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*Published in:*  
Journal of Physics: Conference Series

*DOI (link to publication from Publisher):*  
[10.1088/1742-6596/2600/15/152019](https://doi.org/10.1088/1742-6596/2600/15/152019)

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*Publication date:*  
2023

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*  
Tozan, B., Nielsen, L. H., Birgisdottir, H., & Hoxha, E. (2023). Mitigating carbon emissions of single-family houses: Assessing the need for a limit value. *Journal of Physics: Conference Series*, 2600(15), Article 152019. <https://doi.org/10.1088/1742-6596/2600/15/152019>

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To cite this article: B Tozan *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 152019

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# Mitigating carbon emissions of single-family houses: Assessing the need for a limit value

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**Abstract.** Reducing carbon emissions in the global building and construction sector is a crucial part of achieving climate targets. Laws that aim to limit the carbon emissions of new buildings have yet to be implemented on a larger scale, although some nations already have thresholds. These thresholds may not be sufficient to mitigate carbon emissions, and not all types of buildings are obliged to comply with them. In the case of Denmark, single-family houses (SFH) are not required to not comply with a limit, although they represented approximately 17% of all newly built areas from 2010 to 2022, indicating significant resource use and associated carbon emissions. This study aims to establish sufficient background data to support the need for implementing a limit value for SFHs in building regulations to ensure necessary reductions in carbon emissions. The study finds that the life cycle carbon emissions of Danish SFHs vary between 5.6 and 13.2 kg CO<sub>2</sub>e/m<sup>2</sup>/year, showing that compliance with the current limit value of larger buildings is possible and that a reduction of more than 50% in carbon emissions is possible. However, currently, there is no intentional investigation or achievement of potential carbon emissions in the construction industry. The study's findings inform policymakers that a limit value for SFHs must be introduced no later than 2025 to initiate the necessary reduction of carbon emissions.

**Keywords.** Carbon emissions, life cycle assessment, limit value, single-family houses

## 1. Introduction

Several nations have recognized the need for transitioning to more sustainable ways and agreed-upon global climate policies such as the Paris Agreement, which aims to limit the global surface temperature to 1.5 degrees Celsius and net zero emissions by 2050. The construction and building industry, which are responsible for 37% of global CO<sub>2</sub>e emissions [1], must significantly reduce, and this has been recognized for the past decade. To do so, life cycle assessment (LCA) has been an acknowledged method for quantifying the environmental impacts of buildings over their entire life cycle.

LCA is a standardized holistic approach that evaluates a product's or system's environmental impact over its entire life cycle, including the extraction of raw materials, production, transportation, use, and disposal at the end of life [2]. LCA applied to buildings can help stakeholders identify the main contributors to the environmental impacts of buildings, which can be used to make more informed decisions for mitigating impacts. However, LCA of buildings has been a voluntary practice as it has only been required in voluntary sustainability certification



schemes such as DGNB or BREEAM. However, this is changing in several nations. For instance, since 2020, documentation of carbon emissions with LCA for residential buildings in France has been a legal requirement. In Germany, carbon assessments of all new public buildings must be determined. On January 1, 2023, it is required by Danish legislation to document CO<sub>2</sub>e emissions of new buildings with life cycle assessments. In addition, buildings  $\geq 1000$  m<sup>2</sup> of heated floor area (HFA), must comply with a limit value. Additional nations are planning to implement requirements for carbon assessments of buildings [4].

### *1.1. The need for reductions*

From 2010 to 2022, 4778 single-family houses were built annually in Denmark corresponding to 16.6% of all newly built square meters in the same period. Though these numbers indicate the significant amount of resources expended on SFHs and associated life cycle carbon emissions, these buildings are not obliged to comply with the limit value of 12 kg CO<sub>2</sub>e/m<sup>2</sup>/year. Currently, only the voluntary DGNB Villa certification attempts to measure the carbon emissions of Danish single-family houses. Furthermore, it is unknown if they are required to comply with the next limit values in 2025 and 2027 expected to be 10.5 and 9 kg CO<sub>2</sub>e/m<sup>2</sup>/year, respectively. Motivated by the need to decarbonize Danish SFHs, this study aims for establishing a larger knowledge base of carbon emissions, by determining the life cycle carbon emissions of conventional SFHs in Denmark with life cycle assessments. The life cycle carbon emissions of the SFHs will demonstrate and evaluate the need to implement a limit value to promote decarbonization.

## **2. Method and materials**

### *2.1. Life cycle assessments*

The LCAs follow Danish building regulations (BR18 §298) and use a functional unit of kg CO<sub>2</sub>e per square meter of reference floor area (RFA) per year over a 50-year study period. The LCAs are static and cover the stages and modules: production (A1-3), replacement (B4), operational energy use (B6), and end of life (C3-4). The assessment focuses on global warming potential (GWP) measured in kg CO<sub>2</sub> equivalents as per EN15978:2012. Biogenic materials in modules A1-3 and C3 follow the -1/+1 method. The LCAs include structures, finishes, installations, and occasionally PV panels, with input quantities estimated from construction drawings. The assessments are performed using LCAbyg 2023 (version 5.3.1.0).

### *2.2. Case studies*

The study analyzes carbon emissions from 39 real-life single-family houses in Denmark. Out of these, 28 cases were collected specifically for this study, while 11 were sourced from a previous study [7, 6]. Among the 39 cases, 22 are conventional concrete buildings, reflecting the typical market for new single-family houses, and six are wood buildings with primary load-bearing elements constructed using wood principles. On average, the buildings have a reference area of 180 m<sup>2</sup> and accommodate 4 occupants.

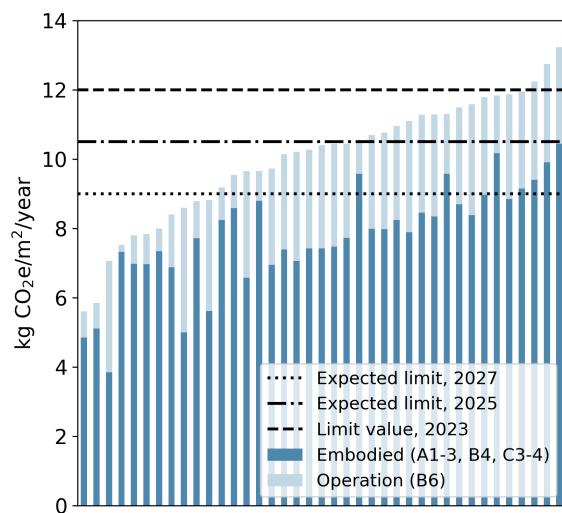
## **3. Results**

### *3.1. Life cycle carbon emissions*

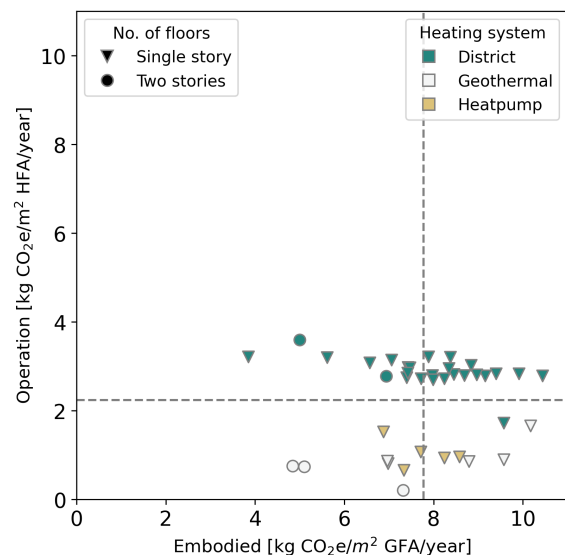
Figure 1 shows how the total carbon emissions vary between 5.6 and 13.2 kg CO<sub>2</sub>e/m<sup>2</sup>/year. The contribution from embodied carbon emissions is between 71% and 97% of the life cycle carbon emissions, while operational carbon contributes between 3% and 29%. The median values are 10.4 kg CO<sub>2</sub>e/m<sup>2</sup>/year (520 kg CO<sub>2</sub>e/m<sup>2</sup>), 2.78 kg CO<sub>2</sub>e/m<sup>2</sup>/year, and 7.88 kg CO<sub>2</sub>e/m<sup>2</sup>/year for total, operational, and embodied carbon emissions, respectively. It is evident from the figure that, if the limit value were currently valid for SFHs in Denmark, only 10% of the 39 buildings

would not be able to comply with it, thus, indicating that SFHs are not motivated for reducing carbon emissions, and probably will not be, unless an appropriate limit value is implemented into the regulation. The significant variance in carbon emissions evidently shows it is possible to reduce more than half of emissions in 2023 and still comply with the expected limit values of the future. The results underline that methods for constructing buildings to achieve 50% reduction in carbon emissions exist today without putting in the effort. If efforts for reducing emissions are accelerated, further reductions will be achieved.

A potential correlation between embodied and operational carbon emissions is investigated and illustrated in Figure 2, but no correlation is found between operational and embodied emissions, but a strong correlation between operational carbon emissions and the heating system is evident. In addition, the graph shows that the combination of two floors and a geothermal heating system results in low embodied and operational carbon emissions, while single-story and district heating result in higher carbon emissions.



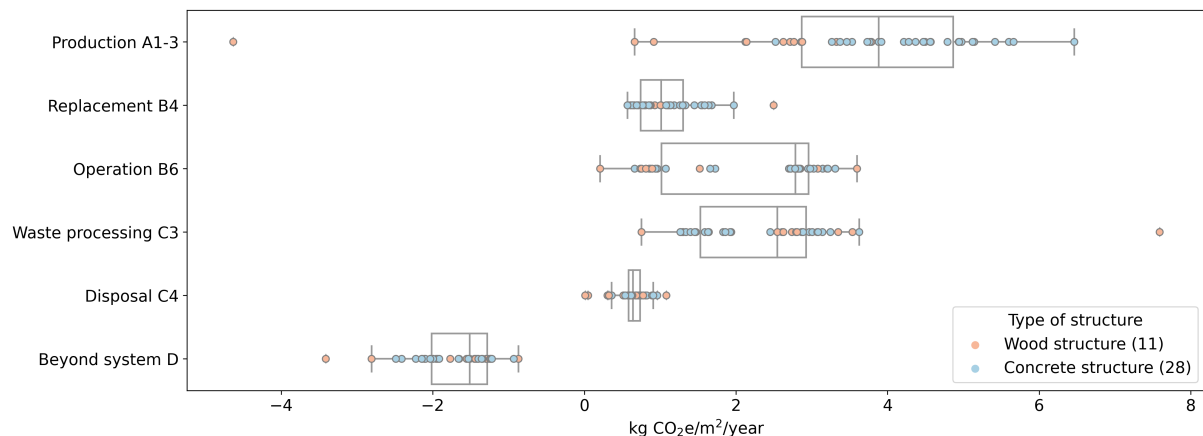
**Figure 1.** The life cycle carbon emissions are reported in  $\text{kg CO}_2\text{e/m}^2/\text{year}$  with a reference study period of 50 years. The dotted line shows the median value of 39 cases of total carbon emissions, and the dashed line shows the current limit value of the building regulations.



**Figure 2.** Scatterplot of embodied and operational carbon emissions to investigate potential correlation. Average emissions are illustrated with grey dashed lines.

### 3.2. Contribution of life cycle modules

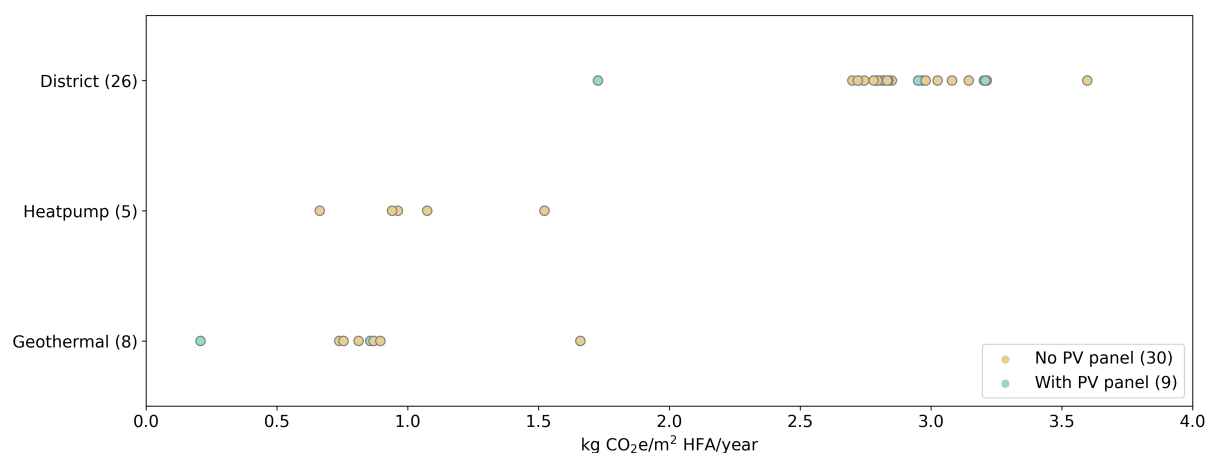
The strip plot in Figure 3 distributes carbon emissions from life cycle modules and shows the distribution of emissions across the entire life cycle. The distribution is wide due to variations between concrete and wood buildings. Overall, there is no clear trend in the life cycle modules when comparing the two types of structures except in modules A1-3. The contribution of modules A1-3 is evidently lower for wood buildings compared to concrete buildings. However, the -1/+1 method is not clearly evident in the graph, since only one case results in negative emissions in module A1-3.



**Figure 3.** Contribution to carbon emissions of life cycle modules shown for 39 single-family houses in kg CO<sub>2</sub>e/m<sup>2</sup>/year with RSP of 50 years.

### 3.3. Variation in heating system and supply

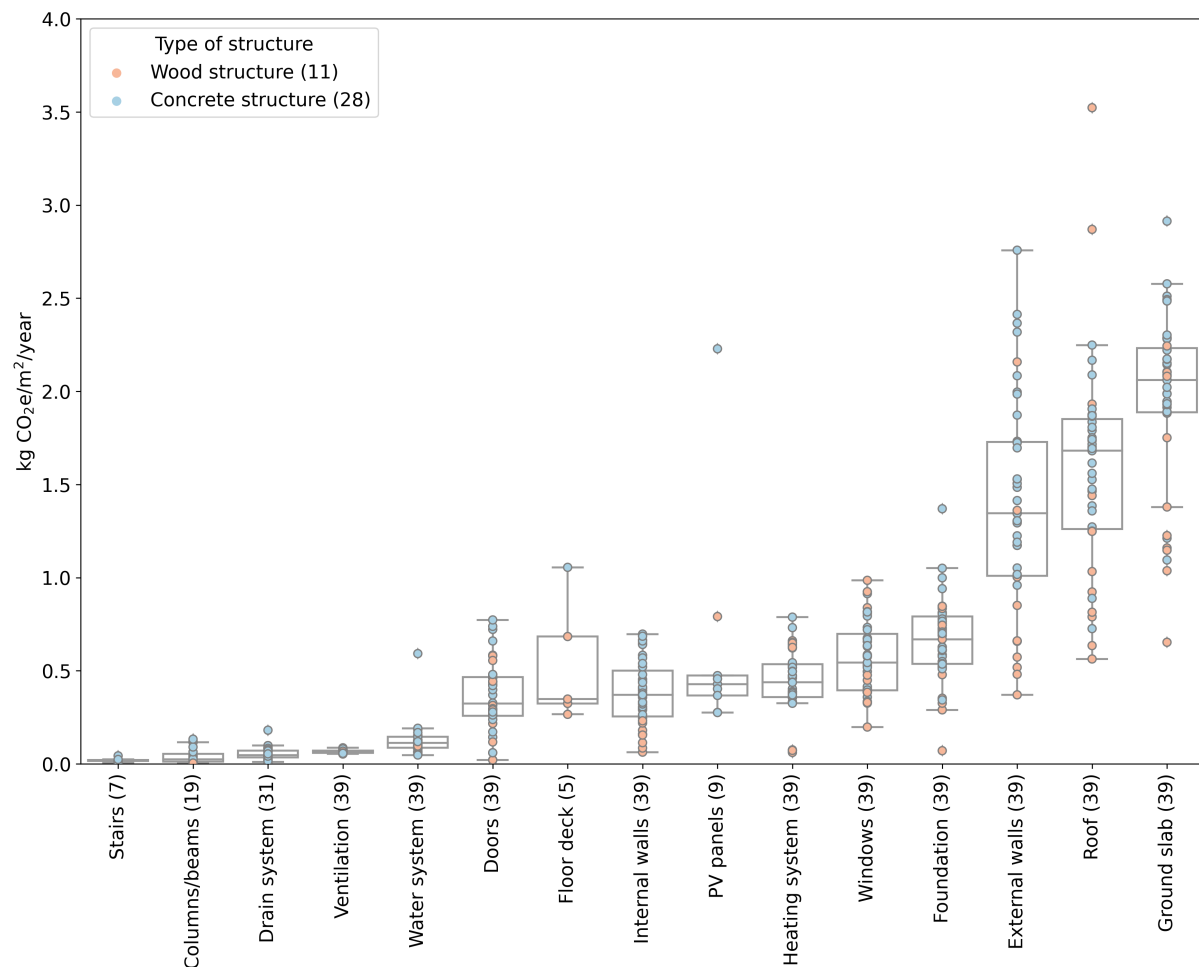
In Figures 1 and 2, it is evident that the operational carbon emissions vary across the 39 buildings due to variations in the heating supply of the buildings. The electrically driven heat pump and geothermal heating system emit less carbon compared to district heating. The graphs also show if photovoltaic panels (PV) are installed in the buildings to investigate the influence of PVs on operational carbon emissions. However, no evident trend seems to be present. None of the PV systems in the case studies generate surplus electricity for sale.



**Figure 4.** The operational carbon emissions in module B6 for 39 single-family houses distributed into heating system in a strip plot. The number of occurrences is given in parentheses.

### 3.4. Contribution of building elements

Boxplots depicting embodied carbon emissions from building elements and technical equipment are presented in Figure 5. The boxplots indicate that the ground slab, roof, and external walls of the buildings are the primary contributors to embodied carbon emissions, although the magnitudes vary. The outlier of a roof with 3.5 kg CO<sub>2</sub>e/m<sup>2</sup>/year has three layers of bitumen and 0.57 m mineral wool insulation, which contribute significantly to carbon emissions.



**Figure 5.** Boxplots of the embodied carbon emissions of building elements and technical equipment reported in kg CO<sub>2</sub>e/m<sup>2</sup> RFA/year. Sample sizes are given in parentheses.

## 4. Discussion

### 4.1. The need for a limit value

The study reveals that only 10% of the 39 buildings would not comply with the current limit value if it applied to small buildings ( $HFA < 1000 \text{ m}^2$ ). Current and future limit values do not appear to pose a challenge, as some buildings in the study already meet the potential limit value for 2027. The significant variation in life cycle carbon emissions indicates that over 50% of emissions can be reduced presently, and further reductions are possible as the buildings have not been intentionally optimized for material quantities or carbon emissions.

However, it is crucial to implement the limit value for single-family houses (SFHs) as early as possible, preferably by 2025, due to the urgency of climate change and remaining carbon budgets. Danish legislation already exceeds the GHG budget by 220% in 2023 [3]. Delaying the implementation of the limit value until 2025 or 2027 would discourage stakeholders in the construction industry, particularly SFH developers, from seeking carbon emission optimization.

To avoid the need for sudden and drastic reductions in carbon emissions when striving to meet national and global climate targets, it is imperative to implement the limit value and initiate the exploration of carbon emission reduction strategies as soon as possible. Failure to do so would leave the construction industry without the necessary knowledge and competencies in reduction

strategies. These conclusions can be drawn in other nations as well, where single-family houses constitute a significant portion of the new building stock, particularly since residential buildings emit an average of 600 kg CO<sub>2</sub>e/m<sup>2</sup> over their entire life cycle. When divided by 50 years, this corresponds to 12 kg CO<sub>2</sub>e/m<sup>2</sup>/year [5].

#### 4.2. Reduction possibilities

The study finds that the major contributors to the embodied impacts are the ground floor slab, roof, and exterior walls. Therefore, it is evident that exploring potential strategies to reduce embodied carbon emissions of these building elements is crucial. The boxplots demonstrate significant variations, particularly in the case of exterior walls, indicating the potential for emission reductions. In the event that a limit value is mandated for single-family houses (SFHs) in Denmark, simplified LCAs based on building element archetypes could be employed to illustrate the reduction potential of these elements. Overall, the efforts to mitigate carbon emissions should primarily focus on upfront carbon emissions (A1-3) as they constitute the most substantial contributions.

### 5. Conclusions

The carbon emissions of the 39 single-family homes (SFH) clearly demonstrate the need for implementing limit values in building regulations. With 90% of the buildings already complying, and significant variation in emissions, it is possible to construct buildings emitting less than 6 kg CO<sub>2</sub>e/m<sup>2</sup>/year without additional efforts. This value exceeds half of the current limit and remains below the projected limits for 2025 and 2027. Thus, the study highlights the necessity of implementing limit values, considering climate change challenges and GHG budget constraints.

### 6. Acknowledgements

The analysis and results described in this paper are related to the development of the DGNB certification for single-family houses composed by the Green Building Council Denmark. The data to conduct life cycle assessments of the 28 case studies are provided by four single-family house developers in Denmark.

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