safe operating space, securing that Denmark stays on the right side of the planetary boundary for climate change [4 TIL 1 PLANET, 2023b]. The baseline for the 75 % reduction target is an average emission of $10\,\mathrm{kgCO_2{-}eq/m^2}$ year in 2022. The ambition is to reduce the emission of dwellings to $2.5\,\mathrm{kgCO_2{-}eq/m^2}$ year by 2030. These figures include emissions from stages A1-3, B4, B6, C3-4 [Zimmermann et al., 2021].

The approach to determine necessary reductions is called the acquired rights principle [Bjørskov and Maagaard, 2023]. This means that industries with high emissions today will continue to have the highest emissions in the future, and is not based on climate science [Birgisdóttir, 2021a][Bjørskov and Maagaard, 2023]. Considering that the reduction targets put forth are not based on climate science and knowledge about how the reductions can be achieved, there is a risk that certain industries are unable to live up to their expected targets. If this is to be the case, a shift in the allocation of emissions may be required, and on account of this, it is desired to ensure as high reductions in the building industry as possible. In the context of this thesis, these considerations are included as part of a discussion, of which drawbacks and benefits exist, in connection to including or omitting certain modules of an LCA.

The following modules are not included in the building regulations:

- A4: Transport
- A5: Construction/Installation Process
- B1: Use
- B2: Maintenance

- B3: Repair
- B5: Refurbishment
- B7: Operational Water Use
- C1: Deconstruction demolition
- C2: Transport
- *D: Reuse-, Recovery- and Recycling Potential*

Module D is considered included in the legislation, as the result is not included in the upper limit of CO_2eq-emissions.

The reason for omitting the above modules are that there is not yet enough data available, there is a lack of experience in documenting them, and finally, a strategic choice to focus on the modules with the heaviest environmental impact [Zimmermann et al., 2021][VCBK, 2022]. It has though been criticized that not all are included, and questioned whether the most impacting modules are included or excluded. By investigating four EPDs, it has been concluded that the 8 modules currently included in legislation cover approximately 96-99 % of the data disclosed in the EPDs, thus concluding that the most important modules are covered [Birgisdóttir, 2021b]. In this article, it is however not mentioned, which modules were declared in the investigated EPDs. Oftentimes, not all modules are declared, and certain modules are dependent on the systems in the building, and not associated with specific materials. For instance, many of the modules in the use stage (B1-7) are associated with emissions during the use stage for maintenance and refurbishment. Therefore, emissions may be overlooked in other stages, which are not declared in an EPD, and the figures stating that 96-99 % of emissions are accounted for, might be misleading.

An additional argument to exclude the remaining 9 modules is that the industry is not used to calculating the environmental impacts associated with these, and there is not sufficient data available. A counterclaim could be that this is the exact reason why the industry should be forced to calculate these figures, as it would increase knowledge of the necessary data and calculations required to successfully determine the impact of the remaining modules. It has often been inquired by the building industry in Denmark that legislation should take the lead in accelerating the green transition. In a recent initiative, Molio and Contech lab has gathered chief executives from the Danish building industry to discuss which steps should be taken to achieve a green industry in the fastest manner. One of the focus points derived from the initiative is that the Danish Building Legislation should play a key role in promoting the green transition, emphasizing that the green transition must be accelerated across the major presences in the industry [mir, 2023]. This is further accentuated in a debate submission on Borsen, stating that a prerequisite towards succeeding is a good collaboration between the industry and the Danish Parliament [Enevoldsen et al., 2023]. In general, there is a consensus in the industry that legislation promotes fast implementation, as was the case with energy requirements in the Danish Building Legislation [Komproment, 2022][Enevoldsen and Garver, 2019][Schefte, 2016].

Arguably, there would be benefits associated with including all the modules. The extent of a building's environmental footprint would be more precisely estimated and the industry would gain more knowledge. By estimating the environmental footprint in greater detail, it allows the industry to know the magnitude of the reduction potential, which will be crucial towards becoming a climate-neutral society in 2050 as Denmark is legally committed to be as part of the European Union's Climate Law [Climate Action European Union, 2023].

Considerations regarding the specific modules also exist. By not including A4, choosing products that are manufactured locally is not promoted. This means that choosing between two products, with the same environmental impact in modules A1-3, but from two entirely different locations, for instance overseas and a Nordic country, does not result in a different LCA. Instead, a product can be selected solely based on the Product Stage with no regard for the environmental impact associated with transportation.

Module A5 of the Construction Process Stage also offers some drawbacks when not included. A5 is the construction and installation processes on the building site as well as material waste, thus resulting in lower emissions the simpler and faster the construction process itself is. This means that a product, which is easier to install and requires less transportation of materials on site, requires less storage of products, or offers faster completion of the building envelope, thus requiring less temporary work, would be promoted if this module is included. This is for instance the case with sandwich panels, with which the building envelope is on the whole complete, once installed at the building site. This advantage of choosing a sandwich panel instead of for instance an exterior wall which is built up of several separate products on site, is not accounted for in the current LCA model in the legislation.

As for the Use Stage, similar aspects are at stake, especially regarding the emissions related to the transportation of products, for instance for maintenance and repair. Because these modules are not included in the LCA, products that require less maintenance and, anticipated, less repair are not promoted. Module B5, regarding refurbishment, offers similar drawbacks, though not directly related to the specific materials. Instead, this module would, if included, promote the design and layout of the building that bids flexibility with the result of fewer emissions in case a refurbishment is needed. During a building's lifetime, its use possibly changes several times, calling for a smart initial design.

In the End-of-Life Stage, C1-2 are omitted. These involve the on-site works to deconstruct/demolish the building and the transportation of the deconstructed building to disposal or waste-processing facilities. When not considered, this means again that certain types of products are not promoted. For instance, a product that can easily be waste processed or reused nearby would cause fewer emissions due to transportation than a product demanding special considerations and care-taking.

Common for the modules omitted, is that it makes the scope of performing an LCA smaller, which allows the industry to sufficiently complete the LCA, which is now part of the Danish Building Regulations.

Module D is partially included in the LCA, as it is mandatory to calculate and disclose the module, but the calculated environmental footprint is not reported as part of the GWP limit. Module D, as indicated by Figure 3.1 and Figure 3.2, is considered happening beyond the building life cycle, as it is the potential resources for future use in another building life cycle. That means that no matter the design and expectations for future use of the building materials, there is no guarantee that it will be implemented in a new building project. For this reason, module D is not allowed to be included in the final reported footprint. However, there are downsides to not including module D in the reported results, despite the valid argument. As long as there are no real benefits of presenting a favourable module D, other aspects in the building life cycle will take priority. To not only reduce emissions but to reduce material consumption, it is important to consider circular principles, which in terms of buildings, are closely related to the potential for future use of the building materials, whose service life is not exhausted at the time of deconstruction of a building [Nielsen, 2022]. This is at risk of being de-prioritised and could also give rise to a different material selection. In the case of the legislation in Denmark, a buildings lifetime is considered 50 years, however, many materials have a longer life, for instance, bricks, with a reference service life of 150 years, which means that it could potentially be used in three buildings in total, but the emissions in the product stage are only distributed over 50 years, favouring materials with a shorter reference service life and lesser emissions.

As indicated by the above section, there are both drawbacks and benefits of omitting modules in the legislation. The aspects of the remaining modules should be sought to consider, even when performing an LCA according to the Danish Building Regulation.

4 Case Studies

The foundation of this thesis sets upon a case study of six different single-family houses from the Danish market, each representing a building concept. Among the building concepts, there are innovative solutions, new solutions to the market, and known and well-established concepts. Single-family houses are chosen as the focus of this thesis on the basis of the reduction potential the building typology possesses. The reduction potential is based on the amount of single-family houses being built on a yearly basis in Denmark. A review of the building typologies in Denmark is found in appendix A.1.

The purpose of the case study is to investigate the current state of the single-family housing industry by conducting life cycle assessments. The results of the LCAs are compared and related to the requirements and GWP ceilings proposed applicable from 2025 going onward.

The LCA calculations are conducted in LCAbyg 2023 (5.3.1.0), based on the Danish Building Regulation. This means, that the modules that should be included, the calculation of the reference area, rules for the use of environmental data, and the lifetimes of products are based on the requirements in BR18. The modules included and elaboration of these can be found in section 3. The results from the LCAs conducted are assessed individually in appendix A.

4.1 Case Study 1: Wood-based dwelling with screw pile foundation

The first case study is from ACERA, a company based in Horsens that specializes in building houses with nearly only wood products, to build low environmental footprint solutions with current technologies.

Figure 4.1: Rendering of the building from ACERA [2023] `https://acera.dk/`.

The case building used in the thesis is shown in Figure 4.1, depicting a modern building, with an architectural design, and varying room heights with floor-to-ceiling window panes. The gross floor area is 147 m^2, one of the smallest case buildings. As shown in Figure 4.1, a garage is designed as well, but neither the materials nor the area is included in the life cycle assessment, as per the building regulations. The net area of the house is 110.3 m^2, utilizing 75 % of the gross floor area. The house consists of three bedrooms, a living room, a kitchen, one bathroom and one utility room. The floor plan is shown in Figure 4.2. The orientation of the house is shown in the figure, along with the area of the rooms and the gross floor area.

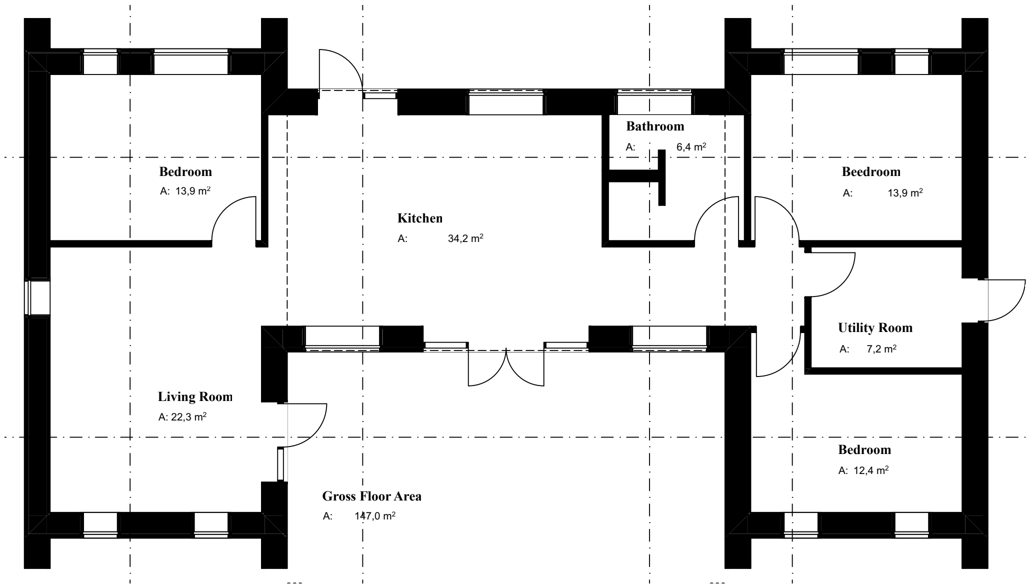


Figure 4.2: Floor plan of Case Study 1 from ACERA [2023].

Building Concept

ACERA has developed its own elements, consisting of construction wood, wood fibre insulation, internal wooden panels, and external wooden cladding. The products used are chosen with a focus on reducing chemical substances and ensuring a healthy indoor environment. The building concept recurs in all of the main building elements. A sectional drawing of the house is shown in Figure 4.3.

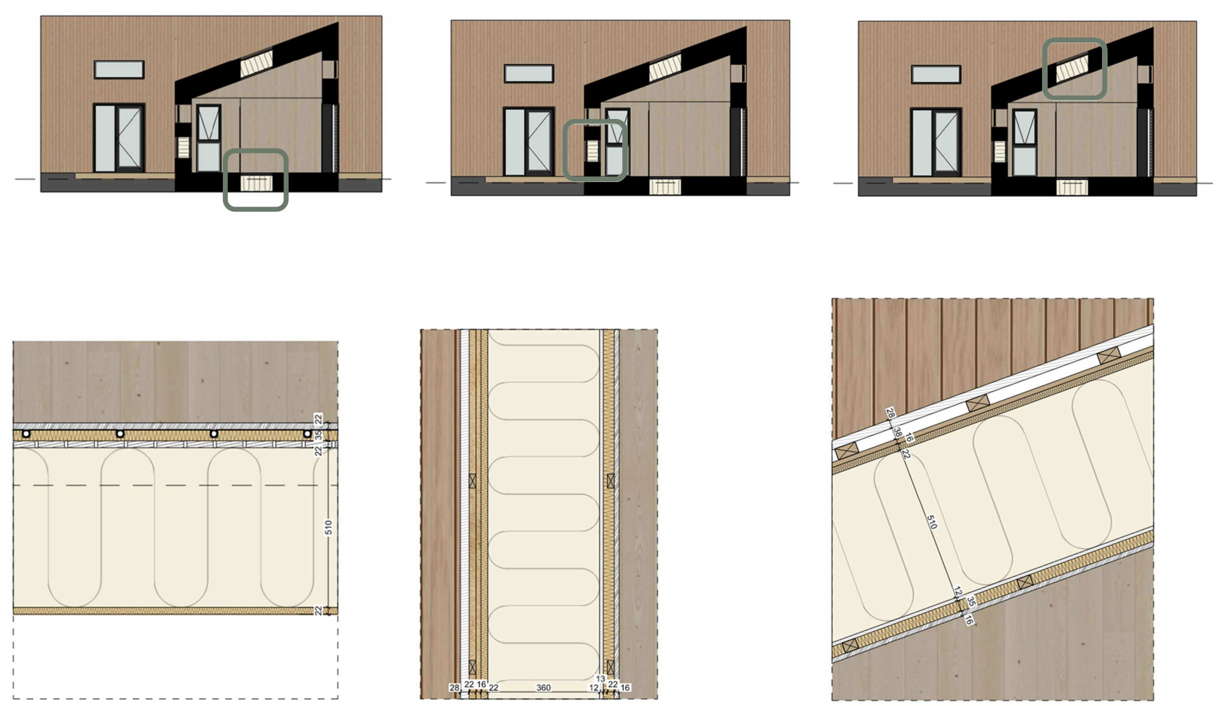


Figure 4.3: Sectional drawing of Case Study 1 from [ACERA, 2023].

The overall concept is a wood-based building, where the roof, external wall, and deck are built using the same method. The construction elements consist of wood framing using 45 mm wood members complemented by wood fibre boards to insulate as well as weatherproof. The cavity is filled with blown-in wood fibre insulation.

For the external wall and roof, an oriented strand board (OSB) board airproof the interior of the building. Both the external wall and roof have interior cladding made with 16 mm wood panels, and the external cladding is made with larch, partially burnt for aesthetic reasons.

In the ground deck, a paper-based vapour diffusion retarder is used, and heat distribution plates and underfloor heating tubes are installed, followed by a wooden floor coating. In the bathroom, the coating is made of clinker, and a thin layer of concrete is used in the utility room. Interior walls are made with a wooden frame, blown-in wood fibre insulation and wood panels for cladding. Gypsum fibre boards and clinker are used for the interior walls in the bathroom.

Instead of a strip foundation, the company uses a screw pile foundation of steel. This reduces the consumption of concrete in the building and is expected to yield a lower environmental footprint. Cement-based cladding plates are used to cover the gap between the ground and the deck.

The house is heated with underfloor heating and a heat pump called a complete heat pump unit. The heat pump makes use of the warm air exhausted from the bathroom, kitchen and utility room, which is used to heat the house as well as produce domestic hot water (DHW). The heat pump, therefore, handles both ventilation, heating and DHW. In addition, some of the windows in the house are ventilation windows. They utilize the energy from the sun, by heating the air as it moves up through the window before entering the house. The U-value of the ventilation windows is lower than standard windows, without compromising the indoor environment. The remaining windows are 3-layer wood windows, as well as external doors. The specifications and results of the LCA of Case Study 1 are shown in appendix A.2.

4.2 Case Study 2: Element-based dwelling with screw pile foundation

The second case study is from a company based in Holstebro, called Holm Huse that builds houses using their own patented building elements. The building elements include the deck, roof, external walls and internal walls. Holm Huse specialises in building smaller low-energy houses, designed for maximum utilization of the square meters available.

The case building used in the thesis is one of the company's most-sold houses. The house has a gross floor area of 149 m^2, consisting of four bedrooms, two bathrooms, one utility room and an open space with a combined kitchen and living room. The simple and compact design of the house is represented by a rectangular geometry with a flat roof. The floor plan is shown in Figure 4.4. along with the rooms' area and the gross floor area.

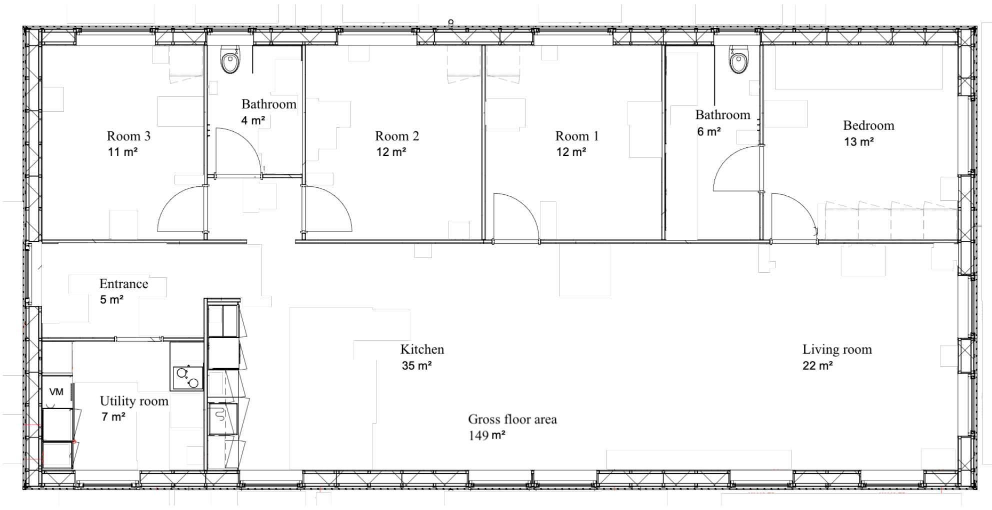


Figure 4.4: Floor plan of Case Study 2 from Holm Huse [2023].

Building Concept

The building concept of Case Study 2 is characterized by the building elements developed by the company. The building elements are used throughout the house and carefully prepared at the production facility for fast assembly on-site. The building elements are load-bearing, thus not requiring any further stabilization.

At the production facility, holes are cut out for windows and doors, which are then assembled. Similarly, all electricity and installations are built into the elements, allowing a fast on-site assembly, typically completed within one day.

The overall concept of the building elements is a cement-based board on the outer side, a wooden frame and polyisocyanurate (PIR) insulation finished off with the cladding/coating chosen by the customer.

The external wall consists of the cement-based board, a layer with 45 mm wooden members every 600 mm and PIR insulation, a layer of PIR insulation, followed by another layer with wooden members and PIR insulation, finished off with one layer of plasterboard on the internal side. As external cladding wood is used, or any of the alternatives provided by the company if so wished.

The deck element consists of the cement-based board, a layer with wooden members of laminated veneer lumber (LVL) every 600 mm with PIR insulation and glued laminated timber (GLT). An extra layer of PIR insulation follows, and then a layer of OSB, which is finished off with a selected coating. In the case study, a laminate floor is used.

The roof element consists of roof coating, an OSB, a wedge construction with PIR insulation to ensure minimum gradient of the roof, and an insulation layer followed by a chosen cladding. In the case study, a painted plasterboard is used.

These elements all make use of PIR insulation with low heat conductivity. This results in thin walls, which allows for effective utilisation of the gross floor area. This case building has a net area of 127 m^2, utilizing 85 % of the gross floor. Internal walls are constructed with gypsum fibre boards and 45 mm wooden members with insulation. The specifications and results of the LCA of Case Study 2 are shown in appendix A.3.

4.3 Case Study 3: Heavy dwelling with strip foundation

The third case study is a traditional standard single-family house from a company called Helios Huse. The house is built with conventional methods for all building elements, including a strip foundation.

The case building included in the case study is shown in Figure 4.5. The house is architect drawn, shaped like a horseshoe with a courtyard in the middle, and large window panes throughout the building. The house is a modern standard-family house with varying heights in the integrated garage of 55 m^2 and the house. Due to the area of the garage and a covered outdoor area, the gross floor area, according to BR18, is 230 m^2.

Figure 4.5: Rendering of the building from Helios Huse A/S [2023] `https://www.helioshuse.dk`.

The floor plan of the house is shown in Figure 4.6, where the shape of the building is clear. In addition to the garage, the house consists of three rooms, one walk-in closet, an office, two bathrooms, a utility room, a cloakroom, a multi-purpose room, a pantry and a wine room next to the kitchen and a living room.

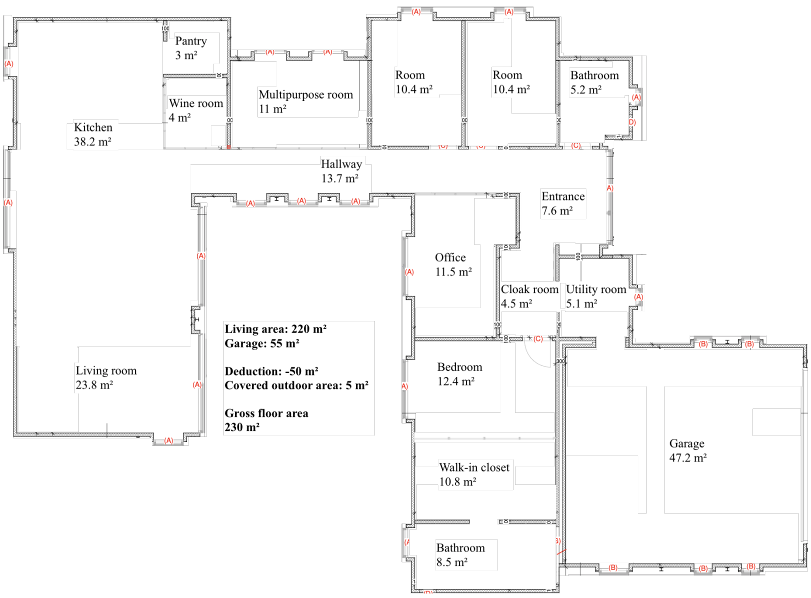


Figure 4.6: Floor plan of Case Study 3 from Helios Huse A/S [2023].

Building Concept

The building concept of Case Study 3 consists of a strip foundation, load-bearing columns and a flat roof. Concrete is used for the ground deck and external wall along with either EPS insulation or mineral wool. A sectional drawing of the building concept is shown in Figure 4.7. The material amounts in the building elements vary between the living space and the garage, but the building concept is the same.

The foundation is reinforced, consisting of a concrete strip foundation, foundation blocks with insulation in the middle, and insulation where there are windows and doors to the floor. The ground deck consists of EPS insulation boards, a reinforced concrete floor and laminate flooring in the living areas and tiles in wet rooms.

The internal walls are made from lightweight concrete, and the internal walls in the multipurpose room stabilise the construction with a partition foundation consisting of a lightweight aggregate foundation block and reinforced concrete.

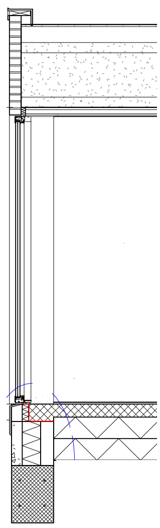


Figure 4.7: Sectional drawing of Case Study 3 from Helios Huse A/S [2023].

The external wall is a brick wall with mineral wool and lightweight concrete. The ceiling consists of plasterboards, acoustic ceiling, laths, and blown-in mineral wool, followed by a light roof made of rafters, plywood and asphalt roofing. The windows and doors are 3-layer wood/alu.

The external wall has a thickness of respectively 408 mm and 348 mm in the living area and garage. Excluding the garage, the net area is 169.3 m^2, which results in a utilization of 77 % of the gross floor area, also excluding the garage. The specifications and results of the LCA of Case Study 3 are shown in appendix A.4.

4.4 Case Study 4: Element-based dwelling with strip foundation

The fourth case study comes from a company based in Aars called DC-System Insulation A/S. The company is leading in producing panels, originally designed for use in cooling rooms, but since developed for houses. The product used in the case study is a load-bearing sandwich panel with PU/PIR insulation.

The sandwich panels are suitable for use as an external wall and as a roof. Therefore, the sandwich panels are combined with traditional building methods to assess the GWP of a building using these panels. The LCA is based on the floor plane area and building design of Case Study 2 given by Figure 4.4, where the building elements are substituted. The external walls and roof are based on the company's load-bearing sandwich panels. Whereas, the remaining building elements are substituted by Case Study 3.

Building Concept

The load-bearing sandwich panels are constructed as seen in the sectional drawing in Figure 4.8. The panels consist of PU/PIR insulation, which is covered with a cement chipboard on each side. A sealant is used to ensure that moisture does not enter the sandwich panel and an embedded eccentric lock is applied to ensure complete assembly of the panels to avoid cold bridges. The external wall is supplemented with a cladding material, a ceramic product. However, the cladding can easily be changed to wood, brick or plastering. The specifications and results of the LCA of Case Study 4 are shown in appendix A.5.

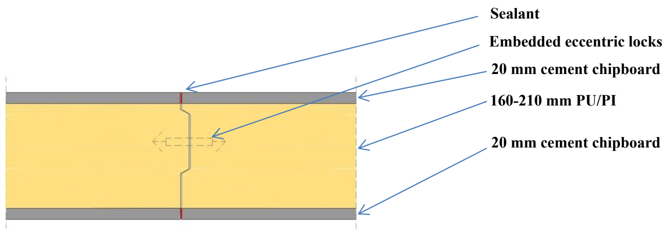


Figure 4.8: Sectional drawing of the load-bearing sandwich panel in Case Study 4 from DC-System Insulation A/S [2023] https://dc-system.dk.

4.5 Case Study 5: Heavy dwelling with strip foundation

Case Study 5 is similar to Case Study 3, as it is also a heavy dwelling with a strip foundation. The building elements are constructed using common methods and represent some of the more conventional solutions on the Danish market. The case comes from a standard-house company in Denmark, and the data is accessible from Weblager, a web page storing documents on buildings and addresses in Denmark.

A picture of the house is shown in Figure 4.9, showing a classic Danish single-family house. It is shaped like a rectangle, with a shed roof, where PV panels are installed.

There is a garage as well but is not integrated and therefore neither the materials nor the area is included in the LCA. The gross floor area is 171 m^2 and the net area is 139.9 m^2, which utilizes 81 % of the gross floor area. The floor plan is shown in Figure 4.10. The house consists of a combined kitchen and living room, three rooms, a walk-in closet, an office, two bathrooms, a utility room and an office.

Figure 4.9: Rendering of the building from Case Study 5 [2020].

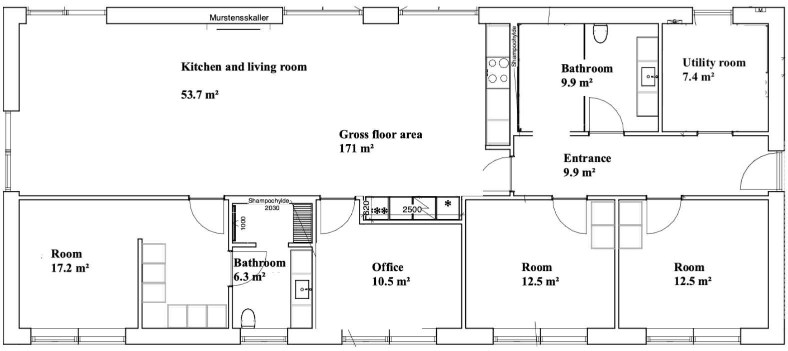


Figure 4.10: Floor plan of Case Study 5 [2020].

Building Concept

The building concept of Case Study 5 consists of conventional construction methods, using concrete and brick. The foundation is a concrete strip foundation, with foundation blocks with insulation in the middle. The ground deck is made of EPS insulation, fibre-reinforced concrete with cast into underfloor heating pipes followed by a coating of laminate flooring.

The external wall is made with brick, mineral wool and lightweight concrete, and the internal walls are made with lightweight concrete. The ceiling consists of the internal cladding of acoustic panels, wooden framework, insulation boards, wooden rafters and blown-in mineral wool. The roof includes trusses, roofing plywood and two layers of asphalt roofing. The load-bearing system consists of columns of wood and steel in the external walls. The windows and doors are 3-layer wood/alu and there are skylights allowing light to enter from above.A sectional drawing of the building concept is shown in Figure 4.11. The specifications and results of the LCA of Case Study 5 are shown in appendix A.6.

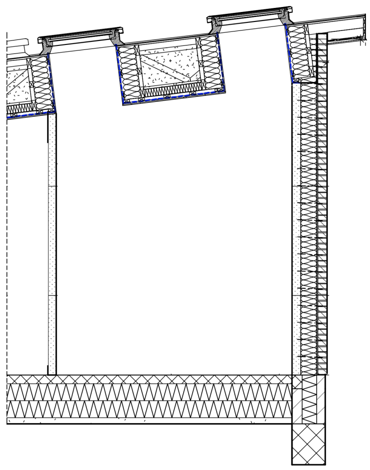


Figure 4.11: Sectional drawing of the building concept showing the deck, external wall and roof of Case Study 5 [2020].

4.6 Case Study 6: Wood-based dwelling with strip foundation

The 6th and last case study is a wood-based dwelling built on a strip foundation. It is a case building released by VCBK (Videncenter om Bygningers Klimapåvirkninger), where drawings are from as well as an already-completed LCA, performed by the developer of the house Søren Jensen Rådgivende Ingeniør in 2019 [Søren Jensen Rådgivende Ingeniør, 2019].

A picture of the house is shown in Figure 4.12. The house is constructed with wooden exterior cladding painted black. The hip roof provides rather large eaves and protects the facade of the house. There is a garage to the house, but as it is not integrated, neither the materials nor the area is included in the LCA, except for the materials for the PV panels that are installed on the roof of the garage, which are included in the energy calculations. The gross floor area of the house is 135 m^2 and the net area is 112.7 m^2, which results in a utilization of 83 %. The floor plan is shown in Figure 4.13. The house consists of two rooms, two bathrooms, a utility room a living room and a kitchen.

Figure 4.12: Rendering of the building from Søren Jensen Rådgivende Ingeniør [2019].

Figure 4.13: Floor plan of Case Study 6 from Søren Jensen Rådgivende Ingeniør [2019].

Building Concept

The concept of the case study is a mix of wood-based building elements and conventional construction methods. A sectional drawing of the house is shown in Figure 4.14. The foundation is a conventional strip foundation of reinforced concrete and foundation blocks with insulation in the middle. There is insulation under the doors to reduce heat loss. Some of the internal walls are stabilising with the same strip foundation beneath. The ground deck consists of reinforced concrete with embedded underfloor heating pipes and EPS insulation. Internal walls are built with a wooden frame, gypsum fibre boards, and wood fibre insulation boards. The external wall consists of gypsum fibre boards for internal cladding, a layer of wood fibre insulation boards, a vapour barrier, an additional layer of wood fibre insulation boards combined with a wooden frame and a wind-screen in the form of a wood fibre insulation board and finally a wooden external cladding.

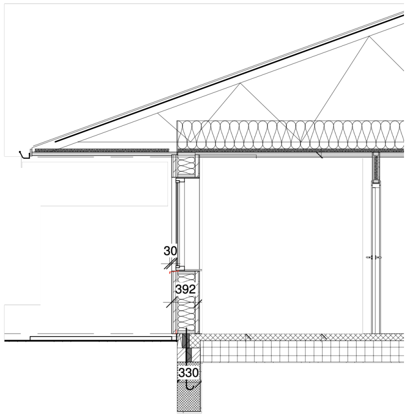
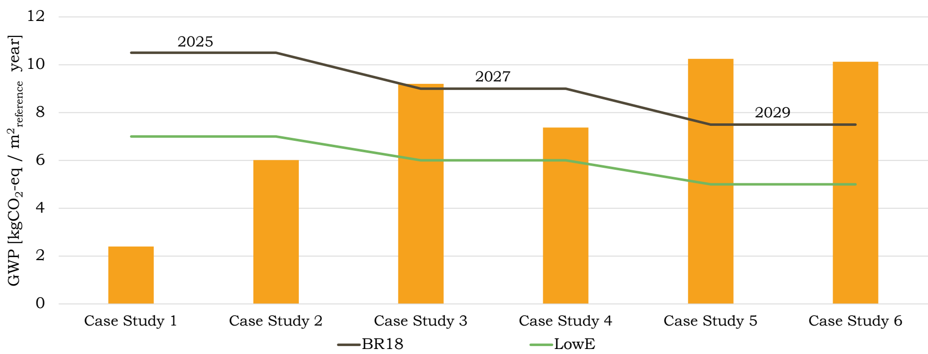


Figure 4.14: Sectional drawing of the building concept showing the deck, external wall, and roof of Søren Jensen Rådgivende Ingeniør [2019].

The roof and ceiling have internal cladding of an acoustic ceiling, wooden framework, vapour barrier, a layer of wood fibre insulation boards followed by blown-in wood-fibre insulation, wood trusses, roof plywood as a weather barrier, and finally two layers of asphalt roofing. Steel is used to a limited extent to reinforce the roof where necessary. The specifications and results of the LCA of Case Study 6 are shown in appendix A.7.

4.7 Comparison Based on the Declared Unit in BR18

Following the presentation of the case studies, the LCAs results are compared. The results are shown in Figure 4.15. Case Study 1 meets all the proposed future requirements, whereas Case Study 2 and 4 meet the BR18 requirements, and Case Study 2 meets most of the low-emission class limits as well. The remaining case studies only meet a few of the BR18 requirements.



2.40 6.02 9.20 7.37 10.25 10.12

Figure 4.15: LCA results for the 6 buildings concepts based on the declared unit in BR18.

In Figure 4.16, the results are shown divided into operational and embodied emissions. The average share of operational emissions is 13 %, but it varies considerably. The share of operational emissions for Case Study 1 is 19 % being one of the highest. The reason is that the embodied emissions have been reduced greatly, thus increasing the operational emission's share.

It is therefore expected that the share of operational emissions decrease as the GWPs increase. It is seen that in most cases the buildings have lower shares of operational emissions than Case Study 1, except for Case Study 5 which has the highest share of all the case studies at 23 %. Considering the energy performance of this case study, the reason for this is that the energy demand for heating is remarkably higher than for any of the other cases. On the other end of the scale, the share for Case Study 3 is only 1 %, which is caused by the low electricity demand for operation derived from the large area of PV panels. Based on the case studies, the expectation is confirmed to an extent, but considering the limited sample size of the case study, it is not possible to conclude for certain.

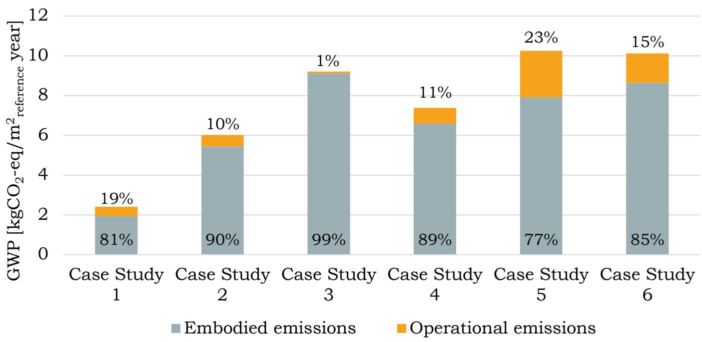


Figure 4.16: Comparison of embodied and operational emissions for the case buildings. The shares are shown in the data labels.

The three main building elements are compared, which in this context include the building envelope, consisting of the roof, the external walls and the ground deck. In the latter, the foundation is included to assess this building element as well. The embodied emissions per square meter building element are shown in Figure 4.17. For the foundation and ground deck, the emissions are per square meter ground deck.

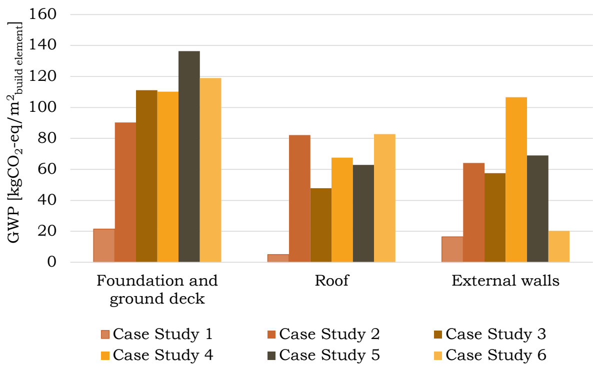


Figure 4.17: GWP per m^2 of the three building elements in the building envelope for all case buildings. The foundation is included in the ground deck, by adding the total emissions of the two building elements together and dividing with the area of the ground deck.

The foundation and the ground deck are in general the CO_2-heaviest building element. The building concept presenting the lowest emissions per square meter of building elements is Case Study 1. The external wall of Case Study 6 has similar emissions as that of Case Study 1.

5 Alternative Assessment Methods

Following the initial comparison, the case studies form the basis of an assessment of the current method of comparison. The assessment is initiated by an investigation of the units for comparison, following a reassessment of the road map proposed in BR18.

5.1 Alternative Units for Comparison

In the following, alternative units to compare the environmental impact of buildings are considered. The main concern regarding the current declared unit for comparison is that it promotes larger buildings. In short, as the total GWP is divided by the reference area, the GWP per square meter will improve with a larger area. The amount of materials is needless to say larger as well, but it does not follow correspondingly. It, therefore, offers an advantage to larger buildings. A concern that is recently expressed by Strateginetværket for Bæredygtigt Byggeri [2023], in a report where the industry contributes with inputs to the method of calculating the environmental impacts of buildings in the future.

Even though the legislation will reduce the GWP per reference area, the development of the heated floor area in Denmark must be considered. Experiences based on the introduction of energy performance requirements in the Danish Building Regulations is therefore considered. Energy demands of buildings was introduced for the first time in 1961 [Birgisdóttir and Aggerholm, 2017]. Since then, the operational energy consumption in buildings has drastically decreased. From 1990 to 2018, the energy consumption per square meter decreased by 15 %. However, despite the effort to reduce the energy consumption of buildings, there has been a small increase in the total energy consumption from buildings. This is caused by a consistent increase in the heated floor area in Denmark by 25 % in the same period [Energistyrelsen, 2019].

Taught by experience, this should be considered when taking on the task of reducing the emissions of buildings. To ensure that the emissions are reduced over time, the trend of an increasingly larger heated floor area should be stopped or even reversed. Various comparable units are therefore tested to determine the advantages and disadvantages of the options available towards mitigation of the total emission of buildings. The LCA's of the six building concepts are compared based on the following below.

(a) $kgCO_2{-}eq/m^2_{reference}$ year
(b) $kgCO_2{-}eq/m^2_{net}$ year
(c) $kgCO_2{-}eq/m^2_{surface}$ year
(d) $kgCO_2{-}eq/m^3$ year
(e) $kgCO_2{-}eq/year$
(f) $kgCO_2{-}eq/kg_{material}$
(g) $kgCO_2{-}eq/person$

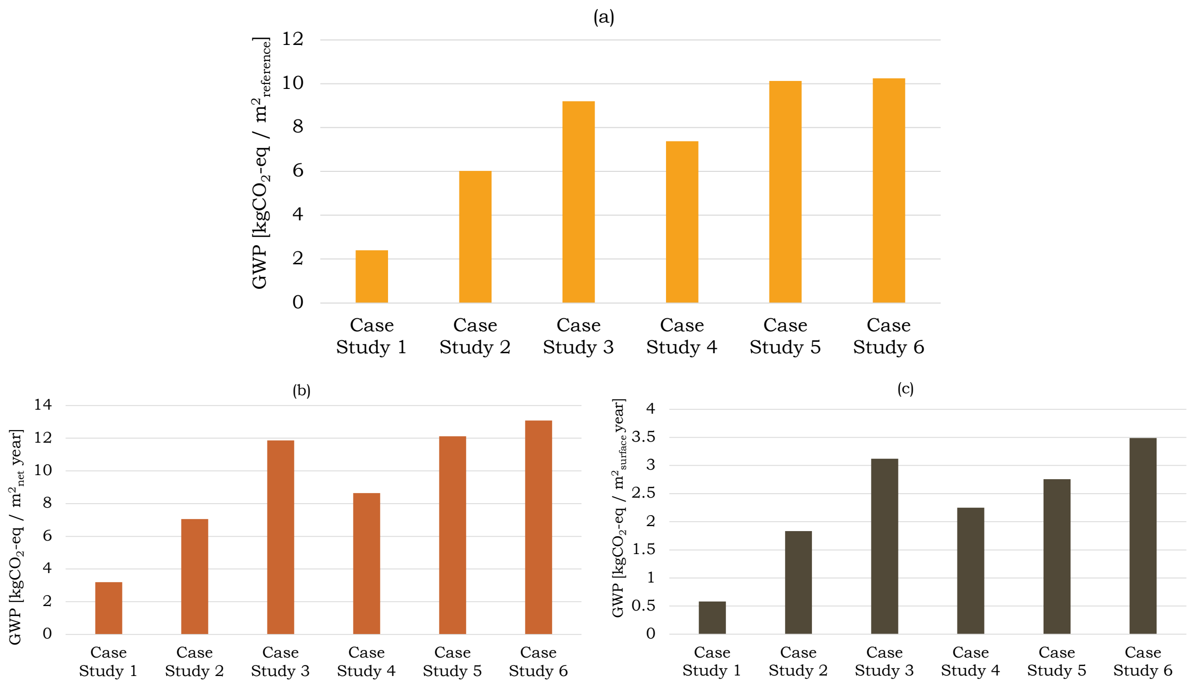
Selected parameters used for comparison are presented in Table 5.1. The GWP is compared based on the net area, as it varies within the buildings in how effectively the heated floor area is utilized. This is due to the thickness of external and internal walls, which takes up space that cannot be used for living spaces.

The number of persons is determined based on DGNB Villa. Each bedroom counts for one person, and one of the bedrooms counts for two people. A room is defined as a bedroom, if there is a window with a minimum 3 % opening area relative to the floor area and a horizontal view out [Green Building Council Denmark, 2023].

Table 5.1: Parameters for comparison of the building concepts with alternative units than the declared reference area.

Building Concept	$A_{reference}$ [m^2]	A_{net} [m^2]	$A_{surface}$ [m^2]	V [m^3]	Persons [-]
Case Study 1	147.0	110.3	607.8	618.2	4
Case Study 2	149.0	127.0	488.3	504.2	5
Case Study 3	248.8	192.9	733.3	982.3	4
Case Study 4	149.0	127.0	488.3	504.2	5
Case Study 5	183.3	136.2	510.5	617.7	5
Case Study 6	135.0	112.7	495.9	365.9	3

As the buildings' sizes and layouts vary substantially, the results are assessed based on the aforementioned alternative units, to see, what the consequences of such would be. The results in the different units are shown in Figure 5.1, from figures (a) to (g), according to the list above.



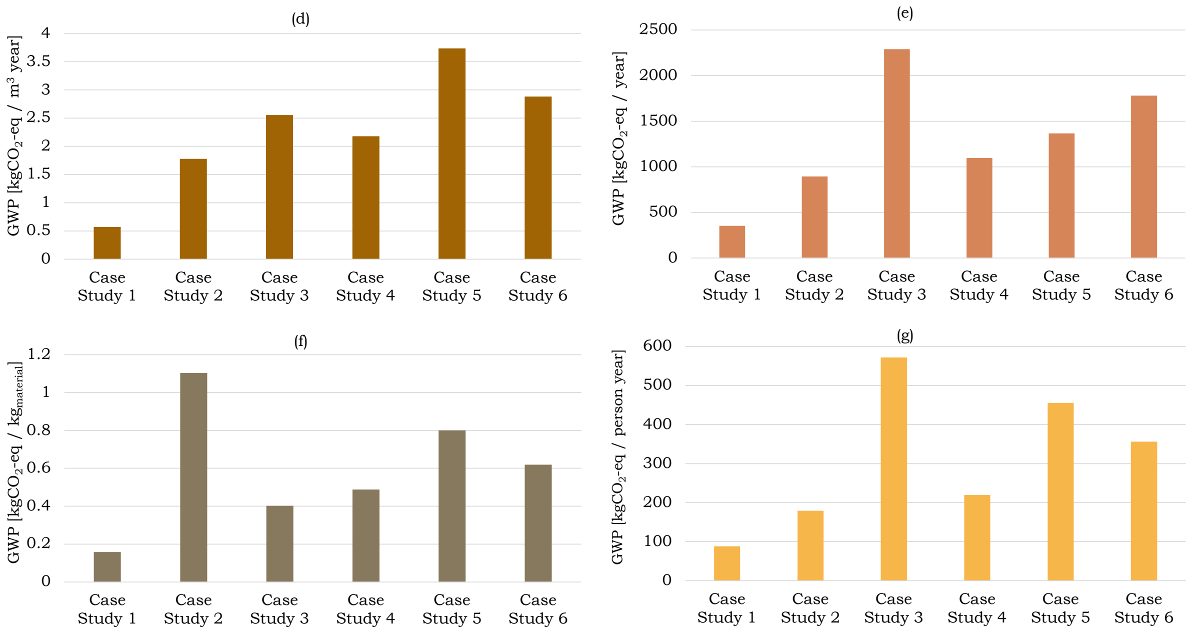


Figure 5.1: Comparison of case studies using different units. (a) is the standard unit in BR18, the GWP per reference area per year, (b) is the GWP per net area per year, (c) is the GWP per surface area per year, (d) is the GWP per volume of the building per year, (e) is the GWP per year, (f) is the GWP per material mass, (g) is the GWP per person per year.

Common for all units, Case Study 1 performs well, being the building concept with the lowest emissions. There are however variations as to which building concepts achieve advantageous results. For instance, Case Study 2 also performs well overall, but when comparing based on the weight of the materials, the results are adverse. This is due to the weight of the building concept being low compared to the other building concepts.

This unit of comparison therefore offers a drawback in the sense that a building with much material use, and use of heavy materials will benefit, whereas buildings with reduced material use will be set back. For many of the units, including figures (a), (b), (c), and (e), the tendency is the same, showing that Case Study 1 ranks best.

The aim of the investigation is to promote smaller houses, and it is therefore of interest to see which units promote the smaller houses of the study and demote the larger houses. The largest house is Case Study 3, which also results in the highest GWP per year. However, it does not perform worst in all the comparison cases. The best unit for Case Study 3 is comparing the building concepts based on the material mass. Comparing based on the volume of the house or the surface area of the building envelope is also favourable for Case Study 3, due to the size and design of the house.

Using the net area instead of the reference area promotes the buildings with thinner walls and higher utilization of the gross floor area, which is exemplified by building concepts of Case Study 2, 4 and 6. These experience a smaller increase in GWP than the buildings with thicker walls and lower utilization of the gross floor area. Using the net area instead of the reference area promotes some of the smaller buildings in this case, however, this is possibly coincidental as these buildings have the thinnest walls.

Most of the units investigated relate to the geometry of the building, for all of which a case can be made that larger buildings yield better results. Building large houses is not necessarily a problem if the house can accommodate a large family. Therefore, the GWP is also investigated based on the number of people per house. Despite the size of Case Study 3' building, it only accommodates 4 residents, allocating 62.2 m^2/person, whereas Case Study 2 and 4 are smaller, while accommodating 5 residents, allocating 29.4 m^2/person. Therefore, Case Study 2 benefits from this unit, whereas Case Study 3 concludes as the building concept with the largest emissions. Supporting figures for this investigation are found in appendix A.10.

5.1.1 Summary

In the section above, different units for comparison have been investigated. Using the material mass of the building, the volume of the building and the surface area of the building promotes large buildings. The remaining units are the net area, the total GWP, and the number of persons.

Using the net area was shown to promote buildings with effective usage of the heated floor area, which could result in a smaller heated floor area, assuming that the area will not be directly converted into for instance an additional room. It would also promote materials that result in thinner walls, for instance, insulation with higher R-values to reduce the amount of material required to fulfil the demands for U-values. Companies with building concepts with thinner walls will be given preferential treatment as opposed to companies with thicker walls.

Since, ultimately, the goal is to reduce the absolute emissions of buildings, the plainest option is using the total GWP. The results would not be biased by the unit used, but would simply reflect the environmental load of the building. The downside to this is that it offers a disadvantage to large families that require more space to accommodate the number of residents.

It can be argued that the key problem to address, is keeping the the heated floor area per person at a reasonable level. It is, therefore, necessary to include the number of residents in the assessments of buildings' environmental load. When comparing based on the number of residents, a house like Case Study 3 and Case Study 6, with a large area per person, are penalized, while the other houses like Case Study 2, Case Study 4 and Case Study 5 improve the results. The apparent challenge related to using the number of persons is how the number of residents should be determined. DGNB Villa determines the number of persons based on the number of bedrooms based on the floor plan and windows. This means that two rooms, which are practically used as offices would be considered bedrooms, assuming there are windows with a horizontal view out. Even though a developer does not intend to accommodate these extra people, the building will obtain an advantage. This means that it would be possible to manipulate the system.

In conclusion, there is no one definite valid option, as there are benefits and drawbacks to all the alternatives.

5.2 Alternative Road Maps for Single-Family Houses

Following the conclusion from the investigation of the alternative units, alternative methods and road maps based are proposed. One method concerns the GWP limits set in legislation, and concerns giving preference to smaller buildings, without directly punishing larger buildings. It is shown in Table 5.2, where the upper limits vary with the building size.

Table 5.2: Proposed system for GWP-limits for different building sizes, referred to as building classes. Interpolation allowed.

Building Class	2025 10.5 $kgCO_2-eq/m^2$ year	2027 9.0 $kgCO_2-eq/m^2$ year	2029 7.5 $kgCO_2-eq/m^2$ year
+ 200 m^2	10.50	9.00	7.50
175 m^2	11.03	9.45	7.88
150 m^2	11.55	9.90	8.25
125 m^2	12.08	10.35	8.63
100 m^2	12.60	10.80	9.00

The system is based on the proposed road map to GWP ceilings in the coming years, which is maintained as the upper limit for the largest building class, that is buildings above 200 m^2. Smaller buildings are accommodated in the sense that the GWP ceiling is lifted continually, offering some leniency in meeting the requirements. By doing such, larger buildings are not penalized, but smaller buildings are promoted.

Another method to mitigate the emissions of single-family houses in Denmark is to determine a reasonable size for a single-family house and allocate an allowed absolute GWP on this account. The average number of people in single-family houses in 2022 was 2.6, with an average area of 59.8 m^2/person [Danmarks Statistik, 2022]. DGNB Villa bases the GWP limits on an average area of 40 m^2/person [Green Building Council Denmark, 2023]. Using this, it would allocate 104 m^2 to a single-family house, which is multiplied with the GWP ceilings in BR18 to determine the maximum absolute emission. The limits based on this method are shown in Table 5.3.

Table 5.3: Proposed GWP ceilings for single-family houses.

	2025	2027	2029
BR18 [$kgCO_2-eq/m^2$ year]	10.5	9.0	7.5
Limit [$kgCO_2-eq$/year]	≈ 1100	≈ 950	≈ 800
Low emission class [$kgCO_2-eq/m^2$ year]	7.0	6.0	5.0
Limit [$kgCO_2-eq$/year]	≈ 750	≈ 600	≈ 500

In case a family requires a larger house for various reasons, it should be possible to apply for a dispensation, whereas if it is desired to build a larger house without a valid reason, the building must be designed with consideration to the absolute emissions to adhere with the GWP limits.

Applying the limits in Table 5.3 to the case studies, the results are as in Figure 5.2, showing that the case studies to a larger extent are challenged in meeting the proposed limits. Case Study 1 can meet all the requirements, while Case Study 2 meets the alternative BR18 requirements for 2025 and 2027 and Case Study 4 meets the alternative BR18 requirement in 2025. Case Study 3, 5 and 6 are not able to meet any of the proposed limits, and particularly Case Study 3 and 5 experience challenges, due to the size of the buildings, which are significantly above the 104 m^2.

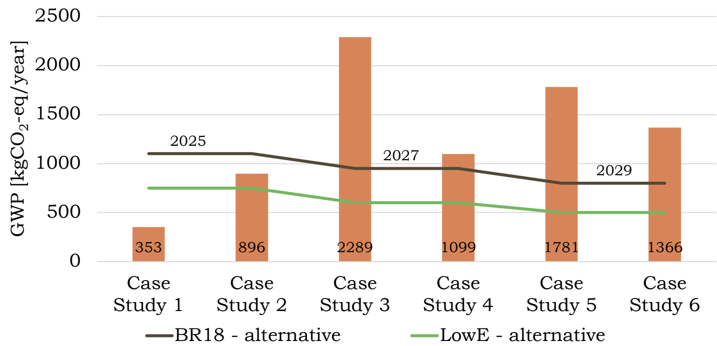


Figure 5.2: Comparison of case studies to alternative GWP limits shown in Table 5.3.

Besides changing the assessment system, it is also relevant to relate the results of the case studies to the various GWP ceilings towards mitigating the GWP of the building industry. In Figure 5.3 the results of the case studies are compared to the proposed GWP ceilings in BR18, both general and low emission, REALDANIAs *4 to 1 - Planet*, and the limit for the planetary boundary [Reduction Roadmap, 2023][4 TIL 1 PLANET, 2023b][Bolig- og Planstyrelsen, 2022].

As previously established, all the case studies meet the BR18 in 2025, three meet the requirement of BR18 in 2029, two meet the requirement for the low emission class in 2027, and finally one case study meets the requirement of REALDANIAs *4 to 1 - Planet*. However, none of the case studies results in the ambitious GWP ceiling for the planetary boundary. Therefore, an attempt to do so follows, using Case Study 2 as the baseline. It is investigated, if it is possible to design a building with a GWP below 0.4 $kgCO_2{-}eq/m^2$ year, using products and technologies available on the market today, and if not, what remains to be improved to succeed.

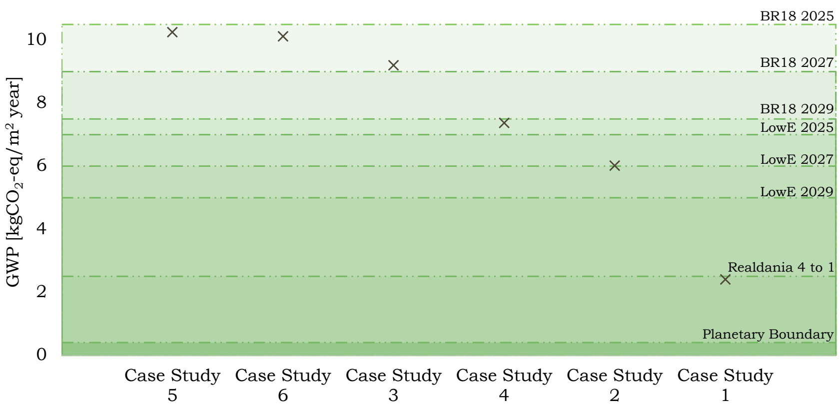


Figure 5.3: Comparison of the LCA results of the Case Studies with alternative GWP ceilings. The 'X' marks show the result of the corresponding case study on the x-axis.

Part II

Article

6 Low-Emission Design Variation of Buildings within the Planetary Boundary

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Keywords

LCA
Planetary Boundary
Low-emission
Design variation
Building
Single-family houses

Abstract

As 37 % of the global emissions originate from buildings, the building industry faces large challenges towards meeting the GWP mitigation goals committed to in the Paris Agreement. By using the allocation principle of the Paris Agreement, it has been assessed that the GWP of buildings must be reduced to $0.4\,\text{kgCO}_2/\text{m}^2$ year before 2036 at the latest, to stay within the planetary boundary for climate change.

This paper examines the potential of reducing the GWP of single-family houses in Denmark, using the products and technologies available today. Therefore, a low-emission design variation is performed, which entails the conduction of LCAs of a variety of building designs generated based on an EPD Database and common construction methods for single-family houses in Denmark.

The paper finds that it is possible to build houses with GWPs as low as $0.87\,\text{kgCO}_2/\text{m}^2$year, however, only with the use of biogenic products that are declared for use outside of Denmark. The paper, therefore, proceeds to identify areas for optimization in order to achieve the required GWP mitigation.

6.1 Introduction and objectives

In January 2023, the first requirements for the environmental impact of buildings became effective in the Danish Building Regulations (BR18) [BR18, 2023]. The requirements reflect the necessity of reducing the environmental impact of the building industry, being responsible for 37 % of the global emissions [United Nations Environment Programme, 2022].

To succeed at limiting global warming to 1.5 °C, as committed to in the Paris Agreement, the mitigation of global warming potential (GWP) of buildings must align the Planetary Boundary for Climate Change, stating that global yearly emissions must be reduced by 96 % [Reduction Roadmap, 2023].

Considering a current median footprint of Danish Housing of $9.6\,\text{kgCO}_2/\text{m}^2$ year and applying the allocation principle from the Paris Agreement, the allowed emission of buildings in Denmark must be reduced to $0.4\,\text{kgCO}_2/\text{m}^2$ year [Reduction Roadmap, 2023]. The sooner this reduction is accomplished, the greater the chances are of limiting global warming to 1.5 °C. If accomplished before 2036, the chances of success are estimated at 50 % [Reduction Roadmap, 2023].

Environmental Product Declarations (EPDs) play a key role in assessing the GWP of buildings, as the use of EPDs increases the reliability of life cycle assessments (LCAs) [Jørgensen et al., 2021]. The objectives of this study are therefore:

- What is the availability of EPDs for single-family houses in Denmark and other markets, and is there any data missing towards staying within the planetary boundary?
- Using only EPDs, what is the possibility of building a single-family house while staying within the planetary boundary?

6.2 Methodology

To investigate the possibilities of single-family houses with GWPs within the planetary boundary, a low-emission design variation is performed. The low-emission design variation consists of testing the possible combinations of EPDs available on the market, in the search of the lowest possible GWPs.

The methodology of the design variation is shown in Figure 6.1. First, a database of EPDs is collected that forms the basis of the design variation. EPDs are collected from the EPD Programme Operators in Denmark and other European countries. Additionally, products found through research are included, refer to appendix A. Afterwards, an EPD Variation Study is performed to investigate the variation of the EPDs of similar products to filter the EPD Database.

The EPDs collected and deemed applicable are used in a low-emission design variation. It is investigated how the main building elements of a single-family house can be built, namely the external wall, the roof, the internal wall, and the deck and foundation combined as one element.

After the compilation of building elements, they are varied using the EPDs in the database relevant for substitution for the material types used. The environmental impact of the generated designs is calculated based on the building combination of a case study, following the requirements of LCAs from BR18. The building elements are then varied on the building level.

6.2.1 System Boundary of LCA

The system boundary of the LCAs in the low-emission design variation is based on BR18 [BR18, 2023]. This entails the calculation of the environmental impact per reference area with a calculation period of 50 years. The modules included are A1-3, B4, B6, C3, C4, and D. D is not included in the re-

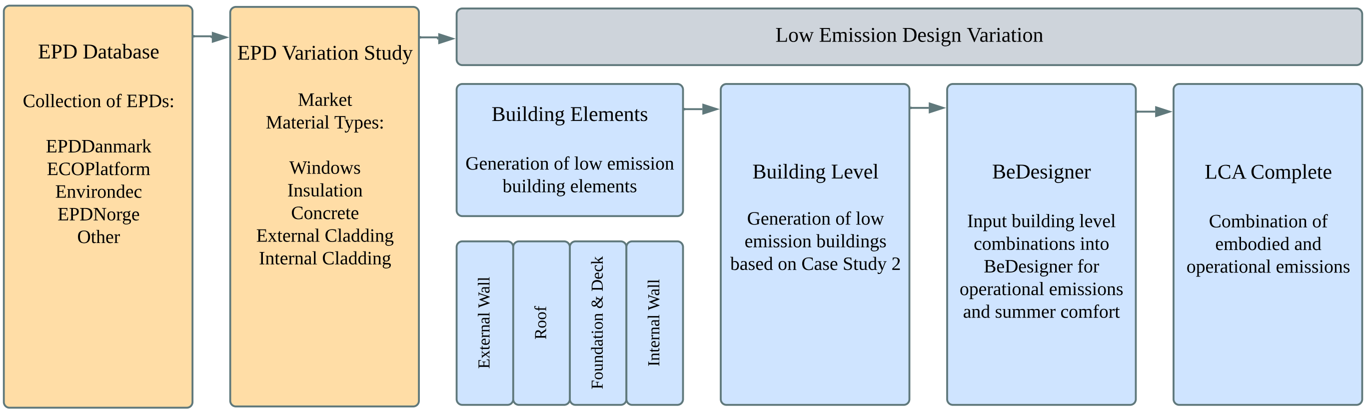


Figure 6.1: Methodology of the design variation

ported results. Lifetimes for materials and embodied emissions of installations are based on BR18 as well. Only the GWP of the generated designs is assessed.

6.2.2 Design Variation

The Low-Emission Design Variation is executed in the open-source Spyder IDE, using the programming language Python. The EPDs collected are varied through the use of a dictionary to define the category of the EPDs based in the attributes. Each number in the dictionary corresponds to a layer in the building elements. An in-depth description of the method of the design variation is found in appendix D.1.

The embodied emissions are calculated by adding the environmental impacts in the included modules, by converting the impacts from the declared unit to the impacts per square metre, if necessary. The design variations are combined factorially to get results from all possible combinations. Various thicknesses of insulation in the building elements are applied.

After the generation of possible designs for the building elements, the building elements are filtered based on the U-value to comply with BR18 and a GWP-limit based on Zimmermann et al. [2021]. These filters are explained further in appendix D.3. To reduce the number of combinations on the building level, only the building elements with the lowest GWP are included. Four elements of each type and thickness are included: Danish market, biogenic, Danish market non-biogenic, Other markets biogenic, Other markets non-biogenic.

The selected building elements are varied factorially on the building level, adding the environmental impact of each building element together. The building combinations are filtered

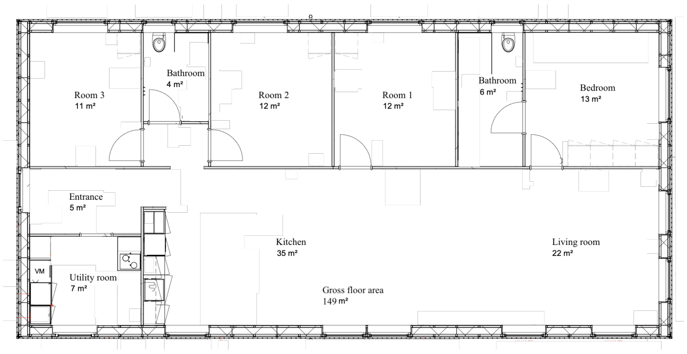


Figure 6.2: Floor plan of case building used for the design variation.

to comply with the energy frame and summer comfort requirements in BR18. For this purpose, BeDesigner Controller is used to generate the energy frames of each building combination. The procedure of the filtration is shown in appendix D.4.

Subsequently, the LCAs are concluded by adding the final emissions. These included operational emissions calculated based on the energy frame and the remaining embodied emissions of installations, wet rooms, windows and doors, crown moulding and paint, explained further in appendix D.4.3.

6.2.3 Case Study

The environmental impact of the building combinations generated is calculated based on the building design of a case study. The building design applied in the calculations is a compact, rectangular building with a flat roof. It is a one-storey house, consisting of four rooms, two bathrooms, a utility room, and an open kitchen and living room space. The gross floor area is 149 m^2, and the floor plan is shown in Figure 6.2. The amount of material used for the design variation is based on the dimensions of the case study. More information is provided in the appendices to the thesis.

6.2.4 Construction Methods

The building elements included in the design variation are the external walls, the internal walls, the roof and the foundation & deck combined as one element. They are based on the typical construction methods for single-family houses applicable to the design of the case study. Using Møller et al. [2016] and Koch [2021], the building elements are assumed viable in single-family houses. This includes the function of protecting from the outdoors, providing a sufficient indoor environment, reducing the transport of humidity from the indoor air, fulfilling fire regulations, as well as being statically sound.

Various types of the aforementioned building elements and insulation thicknesses are included in the design variation. An overview of the building elements included in the design variation is provided in Table 6.1. The insulation thicknesses apply to all types, except for the prefabricated elements, as they are manufactured with a specific amount of insulation.

The building elements included in the design variation do not cover all the embodied emissions in a building. Embodied emissions from windows and doors, installations, wet rooms,

Table 6.1: Building elements, types and insulation thicknesses in the design variation.

Building element	ID	Types	Insulation [mm]	Figure
External wall	1	Heavy	195	6.3
	2	Light, wood framing	270	6.4
	3	Light, steel framing	340	6.4
	4	Prefabricated	-	
Roof	7	Unvented, flat roof	340	6.5
			440	
			540	
Foundation & deck	8	Strip foundation & heavy deck	250	6.6
	9	Strip foundation & light deck	300	
	11	Screw pile foundation & light deck	350	6.7
			400	
Internal wall	12	Light, wood framing	45	6.8
	13	Light, steel framing	45	6.8
	14	Heavy		

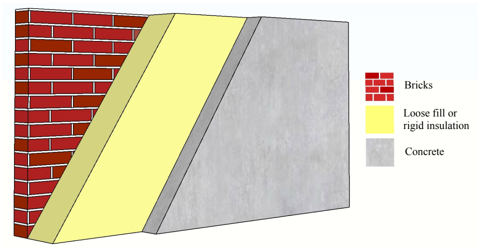


Figure 6.3: Sketch of building element number 1, heavy external wall.

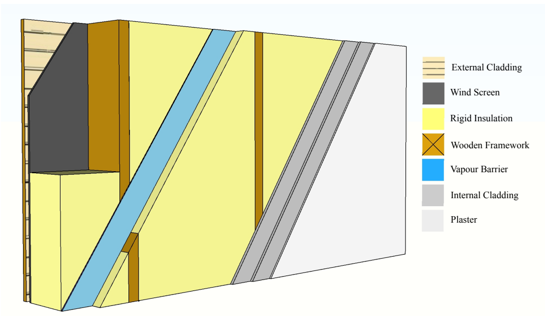


Figure 6.4: Sketch of building element number 2 and 3, light external wall, where the wooden framework can be replaced by steel profiles.

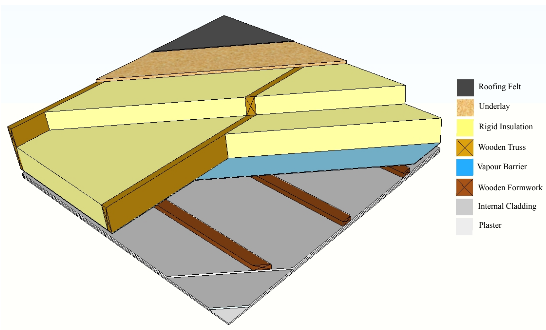


Figure 6.5: Sketch of building element number 7, unvented flat roof.

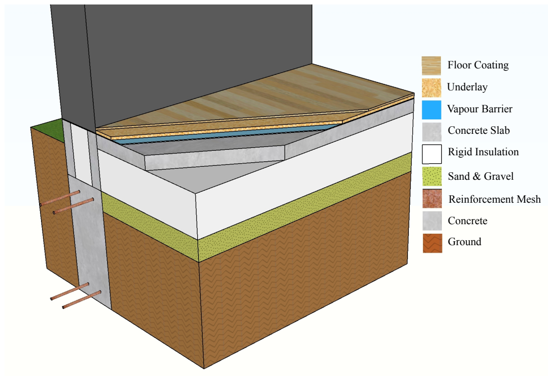


Figure 6.6: Sketch of building element number 8, strip foundation with a heavy deck.

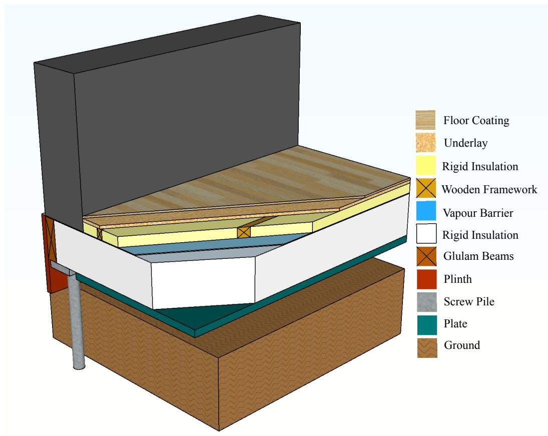


Figure 6.7: Sketch of building element number 11, screw pile foundation with a light deck. Number 9 is a combination of the strip foundation in Figure 6.6 and the light deck.

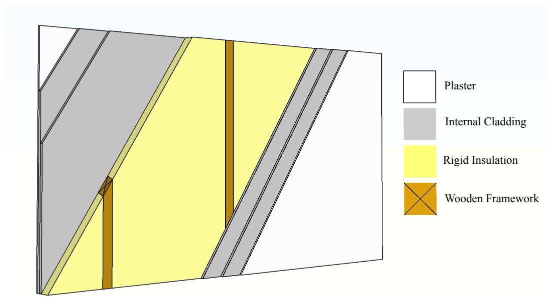


Figure 6.8: Sketch of building element number 12 and 13, light internal wall, where the wooden framework can be replaced by steel profiles.

paint on surfaces, and the crown moulding of the building must be included. These are added afterwards to reduce the complexity of the design variation. The reasoning behind this decision is elaborated on in appendix D.1.

6.3 EPD Database

In Europe, and employed in this work, an EPD is defined as a document devised according to the standards DS/EN15804 + A1 [2013] and DS/EN15804 + A2 [2019]. The emissions declared in an EPD reflect various aspects, including energy and resource consumption, waste generation, environmental impacts in the production stage, application and waste treatment and disposal [EPD Danmark, 2021]. For more information on the definition of EPDs, refer to appendix B.1.

The EPD Database consists of products applicable to one-storey, single-family houses. Primarily, the database consists of EPDs from the EPD Programme Operator EPD Danmark, but other European EPD Programme Operators also contribute. These other EPDs are added based on research on products with the potential to reduce the GWP of buildings, explained further in appendix B.2.

The initial database contains more products than what is possible to handle in the design variation. Therefore, an EPD Variation Study is used to reduce the number of EPDs in the database, by analysing which products can be omitted while maintaining the range of products. Some EPDs contain more than one product, most similar in application, but with different aesthetic expressions causing smaller variations in the environmental load. The products with the lowest and highest GWPs are selected, and the additional products are discarded. The same selection process is performed for similar products in distinct EPDs, for instance, types of mortar. Following the reduction of EPDs, 184 EPDs are included in the database.

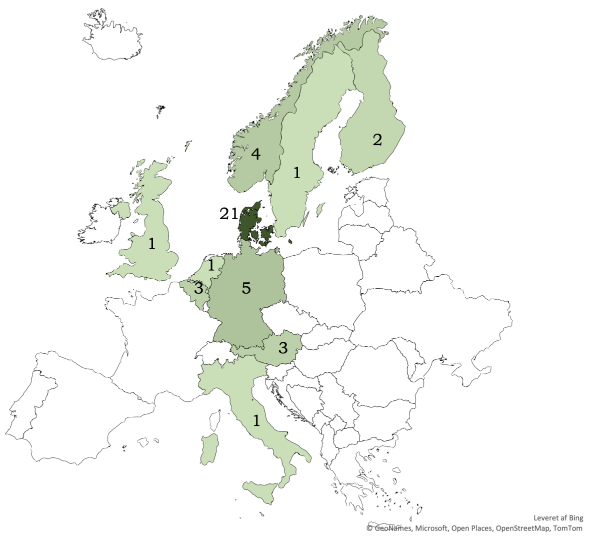


Figure 6.9: Number of EPDs declared as biogenic in the database.

The EPDs in the database are divided into categories. Products are considered biogenic if they mainly consist of organic materials. Materials defined as biogenic in this thesis are referred to as biogenic in Rasmussen et al. [2022]. The materials that are included as either biogenic or non-biogenic include the following material categories: external cladding, internal cladding and insulation. This means that rafters, coating, and construction wood used as framing in the building elements are not considered biogenic. The number of EPDs used in the design variation that is considered biogenic and non-biogenic is shown in Figure 6.9.

EPDs used in LCAs in accordance with BR18 must be valid and relevant [BR18, 2023]. Valid means that an EPD is 3rd party verified, devised according to DS 15804 and published in an EPD Programme Operator, like EPD Danmark [BR18, 2023]. An EPD is relevant if the declared product represents the product used in the building [BR18, 2023]. This means that the declared market of the EPD does not have to be Danish for the EPD to be valid.

In the EPD Database, however, the EPDs are categorised according to the declared market, divided into two categories, "DK" and "Other". If the market is "DK", it means that the product is declared for use in Denmark, the Nordic countries, Europe or globally. If a product is declared for any other geographical region, it is categorised as "Other".

The aim of this is to investigate the gaps between products declared for the Danish market versus other markets. Products declared for "Other" markets use varying grid mixes and the transportation distance is presumably longer. The number of EPDs used in the design variation for the Danish market and Other markets is shown in Figure 6.10.

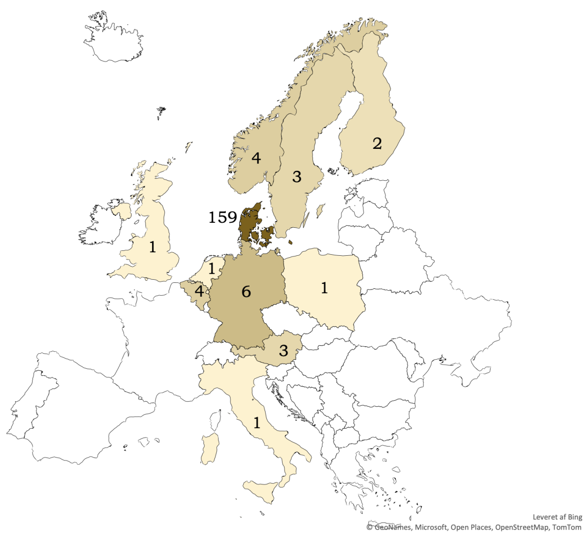


Figure 6.10: Declared market of the EPDs included in the database.

The EPDs are also divided based on which building elements they apply to, shown in Figure 6.11. As an EPD can be applied to more than one building element, the sum of EPDs in the figure exceeds the sum of EPDs in the database. There are most EPDs for the external wall, where more than 120 EPDs are varied in the design variation.

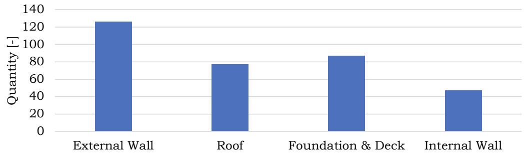


Figure 6.11: Number of EPDs used for each building element in the database.

Figure 6.12 shows which and how many EPDs of each material type are included. The largest category is insulation, with a total of 54 products. Prefabricated elements, including elements for both the external and internal wall and is the second largest group. For some categories, there are only a few EPDs or even just one EPD included, which is deliberately done to reduce the number of products for material types with low variation in the GWP, as seen in the EPD Variation Study in appendix B.3.

More information on the EPD Database is located in appendix B.4, including modules declared and the version of the standard of which, the EPDs are devised.

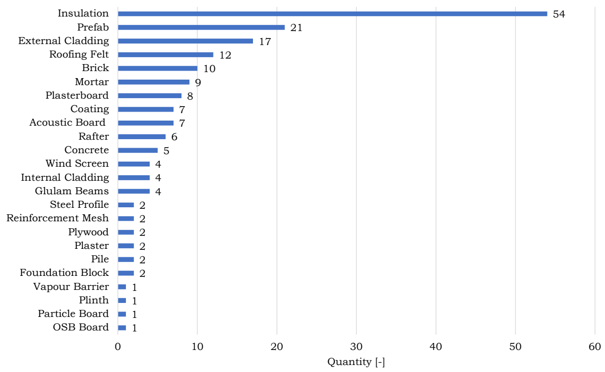


Figure 6.12: Number of EPDs for each material category in the database.

6.4 Generation of Low-Emission Buildings

The generation of Low-Emission buildings consists of the design variation of building elements proceeded by a design variation on the building level.

6.4.1 Building Elements

After performing the design variation of building elements and applying the filters of U-value and GWP-limit, the number of elements exceeds what is manageable of the computer capacity available, as it is desired to perform a factorial combination of building elements. Therefore, a reduction is made based on the building elements of particular interest. The building elements of particular interest, are the ones resulting in the lowest GWP. The GWP includes any replacements relevant to the EPDs included in the generated designs.

To account for the insulation properties of the building elements, the selection of performed based on the lowest GWP per R-value. Four building elements per thickness are chosen based on the market and biogenic content. The internal walls are strictly chosen based on the GWP.

The reduction of building elements results in the number of combinations as shown in Table 6.2. The steps towards the final number of combinations are disclosed in appendix D.3.3.

Table 6.2: Number of combinations of building elements during the process of filtration.

ID	Combinations after filtration	Combinations GWP/R
1	33 830	11
2	9 603 858	12
3	2 480 684	8
4	448	2
7	1 600 256	12
8	3 690 449	16
9	7 161 212	16
11	1 541 604	16
12	56 336	3
13	16 128	2
14	16	2

6.4.2 Building Level

The building elements are then varied factorially on the building level to generate 251 094 buildings combinations. BeDesigner Controller is then used to calculate energy demands of all the combinations. The energy demands of the building combinations are shown in Figure 6.13, where the energy frame from BR18 is marked by the dashed line.

Many of the building combinations exceed the energy frame and are therefore discarded. 66 % are discarded, leaving 85 299 viable combinations. A large share of the discarded building combinations are buildings with a strip foundation. The primary reason is the line losses that are much higher for the strip foundation than the screw pile foundation.

In addition to the energy frame, the building combinations are also assessed based on the summer comfort, calculated along with the energy frame. None of the building combinations exceeds the requirements for summer comfort in BR18. The generation of energy frames in BeDesigner is presented in depth in appendix D.4.

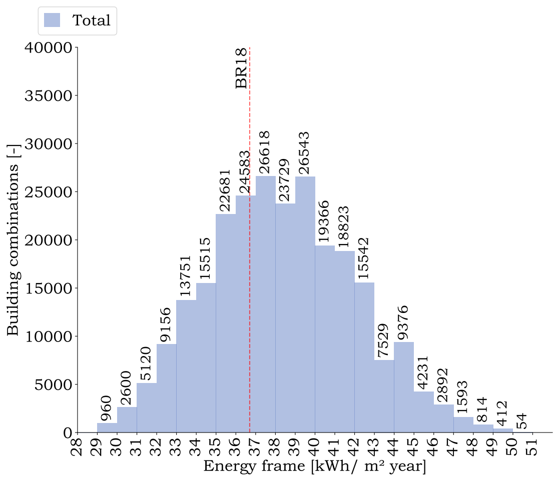


Figure 6.13: Results of the energy frame calculation for each combination on the building level.

6.5 Results

The LCA is then finalised for the remaining building combinations. As the generation of building designs only includes the embodied emissions of the main building elements, additional emissions must be included for the LCA to be complete. Embodied emissions are therefore for windows and doors, the crown moulding on the house, paint on surfaces and installations. The calculation of these emissions is shown in appendix D.4.3. Finally, the operational emissions are included by converting the energy frames into operational emissions using the emission factors from BR18. The results of the final LCAs of the building combinations are shown in Figure 6.14.

The figure shows that it is possible to achieve a GWP below the limit of *Realdania's - 4 to 1 Planet*. The lowest possible range of GWP is 0.8 to 1.2 $kgCO_2/m^2$ year, concluding that based on this study, it is not yet possible to achieve GWP reduction to stay within the planetary boundary.

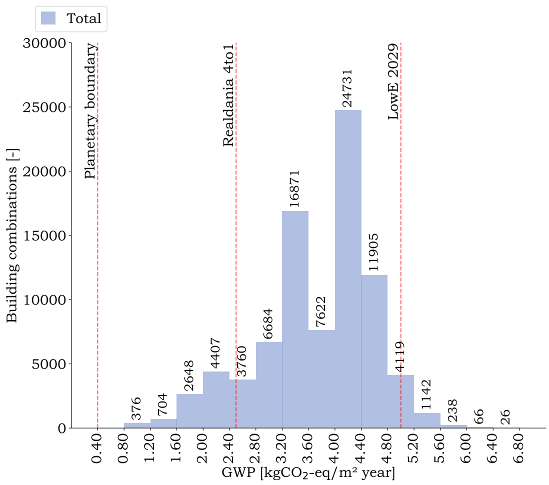


Figure 6.14: Results of the LCA of the low emission building designs. Applicable GWP limits are shown.

6.5.1 Characterization

The GWP of the building combinations is divided into combinations containing biogenic products and non-biogenic products in Figure 6.15. A building design is considered biogenic if just one product in one of the building elements is biogenic. It should therefore be noted that if a building design is included as "biogenic" there is a large chance of non-biogenic materials being used as well. Based on this, the figure shows to a greater extent the possibilities of using only non-biogenic products, than it shows the possibilities of using biogenic products.

Bearing this in mind, Figure 6.15 shows that if only non-biogenic products are used, it is possible to reach emissions in the range of 3.2 to 3.6 $kgCO_2-eq/m^2$ year, still well below the voluntary low emission class in 2029.

Likewise, Figure 6.16 shows that most of the building combinations contain one or more products declared for other markets than the Danish. Only 7 % of the buildings solely contain products declared for the Danish market, rendering it possible to build single-family houses with GWPs around

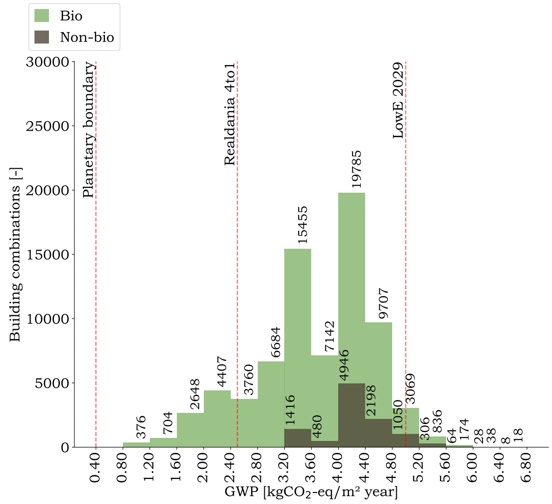


Figure 6.15: Results of the LCA of the low emission building designs, separated into the building combinations containing biogenic products or not. Applicable GWP limits are shown.

3.2 $kgCO_2-eq/m^2$ year as well. The figures indicate a large overlap of combinations only including non-biogenic materials and materials declared for Denmark.

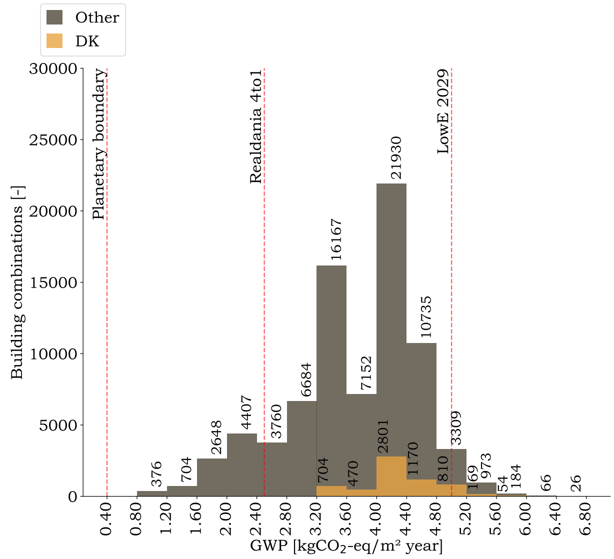


Figure 6.16: Results of the LCA of the low emission building designs, separated into the Danish market and other markets. Applicable GWP limits are shown.

6.5.2 Mitigation towards the Planetary Boundary

The results of 5 selected building combinations are elaborated on in figures 6.17 and 6.18, showing the emissions per module and the embodied emissions of the main building elements included in the design variation. The 5 selected building combinations include those meeting the GWP limits, when applicable, and the lowest possible outcomes for respective the Danish market, and Other markets. The modules are divided into A1-3, C3, C4, B6 and finally "Other". The category "Other" represents the additional embodied emissions added to complete the LCA.

The building design with the lowest GWP results in a GWP of 0.87 $kgCO_2-eq/m^2$ year. The operational emissions cause

0.97 $kgCO_2-eq/m^2$ year, showing that if there were no operational emissions, the GWP of the building would be negative. The GWP of module B6 is very similar for all 5 building designs, resulting in an increasingly larger share, as the GWP of the embodied emissions is reduced.

Module C3 causes a large share of emissions for all 5 building combinations, whereas modules A1-3 separates the five building cases. A1-3 becomes increasingly larger, as the total GWP increases. For the building combinations with the lowest GWP, A1-3 is largely negative, caused by a large amount of wood products.

The category "Other" holds a large share of the emissions. 0.62 $kgCO_2-eq/m^2$ year of the emissions are caused by the installations. In appendix A.3, it was found that using project-specific materials resulted in a lower GWP than using the standard values. The installations accounted for 0.30 $kgCO_2-eq/m^2$ year, suggesting that the results in Figure D.21 could be reduced with 0.32 $kgCO_2-eq/m^2$ year, further approaching the GWP limit of the planetary boundary.

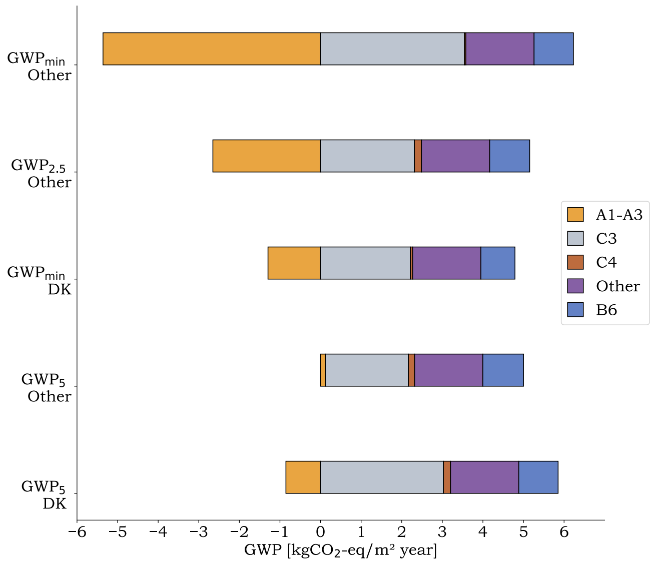
Figure 6.18 shows how the embodied emissions from the main building elements are distributed, shown in percentage. The sum of the absolute percentages is 100 %, and when a building element presents negative net emissions, the percentage is shown negative as well.

for "GWP_{min}, Other", and as the only building element, the foundation contributes positive emissions.

The building combinations with GWPs of 5 $kgCO_2-eq/m^2$ year and 2.5 $kgCO_2-eq/m^2$ year are merely examples and it is important to note that another building combination might result in the same total GWP, but with an entirely different distribution of emissions.

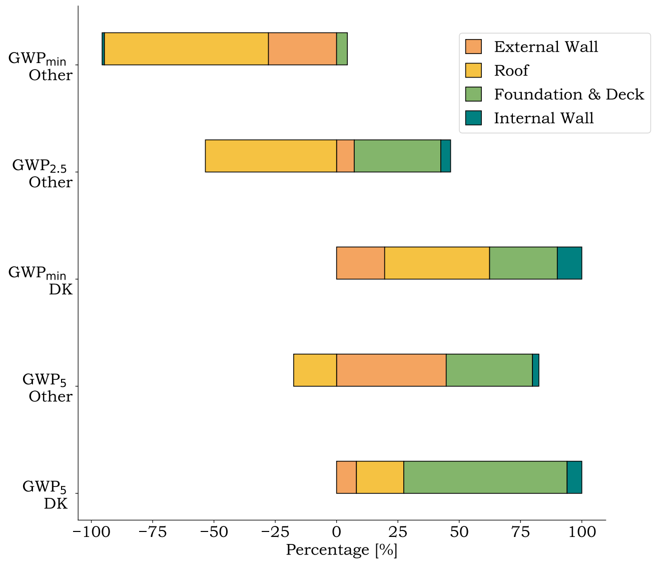
The results do, however, indicate that particularly the foundation & deck are important building elements, as no generated designs result in negative emissions. Therefore, it holds a rather large share of the emissions in all the buildings presented. It is further noted that none of the building elements presented for the Danish market result in negative emissions, which seems to be one of the main differences between the Danish market and other markets.

To investigate which products result in the differences between the Danish and Other markets, the building elements and EPDs of the two building combinations resulting in the lowest GWP, are presented. The lowest GWP of a building combination using only products declared for the Danish market is 3.5 $kgCO_2-eq/m^2$ year. The lowest GWP is 0.87 $kgCO_2-eq/m^2$ year, when using products declared for other markets. The two building combinations are very similar, consisting of a light external wall with wooden framing,



	Total	A1-3	C3	C4	Other	B6
GWP_{min}, Other	0.87	-5.36	3.54	0.04	1.68	0.97
$GWP_{2.5}$, Other	2.50	-2.65	2.31	0.17	1.68	0.98
GWP_{min}, DK	3.50	-1.29	2.21	0.06	1.68	0.84
GWP_5, Other	5.00	0.12	2.04	0.16	1.68	1.00
GWP_5, DK	5.00	-0.85	3.03	0.17	1.68	0.97

Figure 6.17: Results from 5 building combinations from the design variation divided into modules in the LCA.



	External wall	Roof	Foundation & Deck	Internal wall
GWP_{min}, Other	−0.54	−1.30	0.09	−0.02
$GWP_{2.5}$, Other	0.18	−1.30	0.86	0.10
GWP_{min}, DK	0.19	0.42	0.27	0.10
GWP_5, Other	1.94	−0.76	1.53	0.11
GWP_5, DK	0.19	0.45	1.57	0.14

Figure 6.18: 100 % stacked bar plot of the embodied emissions of the four main building elements.

For "GWP_{min}, Other" and "$GWP_{2.5}$, Other" the roof plays a large part in the low GWP of the building. As the only case, the external wall also contributes negative emissions

a screw pile foundation and a light floor, and internal walls with a wood frame. The insulation thicknesses are the same for the external wall and roof, where the thickest generated design is

Table 6.3: EPDs declared for Other markets, used in the building combination resulting in the lowest GWP.

Product	Building Element	Declared market
Grass Insulation Board from Gramitherm	Deck	Belgium
Recycled Newspaper Slabs from Ekovilla Oy	External wall & Roof	Finland
Swedish sawn dried timber of spruce or pine	Wood frame, all elements	Sweden
Wooden parquet floor from Moelven Wood AS	Coating	Norway
Wood panel, unpainted from Bergene Holm	Internal cladding	Norway

applied of 340 mm and 540 mm, respectively. The thickness of the foundation & deck varies, with the thickest design of 400 mm for the Danish building element, and the thinnest design of 250 mm for the Other building element.

Besides the difference in composition of the foundation & deck, it is primarily a few EPDs that result in the difference in GWP. 15 EPDs are used in the building elements for the Danish building combination, and for the "Other" building combination, 17 EPDs are used. 12 EPDs reoccur in the two building combinations, leaving 3 unique EPDs for the Danish building combination and 5 for the "Other". The 5 EPDs in the building combination for "Other" markets are of particular interest and are presented in Table 6.3. A complete list of the EPDs in the building combinations is found in appendix D.6.1.

The EPDs in the table are the primary reason for the reduction in GWP to 0.87 $kgCO_2{-}eq/m^2$ year. It indicates that the Danish market is behind with regard to alternative insulation materials and wood products for coating, cladding and wood framing. 4 of the products come from Nordic countries, where low-carbon sources make up 55 to 70 % of the primary energy, compared to 40 % in Denmark [Ritchie et al., 2022].

The lowest possible GWP, when only Danish-declared EPDs, was 3.5 $kgCO_2/m^2$ year, exposing a gap in the Danish market. The gap includes a lack of EPDs on novel building materials, particularly biogenic insulation materials with low GWP. There was also found a gap in wood products for use as wood framing in all the main building elements, coating, and internal and external cladding between Denmark and the Nordic countries. Wood products are available within the Danish market, but these EPDs result in higher emissions.

It is therefore relevant to investigate which relatable differences exist between Denmark and the Nordic countries. The environmental impact of a product is caused by various factors, including the energy consumption of the product during the production and end-of-life stages. The emissions due to energy consumption are highly dependent on the source of energy in the countries of production, and the sources of energy and electricity are therefore particularly relevant to consider. The countries from which the five products come, all have a high share of low-emission sources in the energy mix, including hydro and nuclear power [Ritchie et al., 2022][IEA, 2023]. This results in low emissions per unit of energy consumed by the product. Thus, it is not necessarily the product itself, but underlying factors that determine the possibilities of manufacturing low-emission products.

The scalability of the alternative products presented is an important factor to consider. It might not be possible to apply the production method of a specific product directly in another setting. Both due to the underlying energy mix, and the resources available. A niche product, like the insulation from recycled newspapers, is produced using a limited resource. It must, therefore, be ensured that any prospective scaling does not convert a low-emission product to a high-emission product if the resources do not correspond to the scale.

For products, with the same low-emission potentials, to be produced and used at a large scale in Denmark, these factors must be considered. An investigation of available resources, for instance for insulation purposes, would therefore be relevant, as well as increasing the share of renewable energy in the energy mix. The latter would also reduce the emission factors, thus reducing the operational emissions of a building.

An additional point to be made towards reaching the planetary boundary for climate change, it was found that the standard values used to calculate the embodied emissions of installations result in higher emissions than using project-specific materials, indicating that a more detailed assessment of the installations can result in further reductions of GWP.

6.5.3 GWP of building features

The work concludes with an overview of the lowest possible GWP outcomes for different features of the building combinations, shown in Table 6.4. Common for the features resulting in the highest GWP, is that the building combinations are either categorised as Danish or Non-biogenic. This means that if it is desired to reduce the GWP of a building further, biogenic products should be used, and it is necessary to apply products with EPDs declared for other markets than the Danish.

The option with the "DK Non-bio" feature consists of A-bats insulation from Rockwool, which concludes as the favourable option for insulation in the Danish market. The option with the heavy wall can be reduced to 1.83 $kgCO_2/m^2$ year with the use of recycled bricks.

Table 6.4: Lowest possible GWP for various features.

Feature	GWP [$kgCO_2{-}eq/m^2$ year]
Heavy wall, strip foundation	1.83
Light wall, strip foundation	1.27
Light wall, screw pile foundation	0.87
DK Bio	3.50
DK Non-bio	3.52
Other Bio	0.87
Other Non-bio	3.50

6.6 Limitations

The methods used, and decisions made in the work, influence the outcomes of the design variation. The initial plan of the low-emission design variation entailed an investigation of the complete scope of outcomes. Therefore, an initial EPD

Database was collected, consisting mainly of EPDs declared for the Danish market from EPD Programme Operators. In addition, EPDs were included for product types not well represented in the Danish market. Then, further products were included based on research of journal articles and searching the web for products with the potential to reduce the GWP of buildings. At this stage, the collection became more random and resulted in an incomplete database.

Some of the included products based on research were not valid EPDs, but environmental data collected that had not been 3rd party verified. It was desired to include all these products to further investigate, which potentials for reduction exist. However, due to the computational capacity available, a filtration of the EPD Database was performed. First, based on the validity of the EPDs followed by a filtration of products based on the variation study. In the case of products with similar environmental impact, only one was included. In the case of EPDs that contain many products that are nearly the same, but with for instance varying surface treatments, the products with the highest and lowest environmental impact were included. The incentive for these actions was to reduce the number of EPDs while covering the solution space.

An alternative, more structured method to reduce the number of combinations, would have been to perform a sensitivity analysis to determine, how much each layer impacts the GWP of the building elements. Then a selection of just one or two EPDs could have been applied for the insensitive layers, and more EPDs applied for the layers of greater importance.

As the low-emission design variation is based on the EPD Database, it is important to note that a more structured search for EPD beyond the EPD Programmes and inclusion of all products, would have provided better coverage of the solution space and could have shed light on further areas of interest.

Following the filtration of the EPD Database, the computational capacity continued to impact the design variation. The combinations of building elements continued to exceed what was possible to include on the building level. Therefore, the number of combinations was drastically reduced, only including four building combinations of each thickness of the building elements, reducing the number of building elements from 26 184 821 to just 89. Since the low-emission design variations were of specific interest, only the building combinations with the lowest GWP were chosen. An attempt to consider the insulation properties of the building elements meant choosing the lowest GWP per R-value. However, as the filtration was performed before the energy frame calculations were performed, it is possible that a combination of building elements excluded would have yielded results of interest.

Another choice made concerning the low-emission design variation was the choice of case building. It was chosen to perform the design variation on the building design of Case Study 2. The geometry of Case Study 2 is very simple, being a rectangular building with a flat roof. The reason for choosing Case Study 2 is the compactness of the building. In the investigation of alternative units for comparison, the main focus was the reduction of the absolute emissions of the building industry, which leads back to the sizes of the houses being built. As it was desired to convey results with the potential to reduce the absolute GWP the low-emission design variation was performed on a compact and efficiently designed building. It was an active choice, where the representativity of the building was chosen to carry less weight than the overall aim of the study.

A direct consequence, however, is the types of building elements that were included. As the building is designed with a flat roof, the investigation was limited to this type of roof.

6.7 Conclusion

This article presented an exploration of the possibilities of building single-family houses within the planetary boundary. The conclusion is that the lowest GWP outcome is $0.87\,\mathrm{kgCO_2/m^2}$ year, thus showing that as of now, we are unable to build houses within the planetary boundary.

To achieve GWP mitigation towards the planetary boundary, material selection is a key element. Not only the overall type of product, for instance, wood versus concrete, but the specific product and its environmental impact declared in EPDs is a vital factor. As part of this, the development of novel materials in Denmark is important too. In the current state, conventional products are not sufficient to reach the planetary boundary. To be used, materials like concrete, mineral wool, bricks and tiles must be environmentally optimized.

Wood-based building elements play a key role in building combinations with the lowest GWP of this study. To be able to apply the solutions to a larger scale, a continued effort is required to ensure the planting of new trees to replace the ones being used in the industry.

In the process towards staying within the planetary boundary, the energy mix is an important factor. The emission factors of the energy mix impact both the embodied emissions and the operational emissions. As the operational emissions will account for a large share of the total GWP of a building it is necessary to produce the energy for operations with the lowest emissions possible.

6.8 Further Research

The limitations of this study suggest a further examination of the solution space. While this study proposes areas relevant for optimization, the results reflect the inclusion of EPDs on which the study is based. A more systematic collection of an EPD Database would therefore further allow further investigation of the gaps and deficiencies in low-emission products available in Denmark and surrounding countries, towards meeting the limit for the planetary boundary. The inclusion of more products as well as environmental data of products that are not considered EPDs would give a more comprehensive view of novel materials possessing a reduction potential.

The results of the study also revealed large differences in the environmental impact of similar products, for instance, the wood products available in the Danish market compared to the other Nordic countries. A further examination of the causes hereof is desired, specifically what the impact of the energy mix is, which also includes the use of Guarantees of Origin certificates that companies can buy and implement in the EPDs.

Moreover, the parameter included in the EPD Database is limited to only include the environmental impact indicator of GWP. As many other factors determine the environmental impact of a building, it would be interesting to include more indicators, to perform a more holistic assessment.

Similarly, only the thermal properties U-value and the heat capacity are considered, when filtering the building element solutions, along with the calculation of the energy frame and the evaluation of the summer comfort. Thus, other parameters should be added to the database to provide a complete analysis of the building solutions generated through the low-emission design variation. For the indoor environment, the humidity could be considered with the addition of a material's z-value. Additionally, the fire regulations can be included.These additional parameters would be beneficial for the low-emission design filtration since a large number of combinations are expected to be discarded on account of these parameters.

Part III

Recapitulation

7 Discussion

In addition to the discussion provided in the article, a discussion of further aspects of the thesis is provided. This includes the current state of the Single-Family housing market in Denmark, the basis of the assessment and the alternative road maps discussed and proposed previously in the report. The results of the article is The method of the design variation is discussed, as are the results regarding the potential of mitigating the GWP of the building industry.

7.1 Current State of Single-Family Houses

The case study of the thesis is included to assess the current state of the single-family housing industry in Denmark. The case studies included each represent a building concept, some novel, some conventional. One of the companies that have provided building information has worked specifically towards reducing the GWP of their buildings and represents a novel building concept. Another company has worked specifically towards optimizing the energy performance of their concept as well as reducing material waste as much as possible via their novel building concept, as well as focusing on compact houses. Two case studies represent more conventional building concepts, not directly implementing GWP mitigation and optimization. A fifth case study presents elements for the external wall and roof, with a focus on material and space optimization. The building concept, however, is not as complete as the other building concept. Finally, a case study aiming towards being a sustainable project with a DGNB certification is included.

While these case studies cover a segment of the housing industry in Denmark, it must be emphasized that they also represent what information was available and do therefore not cover the whole market. It can also be discussed how representative the building concepts are, as not all the building concepts are equally distributed in the market. This was, however, not the purpose of the case study, as the aim of the case studies not only were to assess the buildings being built currently but also what is currently possible to build.

The case studies showed the range of which, this section of building concepts, performs concerning the GWP. With results varying from 2.4 to 10.42 $\mathrm{kgCO_2{-}eq/m^2}$ year, the case studies emphasize that depending on the focus on reducing the GWP of the building, it is possible to achieve rather sound results. The two companies that have worked specifically with consideration to optimization also result in the two most advantageous results, providing concrete examples of how the GWP of buildings can be reduced.

7.2 Basis of Assessment

In addition to motivating a discussion regarding the potential of mitigating the GWP of the building industry, the case studies also laid the groundwork for a discussion regarding the basis on which the GWP of buildings is currently assessed in Denmark. In the current version of the Danish Building Regulations, where demands regarding the environmental impact of buildings, for the first time implemented, the environmental impact is assessed based on the gross floor area of the building and a calculation period of 50 years. This results in the unit $kgCO_2{-}eq/m^2$ year.

As mentioned, the current requirements for the environmental impact of buildings are the first ever implemented in Denmark. This means that there is still a basis for evolvement and adjustments of the requirements. In a recent report published by the Strategic Network for Sustainable Buildings (Strateginetværket for Bæredygtigt Byggeri [2023]), several suggestions have been presented.

The first suggestion relates to the GWP limit for new buildings and proposes differentiating between building types. The advantage of separating the GWP limits for building types is that it allows for separate considerations based on the application of the building. This is likewise the chosen method for energy frame calculations, where different energy frames exist for different types of buildings [BR18, 2023]. If the same GWP limit applies to all building types, we are at risk of not harnessing the reduction potential possessed by different building types [Strateginetværket for Bæredygtigt Byggeri, 2023].

Separate requirements for building types would allow for the reassessment of the unit used today, and apply units that are specifically applicable to the building type in question, a point also made by the Strategic Network. In the thesis, a variety of alternative units were investigated, specifically to encourage smaller buildings to ultimately reduce the total GWP of buildings, instead of solely focusing on the reduction per square meter. The investigation concluded that most of the units easily available provided advantageous results for larger buildings, as many relate to the geometry of the building. However, the results showed that considering the number of people in a household as well as including the total GWP of the building when devising the requirements, would compel smaller buildings.

While the inclusion of the aforementioned factors would compel smaller buildings, there are challenges related to the execution of such a requirement. Using the total GWP means that families that require more space would be put at a disadvantage. Using the number of people could pave the way for manipulation of the regulations, as it would be difficult to settle on a method to determine the number of people that aligns with the actual number of people that are to be accommodated.

Motivated by these challenges, alternative systems were proposed in section 5.2. The alternative GWP limits presented all relate to single-family houses specifically, where one suggestion concerns the determination of GWP limits based on the size of the house, where people who are willing to build smaller houses are offered an advantage. Another method suggests determining the GWP limit based on a specific size of a house, which has been deemed acceptable for a single-family house, urging people to build smaller houses or work harder towards designing a building with a low environmental impact.

Of course, these proposed methods would require the collection of data to determine how the limits should vary with size, as well as starting a discussion of what size of a house would be deemed acceptable. Agreeing on such a figure might pose a challenge, as it would impact many people's lives by determining what they are allowed to build.

8 Conclusion

The aim of the master thesis was to investigate the potential of meeting the GWP mitigation goals to stay within the planetary boundary for climate change. The assessment of the current state of the single-family house proved already by today, the proposed GWP-limits of BR18 and the voluntary low-emission class, can be met. Following the alternative assessment methods, the case studies were also compared to alternative road maps and GWP-limits than the ones proposed in BR18. Of the limits applied, only the most ambitious of $0.4\,\mathrm{kgCO_2/m^2}$ year, to stay within the planetary boundary, was unable to be reached by any of the case studies.

The thesis emphasizes a necessary focus on the total emissions of the building industry, and the case studies were compared based on alternative units. The investigation concluded that many of the units relate to the geometry of the building, thus promoting larger buildings. The two units assess the building based on the GWP per year and based on the number of people accommodated, but these units present drawbacks related to the execution of a possible requirement.

Motivated by the lack of a preferred alternative, alternative assessment methods of the environmental impact of buildings were proposed. These include relating the GWP-limits to the size of the building to nudge developers to reduce the area of the houses and relating the GWP-limit to a politically determined size of a house. The latter would force developers to integrate the GWP of a building as a central part of the design process if it is desired to build a larger house than politically determined.

The low-emission design variation concluded with a building combination with a GWP of $0.87\,\mathrm{kgCO_2/m^2}$ year, thus concluding that on the basis of the assumptions of and decisions made in the design variation, current materials and technologies do not yet allow for buildings to be built within the planetary boundary.

The lowest GWPs achieved used biogenic materials declared for other markets than the Danish, revealing a gap in the Danish market of biogenic materials. Areas for optimization were highlighted, including more detailed calculations of the embodied emissions from installations, as well as continuing development toward an energy mix based on low-emission energy sources to reduce the emission factors of the Danish energy mix.

Based on the current state of the single-family house industry, in combination with the results of the low-emission design, it is concluded that the GWP-limits in the Danish Building Regulations are unambitious, as the potential for reduction is much larger today. Considering the proximity to the planetary boundary revealed in the low-emission design, the thesis concludes that GWP mitigation requirements can and must be implemented at a faster rate.

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