Living Places: Healthy Homes for People & Planet

A single-family home with ultra-low carbon footprint

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ABSTRACT: This research focuses on designing and constructing ultra-low-carbon homes within the Danish building industry. The primary objective was to showcase the feasibility of building homes with significantly reduced carbon footprints while maintaining superior indoor environments and adapting to regulations and market conditions. Two unique houses were designed and constructed to exhibit alternative approaches to achieving a very low carbon footprint while incorporating aesthetic value to promote a sense of community. The study utilised a comprehensive life cycle assessment (LCA) methodology to evaluate the environmental impacts of construction materials and operational energy use. Results indicated that both houses achieved more than a 64% reduction in global warming potential (GWP) compared to a benchmark house, staying well below the maximum threshold established by Danish legislation. The study further emphasised the importance of material selection in reducing carbon footprints and highlighted the availability of a diverse range of low-carbon materials in the market. This research demonstrates that designing cost-effective, ultra-low-carbon homes using existing materials and technologies is feasible, paving the way for higher ambitions in the construction sector to meet climate targets.

KEYWORDS: Ultra-low-carbon homes, Life Cycle Assessment, Global Warming Potential, Building Industry, Design Optioneering.

1. INTRODUCTION

Energy use in the built environment accounted for 27% of the world's CO_2 emissions in 2022 and building materials for an additional 10% [1]. As energy efficiency progresses, the contribution of embodied emissions to the building's whole lifecycle carbon footprint is becoming more apparent. Legislation across Europe is therefore increasingly adopting a lifecycle approach to carbon emissions in buildings: in France, Denmark and the Netherlands, lifecycle global warming potential (GWP) thresholds have already been established for new construction, and more countries are planning to implement such legislative requirements in the years to come [2]. The European Union's (EU) revised Energy Performance of Buildings Directive is expected to bring similar requirements for all European countries by the end of this decade [3]. These initiatives are necessary to bring the European Union on track with its CO_2 reduction commitments, but the few proposed thresholds are not yet ambitious enough to reach the 1.5-degree target set by the Paris Agreement [4].

The construction industry is a key sector in which to intervene and must, therefore, learn how to design and operate buildings with a much lower carbon footprint than what is (or will be) required. The EU is taking a proactive approach to address the urgent challenges of resource depletion and climate change. This involves implementing a new sustainable construction strategy, which aims to consider End-of-Life scenarios from the product design stage and optimise energy efficiency throughout the entire lifespan of constructed assets. The ultimate goal is to extend the useful life of constructed assets and promote environmental sustainability. Therefore, it is crucial to consider Life Cycle Assessment (LCA) when designing future-proof constructions.

The building industry is a slow-moving sector, but its decarbonisation is urgent. Many solutions already exist to build with a very low carbon footprint, but a share of the industry lacks knowledge about these solutions [5]. Cost is often seen as a barrier to the development of green buildings, as many players assume such solutions will be more expensive [5-6]. Finally, while many pilot low-carbon buildings have been built over the years [7], they are not always replicable at scale in an affordable way.

The project described in this article seeks to demonstrate the feasibility of affordable, ultra-low carbon homes with excellent indoor environments, built with today's materials and technologies and adapting to local customs, regulations, and market conditions. This paper introduces Living Places, a single-family home concept developed and built by three players in the Danish building industry (i.e., VELUX, EFFEKT Architects and Artelia Denmark). This article presents the design process, the final concept, and the results in terms of the project's carbon footprint.

2. METHODS

The project's goal and scope were defined, and LCA was performed using a design optioneering approach to calculate the materials' overall impact. From a theoretical viewpoint, this section also explains the methodology used to assess the carbon footprint of the single-family houses executing LCA.

2.1 Construction program and benchmark house

Two single-family houses were designed and built with the goal of showing two alternative ways to reach a very low carbon footprint while maintaining durability and affordability. The houses were intended to host a family of four, with three bedrooms, one bathroom and a combined kitchen-living room. The building design arose from the amalgamation and integration of the partners' expertise and creativity, with a focus on incorporating aesthetic value and creating a communal atmosphere that fosters a sense of belonging.

A benchmark house was also defined, representing a typical Danish single-family house with the same function. The benchmark house was a single-plan, 184 m^2 detached house with three bedrooms. It had a concrete foundation and floor slab, concrete external walls with mineral wool and a brick façade, aerated concrete internal walls, a barred roof construction with roof tiles and a ventilated attic. It had underfloor heating and was connected to district heating. The house also had a balanced mechanical ventilation system with heat recovery and was equipped with a 7 m^2 photovoltaic installation.

2.2. LCA method

The ISO Standard 14040:2006 [8] defines the functional unit in an LCA as the quantified performance of a product system. In this study, the functional unit is a single-family house. LCA was carried out following the methodology adopted in the Danish legislation in January 2023. Three distinct phases were undertaken to conduct a comprehensive LCA of the houses. Firstly, a life cycle inventory analysis (LCI) was conducted, encompassing a thorough review of the product's inputs and outputs from acquiring raw materials to production, use and disposal. The second phase involves the life cycle impact assessment (LCIA), estimating the potential environmental impacts of these inputs and outputs. The final phase, known as life cycle interpretation, involved interpreting the inventory analysis results and impact assessment phases concerning the study's objectives. The system boundary includes the lifecycle stages A1-A3, B4, B6, C3 and C4, which were evaluated using the Danish LCA compliance software LCAbyg according to EN 15978:2012. The evaluation period was 50 years.

LCAbyg's database is modelled after the German ÖKOBAUDAT database for construction products, utilising Environmental Product Declarations (EPD) to represent available products comprehensively. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) oversees ÖKOBAUDAT for in-depth cradle-to-grave analyses of building products and services. This database contains standardised data sets for various construction materials and processes, organised according to European standards for assessing environmental quality. However, as a result of new Danish regulations, LCAbyg's database now supplements ÖKOBAUDAT data with an additional 10-30% of generic data, as outlined in BR18 annex 2 table 7 [9]. Moreover, transport and site processes are not considered in the calculations and can be entered into the tool in relation to the individual product.

The energy use during the building's lifetime was estimated using the Danish energy frame calculation method and inserted as an input into LCAbyg. The calculation of operational emissions from energy use was done considering an average carbon intensity of electricity of 56 gCO_2/kWh in Denmark between 2021 and 2071 (starting in 2021 with 238 gCO_2/kWh and assuming a greening of the electrical grid reaching 40 gCO_2/kWh in 2040).

The impact categories supported by LCAbyg calculate the environmental profile results describing (1) environmental impacts[1], (2) resource use, primary energy[2], and (3) resource use, secondary materials and fuels, and use of water[3]. This project focuses on optimising the global warming potential (GWP) of the houses; therefore, the results achieved in the other impact categories are not discussed in this article.

The LCA calculation was carried out by the project's engineering consultant and verified by independent researchers via LCAbyg. The buildings' environmental profiles analysed were obtained by combining the

[1] GWP = Global Warming Potential; ODP = Ozone Depletion Potential; POCP = Formation potential of tropospheric Ozone; AP = Acidification Potential for Soil and Water; EP = Eutrophication Potential; ADPE = Abiotic Depletion Potential Elements; ADPF = Abiotic Depletion Potential Fossil Fuels.
[2] PENRT = Total Use of non-renewable primary energy resource; PERT = Total Use of renewable primary energy resources.
[3] RSF = Use of renewable secondary fuels; NRSF = Use of non-renewable secondary fuels.

environmental impacts associated with the operation and those attributed to building materials.

2.3 Design Optioneering approach

A tool was developed in order to determine the optimal design choices for materials and services iteratively to achieve ultra-low carbon homes. A comprehensive list of materials and products utilised in the construction of each building element, including external and internal walls, windows and doors, floors, roofs, and foundations, as well as relevant information regarding operations such as heating systems, ventilation, storage, and PV systems, were meticulously identified. The carbon footprint of each of these construction elements was extracted from environmental product declarations (EPDs) and inserted into the tool developed for this project. Cost information was also included in the tool. This tool enables the selection of design options for various building components, such as foundation, ground floor, external and partition walls, and more. Each choice was already associated with a value in kg CO_2/unit yr. based on an LCA per component and a value in DKK/unit based on market prices. After selecting the desired components and materials, the tool calculates the building's total GWP in kg CO_2/m^2/yr. Through this iterative process of selecting and comparing building components, the final materials for the house were chosen in such a way as to reach the carbon footprint goal.
Subsequently, the LCAbyg tool was utilised to calculate multiple impact categories, thereby verifying the construction's overall environmental impact throughout its life cycle.

3. RESULTS

The process described in Section 2 resulted in the design of two distinct houses with mirrored floor plans, one with a timber frame structure and the other with a CLT-based structure.

3.1. Architectural design and services

The houses were designed as 3-story single-family houses with a pitched roof on the two upper floors. The total floor area was 147 m^2, which was purposefully chosen to be slightly smaller than the benchmark house and the Danish average in order to showcase smaller living as one strategy to reduce the overall carbon footprint of the built environment.

Regarding the building services, both houses were equipped with an air-to-water heat pump and radiators. The timber frame house was purely naturally ventilated via automated façade and roof windows reacting to indoor temperature, humidity and CO_2 concentration signals. Windows could also be operated manually by the occupants. A balanced mechanical ventilation system with heat recovery was installed in the CLT house, complementing the manual and automated windows and enabling hybrid ventilation. Both houses had 11 m^2 PV panels located on the flat part of the roof.

The energy frame calculation gave a net yearly electrical consumption from the electrical grid of 5.1 kWh/m^2/yr. – the electricity produced onsite by the photovoltaic panels is already deducted from this number. The operational emissions of the house were calculated to be 0,28 kgCO_2/m^2/yr.

3.2. Choice of materials

The details of the investigated design options are shown in Table 1. The comparison of the Global Warming Potential of these different options is shown in Figure 1 for each of the main construction element categories. The GWP is shown per m^2 of floor area. Figure 1 and Table 1 also show the chosen options for the timber frame house and the CLT house. The cost of each option was also estimated and considered in the choice of materials but not shown in this article.

Choosing a foundation and floor based on screw piles and a wooden cassette, instead of the traditional concrete-based foundation and floor slab, permitted to divide the carbon footprint of these elements by a factor 2 to 3.

Both houses looked similar from the outside, with untreated wooden cladding, a steel roof and a 3-layer façade and roof windows. However, they were based on different construction principles: one of the houses had a traditional timber frame structure and a wooden skeleton for internal walls, while the other used CLT in external and internal walls, floors and the roof. Paper wool and wood fibre insulation were chosen for external walls and roofs.

3.3. LCA of the two houses

The final results of the LCA in terms of the total Global Warming Potential (GWP) of each house are shown in Table 2.

Table 2: Global Warming Potential results.

GWP (kgCO_2eq/m^2/yr.)	Benchmark house	LP timber frame	LP CLT
Embodied	8,2	3.5	3.6
Operational	2,9	0.3	0.3
Total	11,1	3.8	3.9

Show visualization instead

Table 1: Detail of the investigated design options for each construction element.

Option	Foundation	Floor slab	External wall	External wall cladding	Interior walls	Floor deck	Roof	Roof cladding	Windows
1	Traditional strip foundation in Leca and concrete	Traditional concrete slab + polystyrene insulation	Wooden cassette + mineral wool	Wooden cladding, untreated	Steel skeleton + mineral wool + 2 x gypsum pr. side	Ribbed deck + apparent beams	Light wooden cassette + wood fiber insulation	Roofing felt	3-layer wood-alu façade windows
2	Strip foundation in Leca and concrete + FutureCem	Concrete slab with FutureCem +polystyrene insulation	Wooden cassette + I-joists + wood fiber insulation	Wooden cladding, heat-treated	CLT	Ribbed deck + apparent glulam beams	Light wooden cassette + paper wool insulation	Steel sinus plates	3-layer wood-wood façade windows
3	Screw pile foundation	Concrete slab with FutureCem + Rockwool Terrænbats	Wooden cassette + paper wool insulation	Wooden cladding, painted	Wooden skeleton + mineral wool + 2 x gypsum pr. side	Ribbed deck + gypsum ceiling	CLT with wood fiber insulation	Zinc	3-layer alu façade windows
4	L-element	Light wooden cassette, raised	Wooden cassette + paper wool insulation, thin	Sinus plates, steel + zinc magnesium	Wooden skeleton + wood fiber insulation + 2 x gypsum pr. side	CLT		Roof tiles	3-layer PVC façade windows
5		Light slab + polystyrene insulation	CLT with wood fiber batts	Tiles	Wooden skeleton + wood fiber insulation + OSB and gypsum pr. side			Wooden slats on the roofing felt	3-layer wood-alu sloped roof windows
6		Light slab + Rockwool Terrænbats	Insulated bricks	Slates	Wooden skeleton + wood fiber insulation + 1 x gypsum pr. side			Wooden cladding, untreated	3-layer alu-PU sloped roof windows
7		Light wooden cassette, raised (alternative)	Concrete wall + mineral wool	Fiber cement	Insulated bricks			Wooden cladded, heat-treated	2-layer modular skylight
8			Rockwool RedAir	Plaster	Aerated concrete			Wooden cladding, painted	3-layer modular skylight
9					Wooden skeleton + wood fiber insulation + plywood			Slates	
10								Fiber cement	

Legend:

Chosen option in the CLT house

Chosen option in the timber frame house

Chosen option in both houses

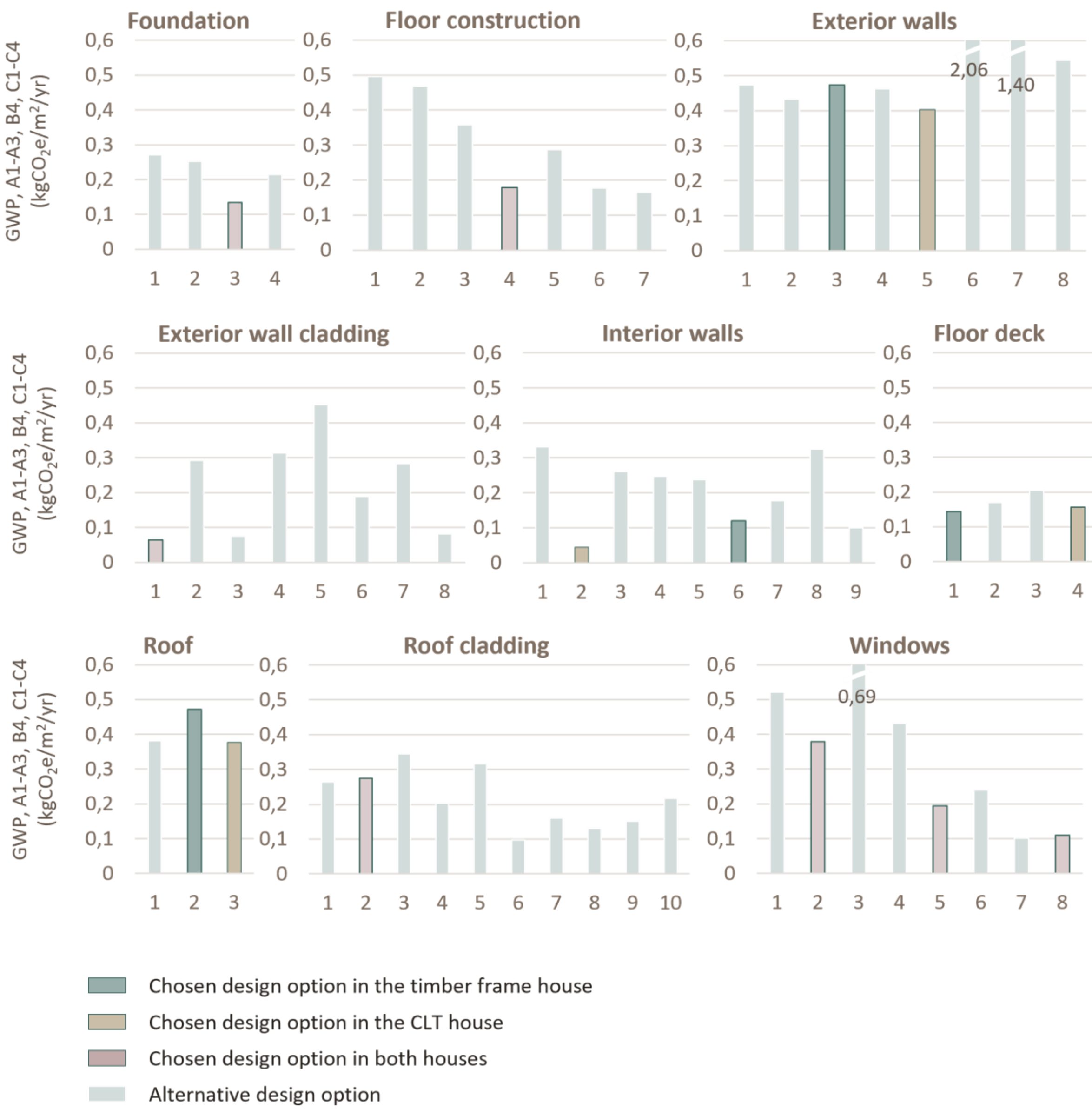

Figure 1: GWP of different design options for each construction element. The numbers on the x-axis correspond to the design option details shown in Table 1.

The timber frame house achieved a 65,8% reduction in GPW compared to the benchmark house, while the CLT house achieved a 64,9% reduction. In both cases, the achieved GWP was more than three times lower than the maximum threshold set by the new Danish legislation of 12 $kgCO_2eq/m^2/yr$.

Both houses were built in Copenhagen in 2023, showing the practical feasibility of these designs. Figure 2 shows pictures of the realised houses. Simulations carried out during the design process showed that both design concepts also achieved excellent indoor environmental quality – these results are presented in another contribution to the PLEA 2024 conference.

4. DISCUSSION

This study highlights the importance of carefully selecting building materials in order to achieve a low carbon footprint. The design optioneering approach revealed the significant differences between materials – and even between brands – when it comes to their global warming potential. However, the example of Living Places shows that a large range of low-carbon materials exists today. There is potential for overcoming the current challenge of creating low-carbon pilot buildings that can be economically replicated at various scales. The method used in this study is transparent, and the assessments demonstrate the practicality of designing cost-effective, ultra-low carbon homes with exceptional indoor environments, utilising today´s materials and technologies.

A limitation of this study resides in the quality of the data used to perform the LCA. It is difficult to find environmental product declarations for all used materials. Therefore, the LCAs conducted for this project included 22% and 20% generic EPDs for the timber frame and CLT houses, respectively.

Moreover, designing this project and comparing different materials based on their carbon footprint is a time-consuming operation that requires a larger budget as well as close cooperation between the different involved parties – developer, architect, engineer, etc. While this is difficult in most mainstream construction projects, the Living Places case shows the value of a deeper collaboration between parties in the early stages of the building design process.

5. CONCLUSION

With the two presented design concepts, the Living Places initiative showed that it is possible, with today's materials and technologies, to build single-family houses with a lifecycle carbon footprint three times lower than what is currently required by legislation. This paves the way for legislators and the building industry to raise their ambition level in order to bring the construction sector on track to meet the targets set out in the Paris Agreement.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the invaluable contribution of the project partners – VELUX, EFFEKT Architects and Artelia Denmark.

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Figure 2: Pictures of the built houses in Living Places Copenhagen. a: Overall view of the area; b and c: Outside view; d: Inside view of the timber frame house; e: Inside view of the CLT house. Photos: Adam Mørk