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Embodied GHG emissions of buildings – Critical reflection of benchmark comparison and in-depth analysis of drivers

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Abstract. In the face of the unfolding climate crisis, the role and importance of reducing Greenhouse gas (GHG) emissions from the building sector is increasing. This study investigates the global trends of GHG emissions occurring across the life cycle of buildings by systematically compiling life cycle assessment (LCA) studies and analysing more than 650 building cases. Based on the data extracted from these LCA studies, the influence of features related to LCA methodology and building design is analysed. Results show that embodied GHG emissions, which mainly arise from manufacturing and processing of building materials, are dominating life cycle emissions of new, advanced buildings. Analysis of GHG emissions at the time of occurrence, shows the upfront 'carbon spike' and emphasises the need to address and reduce the GHG 'investment' for new buildings. Comparing the results with existing life cycle-related benchmarks, we find only a small number of cases meeting the benchmark. Critically reflecting on the benchmark comparison, an in-depth analysis reveals different reasons for cases achieving the benchmark. While one would expect that different building design strategies and material choices lead to high or low embodied GHG emissions, the results mainly correlate with decisions related to LCA methodology, i.e. the scope of the assessments. The results emphasize the strong need for transparency in the reporting of LCA studies as well as need for consistency when applying environmental benchmarks. Furthermore, the paper opens up the discussion on the potential of utilizing big data and machine learning for analysis and prediction of environmental performance of buildings.

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1. Introduction

1.1. A global target: Net-zero GHG emissions across the life cycle of buildings
Climate change is real and the fight to limit global warming and avoid ecosystem collapse are considered the major challenges of our time [1]. Environmental impacts from building construction and operation are substantial, as commonly more than 40% of global GHG emissions are attributed to it [2]. The global efforts to limit climate change require strong contributions from all sectors, with a special role for buildings and construction. In the latter sectors, this leads to a new approach in setting benchmarks and specific design goals. In the past, these were often exclusively aimed at limiting the operational energy consumption, since indeed, building operation still predominantly relies on fossil primary energy and hence causes significant amounts of GHG emissions. However, as the climate crisis is becoming increasingly evident, the main target now becomes minimizing GHG emissions across the full life cycle of buildings. Aiming to either bring life cycle-related GHG emissions down to 'zero' or achieve a 'net-zero' balance (mainly by offsetting emissions, on- or off-site) leads to a new phenomenon. While in the past, there were various design goals and legal requirements for different types of buildings, in specific climatic zones, and adapted to political, cultural and other circumstances, the new target is a common one globally: to construct and operate buildings that no longer (or only to a necessary minimum) contribute to further GHG emissions.

1.2. Assessing life cycle related environmental impacts caused by buildings
The methodology of life cycle assessment (LCA) is increasingly applied to buildings to model and assess their GHG emissions (and other environmental impacts) across the full life cycle. The LCA methodology has been standardized, both in general (e.g. ISO 14040/14044), as well as, in particular to support environmental performance assessments of construction products (e.g. EN 15804) and buildings (e.g. EN 15978). The LCA methodology and its application to buildings are continuously evolving. They have been and are the subject of international research projects under the framework of the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) program, such as, e.g., the IEA EBC Annex 57 [3,4] on 'Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction' (finished in 2016) as well as the ongoing IEA EBC Annex 72 [5,6] on 'Assessing Life Cycle Related Environmental Impacts Caused by Buildings'.

1.3. Meta-analysis of GHG emissions across the life cycle of buildings
In order to understand the latest developments and current challenges for reducing life cycle-related GHG emissions of buildings, the authors reviewed the existing body of scientific literature and systematically collected and analyzed more than 650 building LCA cases. To ensure reproducibility, the meta-analysis followed the protocol for systematic literature review including snowball studies. To ensure quality and make the studies comparable, rigorous exclusion criteria as well as a comprehensive data harmonization procedure were applied. For interpretation purposes, custom categories were defined and applied to structure the results. Categories presented in the following are: the type of building (residential and office), building's energy performance class (existing standard, new standard, new advanced), as well as features related to local context and site (world region and climate zone). The details on this meta-study have recently been published and are available 'open access' [7].

The present paper builds on this research by emphasizing its key findings, as well as elaborating on the application of environmental benchmarks. It also presents preliminary results from an extended, in-depth analysis of features driving the 'best cases' identified in the former study [7].

2. GHG emissions across the life cycle of buildings – key findings
As presented in Röck et al. [7], the systematic analysis of building LCA studies showed that GHG emissions across the life cycle of buildings are reducing. This is because operational GHG emissions of new buildings are reducing, mainly due to stricter regulations on energy efficiency requirements for building operation. However, at the same time we observe an increase in embodied GHG emissions for 'New Advanced' buildings. For these 'New Advanced' buildings, both the relative share as well as

absolute contribution of embodied GHG emissions is increasing. Hence, besides a historic focus on reducing energy and GHG emissions from building operation and the success achieved through related regulations, it is now important to further reduce life cycle emissions by focusing on reducing embodied GHG emissions and optimizing the building life cycle.

By analysing GHG emissions at the time of occurrence, the study further showed the upfront 'carbon spike' from building production, highlighting the need to address and reduce the GHG 'investment' for new buildings. By example of the average values obtained for 'New Advanced' buildings, the study showed new building's upfront GHG investments embodied in initial building production dominating the timeframe for climate change mitigation. The 'break-even' point of embodied and operational GHG emissions, only occurs in year 35 after construction, considering static (constant) GHG emissions from building operation. In order to be in-line with a 1,5°C target, the GHG emissions related to building operation would have to be 'net-zero' by 2040 (preferably) and 2055 (at latest), according to the related IPCC special report [8]. This is considering the average energy consumption and related GHG emissions from building operation, as obtained from the meta-analysis. Assuming an improvement of the energy mix, i.e., by example of the projected reduction of emission-intensity (CO_2eq/kWh) of the electricity mix according to IEA scenarios [9], we find that a 'break-even' for operational and embodied GHG emissions for 'New Advanced' buildings could occur post year 50. This perspective shows the increasing importance of reducing embodied GHG emissions with a focus on the initial, upfront 'investment' for building production. Furthermore, operational GHG emission – even for 'New Advanced' buildings – are by no means close to being 'net-zero' in the time frame available for global decarbonization. Hence, in order to meet net-zero life cycle targets and avoid lock-in effects, large improvements are needed for both, GHG emissions from industry sectors related to energy provision and construction materials, as well as in building design practice. To address the global climate crisis, both building construction and operation have to follow strict environmental targets.

3. Environmental targets and related benchmarks for buildings

3.1. General targets for the environmental performance of buildings

The estimation of maximum environmental impacts of buildings, in other words the GHG emissions budget still available, is typically based on the capacity of the ecosystem, in the long-term, and a share of the global GHG emissions budget allocated to the building sector for transition towards 'net-zero' in the intermediate term. However, while this is a globally uniform goal, it still must be pursued and achieved with specific means in the respective contexts. Hence, the specific solutions are affected by not only climate zones and economic areas but also building types and use scenarios. The long-term environmental targets have to be based on the capacity of the ecosystem following, e.g., the 'planetary boundaries' approach and its application for defining environmental budgets for the built environment, which showed the need to rethink current building practice fundamentally [10,11]. So far, apart from very general formulations in the direction of 'climate-neutral buildings', there have been hardly any quantitative requirements for a GHG emissions budget that can be interpreted as a design goal or legal requirement.

In a simplified calculation, for limiting global warming to 1.5 degrees, reducing GHG emissions to 1 ton of CO_2eq per capita and year can be an intermediate target for taking us on a path towards 'net-zero'. **Table 1** shows the estimated GHG emission budgets across the life cycle of residential buildings, expressed as CO_2 equivalent per living area (or net floor area) and year, i.e. CO_2eq/m²NFA*a. It assumes that around 30% of all GHG emissions are used for construction and operation of residential buildings. Furthermore, it is assumed that, based on existing sample projects, buildings can – and will have to be – designed in such a way that they achieve 'zero' or 'net-zero' GHG emission performance in operation. In this context, a 'near-zero' can be interpreted with 1-2 kg CO_2eq./m²NFA*a. Assuming 'net-zero' or 'near-zero' operational GHG emissions means that the GHG emissions budget becomes (almost) entirely allocated for embodied GHG emissions. Hence, this budget is available for building construction and repair, including the replacement of structural parts and building services systems in the life cycle, as well as the deconstruction, recycling and other end-of-life processes.

Table 1. Estimated design target for residential buildings (construction and operation) [CO_2eq/m²*a]

Living area [m²/cap]	Budget for housing (building construction and operation) [kg CO_2eq/cap*a]						
	600	**500**	**400**	**300**	**200**	**100**	**0**
60	10,0	8,3	6,7	5,0	3,3	1,7	0,0
55	10,9	9,1	7,3	5,5	3,6	1,8	0,0
50	12,0	10,0	8,0	6,0	4,0	2,0	0,0
45	13,3	11,1	8,9	6,7	4,4	2,2	0,0
40	15,0	12,5	10,0	7,5	5,0	2,5	0,0
35	17,1	14,3	11,4	8,6	5,7	2,9	0,0
30	20,0	16,7	13,3	**10,0**	6,7	3,3	0,0
25	24,0	20,0	16,0	12,0	8,0	4,0	0,0
20	30,0	25,0	20,0	15,0	10,0	5,0	0,0
15	40,0	33,3	26,7	20,0	13,3	6,7	0,0
10	60,0	50,0	40,0	30,0	20,0	10,0	0,0

As shown in **Table 1**, assuming a budget of 300 kg CO_2eq/cap*a, a building service life of (at least) 50 years, and an average living space of 30 m²/person as appropriate, the available budget in the building design context is approx. 10 kg CO_2eq/m²*a. This is an estimate target values for a transition period, within which budgets are used to develop 'buildings' towards 'net-zero' GHG emissions across the life cycle.

3.2. Comparison with existing life cycle related benchmarks for buildings (SIA 2040)

Besides analysing the global trends based on average values, building cases were investigated in relation to the Swiss SIA 2040 benchmarks for the life cycle-related GHG emissions of buildings **Figure 1**.

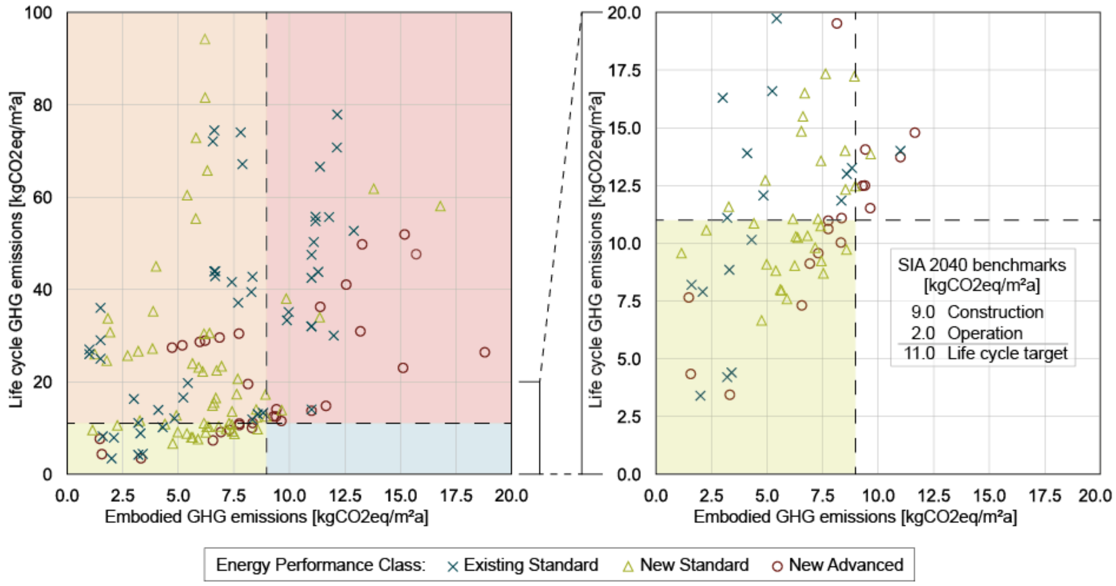

Figure 1: Life cycle-related GHG emissions and absolute embodied GHG of European residential buildings in relation to SIA 2040 benchmark – as published in [7].

As recently acknowledged in a publication related to the 71st LCA forum dedicated to environmental benchmarks for buildings [12], benchmarking and meaningful benchmark comparison can only be applied in the context of specific calculation methods and databases and should therefore be applied within a consistent (national) framework.

Although the SIA 2040 benchmark values, too, adhere to a specific method and to specific background data and should therefore preferably be used for buildings planned in Switzerland, we consider it useful to work with it, as it gives a specific example of life cycle related benchmarks already applied in design practice. Furthermore, the general target values presented earlier – rough estimates, yet globally valid under the specified boundary conditions – are surprisingly close to the more advanced calculations of life cycle related target values specified in the Swiss SIA 2040 guideline [13]: The SIA benchmarks are 2 kg CO_2eq/m^2*a for building operation and 9 kg CO_2eq/m^2*a for construction and maintenance over a reference study period of 60 years. Hence, the total design target, i.e. for building construction and operation, is 11 kg CO_2eq/m^2*a.

However, applying such (or any) benchmarks to the studies in this meta-analysis requires the consideration of the vast differences amongst the cases, which exist in data bases, calculation rules, energy supply situation, as well as political and socio-cultural context, among others. This raises the crucial question: How and under what conditions case studies in our sample reach these target values?

4. Findings from in-depth analysis of features driving 'best' cases

4.1. In-depth analysis based on extended list of features

Building on the analysis presented thus far, this section presents the critical investigation of what makes the 'best cases' meet the benchmark. For this purpose, an in-depth analysis of said cases was conducted based on an extended data extraction, focusing on studies' scope and building design-related features. Whilst a strong influence from the scope of a building LCA study, e.g. the completeness in terms of life cycle stages and building elements included, is obvious, standards hardly require a minimum scope but rather ask for transparency in reporting of the chosen scope and method. This fact leads to the challenge of having to account for said differences when comparing building LCA results reported in studies, even for largely similar buildings. Besides building LCA studies' scope, past research has shown various features influencing the results, amongst them i) the type of building and its use [14,15]; ii) site-specific properties (e.g., country, climatic zone, seismic zone) [16,17]; iii) the energy performance standard [18,19]; iv) construction method (choice of main building materials (e.g., for structural system, envelope, internal walls) [14,20–22]; and v) the size and shape of the building (e.g., floor area, number of stories, general shape) [14,23]. The in-depth analysis hence included all of these aspects, aiming to reveal whether the case study buildings show low GHG emission values because of 'good' design choices (e.g., related to building shape, construction materials, energy efficiency, etc.) or because of 'bad' LCA practice, e.g., a tiered and incomplete product system (missing potentially relevant building parts).

The extended data extraction and in-depth analysis was conducted on those cases of residential buildings that met the SIA benchmark, i.e., analysing 28 residential building cases from six papers. Already within this limited number studies analysed in-depth, a number of challenges and important data gaps became evident. Large data gaps were identified for features related to 'Building design decisions', where crucial information on both 'geometry' (e.g., general description of shape, volume, envelope area, window/wall ratio) as well as building 'performance' (e.g., number of user/occupants, energy provision, sources and distribution, u-values) had not been reported in the respective building LCA studies. It was shown in previous LCA studies that parameters such as, e.g., building geometry or u-values of the building envelope influence environmental performance of a building and should hence be documented as key features of building LCA studies. The following analysis focuses on the influence of selected features on embodied GHG emissions.

4.2. Influence of features related to LCA methodology and building design decisions

Amongst the most crucial aspects of LCA studies is the definition of the scope, system boundaries and respective life cycle inventories. To understand the influence of these methodological decisions on the results in terms of embodied GHG emissions, we analysed the scope regarding building parts and life cycle stages included in the "best cases". For building parts, abbreviations describe the parts included in the respective study: (S) structure; (F) foundation; (I) internal elements; (B) building services; (+) other elements (beyond conventional system boundary definitions). The definition of building life cycle stages (LCS) follows the EN 15978 standard. The type of structural system groups different structural systems and main construction materials: solid heavy (mass brick or concrete), solid light (mass timber), frame heavy (skeleton concrete or steel), frame light (skeleton timber).

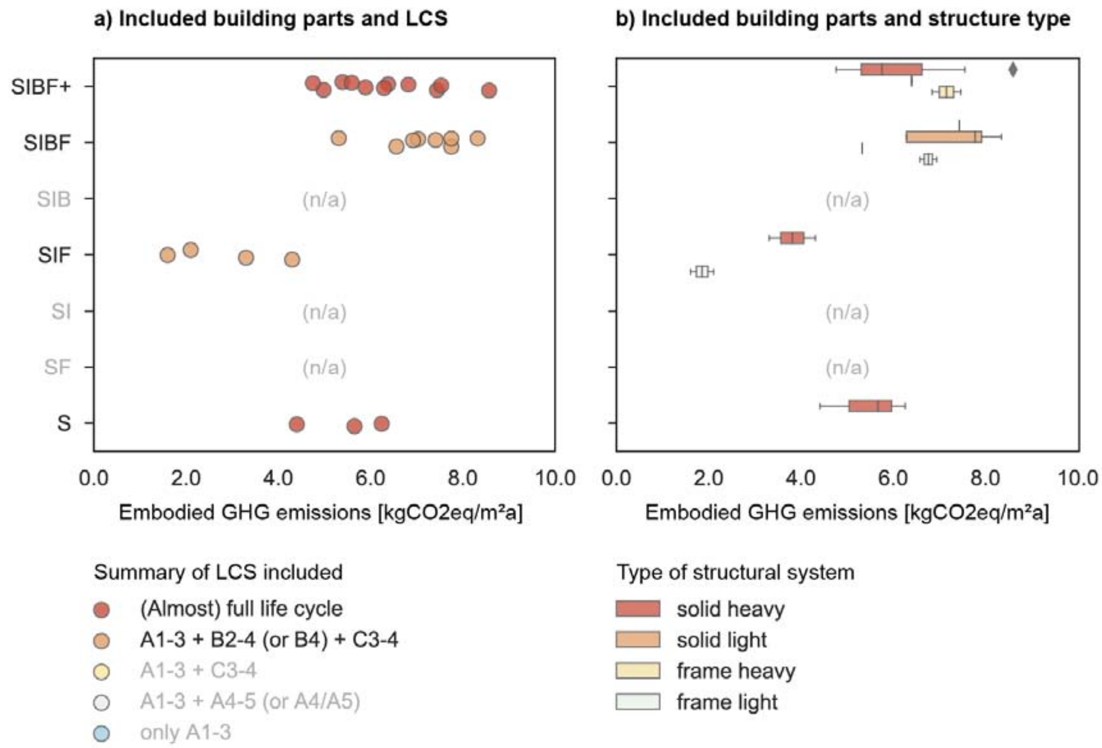

Figure 2. Analysis of the influence from features related to LCA methodology and building design decisions based on 28 residential building cases, plotting embodied GHG emissions (a) by the scope of life cycle inventories (building parts included, and life cycle stages covered), and (b) by building parts included for assessment and type of structural system.

As shown in **Figure 2.a**, plotting cases' embodied GHG emissions based on the building parts included and life cycle stages covered in the assessment suggests that with the increasing 'completeness' of the inventory, also the related embodied GHG emissions are increasing. Following the same structure, i.e. plotting embodied GHG emissions based on building parts included for assessment, additional analysis was conducted on the building design related drivers, namely of type and material of the structural system, see **Figure 2.b**. When compared to the increase trend in embodied GHG emissions associated to the inventory's level of detail, the type (and main material) of the structural system seem to play a secondary role in the results. The current data suggests that wood structures generally perform better than concrete structures, but there are cases where massive wood shows higher embodied GHG emissions than concrete frame and massive brick structures. In these cases, LCA methodology features seem to dominate the observed results and trends.

4.3. Need for further improvement – Quantity, quality and methods

Considering the limited number of cases in the presented in-depth analysis, as well as the challenges and data gaps identified during data extraction for the extended list of features, improvements on both the quantity and quality are needed. In order to account for the diversity in the studies and handle the large amount of features influencing the results, the application of dimensionality reduction methods

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and machine learning will be next steps in exploring the dataset, as promoted in earlier studies [24]. Identifying the influence of different features (and cases) could enable many possible applications, e.g., to show which are the most important features to be documented for building LCA studies in order to ensure quality, reproducibility and comparability of the studies. This is especially relevant in the context of operationalizing the Sustainable Development Goals (SDGs) for climate action (SDG 13) and sustainable cities and communities (SDG 11), i.e. for making sure to not compare 'apples with pears' when applying environmental benchmarks to buildings and cities. Furthermore, 'minimum documentation requirements' for building LCA studies could inform 'decision requirements', i.e., decisions related to the 'most influential environmental design parameters', to be decided on early in the building design process.

The ongoing research activities of IEA EBC Annex 72 aim to address several of these challenges through harmonized definitions of minimum documentation requirements and guidelines on the application of environmental targets as well as LCA along the building design process.

5. Conclusions

The paper builds on a recently published meta-analysis investigating more than 650 building LCA studies by elaborating on the benchmark comparison using Swiss SIA 2040 life cycle-related benchmarks, as well as by conducting additional in-depth data extraction and analysis on the 'best cases'. The results show that the reporting of relevant features of building LCA studies is (still) a big problem and that there is a need for clear guidelines on transparency standards and minimum documentation requirements to ensure quality and reproducibility of building LCA studies. The analysis of the limited amount of cases showed that features related to methodological decisions, by example of building parts included and life cycle stages covered in the study, have more influence on the results than building's structural system and main construction material. Hence, interpretation of the results of an LCA study, not to mention using it for benchmark comparison, can only be valid for studies considering – and transparently reporting on – specific calculation methods and databases as well as relevant features related to the object of assessment, the building and its design parameters. As a next step, in-depth analysis of a larger number of studies should be conducted to allow application of more sophisticated quantitative assessment methods, e.g., for dimensionality reduction, and a solid identification of the dominant drivers and relevant patterns behind a diverse set of building LCA studies. Improving the quantity and quality as well as standardisation in reporting of building LCA studies could further enable the use of machine learning, e.g., for estimating environmental performance based on a limited number of key features. A basic requirement for this to happen, are clear methodological guidelines and standardized minimum documentation requirements including a list of key features to be documented for *every* building LCA study.

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