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Whole-life-cycle benchmarks for domestic and non-domestic buildings: A method for definition and communication applied to the German building stock

COLLECTION: BUILDINGS AND APPLIANCES

PEER-REVIEWED PAPER

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ABSTRACT

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Benchmarking whole-life-cycle impacts is critical for aligning building design with sustainability targets. Current standards and studies recommend the definition of target-, average-, and limit-values, implemented through various methods and data sources. However, although several benchmarks already exist, a systematic process for their derivation is lacking. This paper adopts the method of the ISO 21678 to provide a clear roadmap for defining LCA benchmarks based on transparent calculations and data sources for 13 different domestic and non-domestic building usages. The methodology is designed to create a unified evaluation framework where a single benchmark scale is applicable to both new constructions and refurbishment projects, facilitating direct comparison. It combines existing top-down climate targets with bottom-up survey data and statistical sources to define key benchmark values. Further, it integrates an intuitive communication format, developed during an interdisciplinary and participative process with practitioners, to enhance usability and raise awareness for a large audience. The benchmark methodology is demonstrated through a case study for the German building stock. Results show that this method enables a structured and adaptable benchmarking process that can support integration into tools, certification schemes, and policy development. By clarifying how benchmarks could be defined, applied, and communicated, this contribution aims to foster the broader adoption of LCA benchmarking practices.

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INTRODUCTION

The building sector and construction industry account for approximately 37% of global greenhouse gas (GHG) emissions (United Nations Environment Programme 2024). At the same time, recent developments in energy efficiency regulations in the European Union (EU) are leading to a shift in focus: while operational impacts were historically dominating the environmental footprints of buildings through e.g. heat generation, electricity consumption and cooling, new efficient constructions tend to show ever larger embodied impact shares (Röck et al. 2020). To meet net GHG neutrality targets set by the EU Green Deal, a shift from operational-centric regulation to Whole Life Cycle (WLC) assessment is required. The building sector must reduce both operational and embodied GHG emissions to stay within climate-consistent carbon budgets.

Benchmarking is a practical instrument for turning large-scale mitigation goals into project-scale design guidance. Over the past few years, several WLC benchmark systems were developed worldwide, within certification schemes, national frameworks, and research projects, each relying on their own methodologies and system boundaries, making them heterogeneous and often difficult to compare (Rasmussen et al. 2022; Trigaux et al. 2021). Most benchmarks focus on new construction and on residential buildings, while refurbishments and non-residential buildings are less often considered, as highlighted by Trigaux et al. (2021). When refurbishments are considered, they are often benchmarked on a different scale than new constructions, such as in the Swiss standard SIA 390 (Schweizerischer Ingenieur- und Architektenverein (SIA) 2025). Such differentiated benchmarks do not enable the comparison of e.g. refurbishment vs. equivalent new construction, although the long-term target of net GHG-neutrality apply to both.

This gap is also visible in the German context. Previous studies proposed benchmark-related values for narrower scopes, for example for new office buildings (Braune et al. 2021; Schlegl et al. 2019) or residential target values (Özdemir et al. 2022). Other studies quantified the environmental footprint of the German building sector at an aggregate level, including planetary-boundary perspectives, but did not derive directly actionable benchmark values for broad building application (BBSR & BBR 2020). Similarly, recent work on German benchmarks remains limited for universal application because it focuses mainly on embodied emissions in modules A1–A3 and primarily on new residential and office buildings (Agora Industrie, ifeu, RISE und Ramboll 2024). Overall, there remains a need for a transparent benchmark-definition approach that covers a wider range of building uses, enables comparison between new construction and refurbishment, and supports practical communication beyond expert audiences.

This study addresses that gap by proposing a method to derive WLC benchmark values and communicate them intuitively within one coherent framework. The method is then applied to the German context, for 13 building usage categories. More specifically, the paper develops benchmark classes based on target, reference, and limit values for fossil global warming potential (GWP_{fossil}) over the building life cycle, while also distinguishing between embodied and operational contributions in the communication concept. This method enables the initial design of a universal benchmarking system in relation to a specific building type, which can evolve over time, as scientific knowledge improves (i.e. as more accurate target, reference and limit values are calculated, or more data becomes available).

In the following, the methodological principles required to derive the benchmark values, and the associated communication concept are detailed. Next, the method is applied to the German case study, where the resulting benchmark classes are established. To conclude, the significance, assumptions, limitations, and practical implications of the proposed framework are discussed.

MATERIALS AND METHODS

BENCHMARK DEFINITION PRINCIPLES

The derivation process builds on the general principles of Life Cycle Assessment (LCA) standardised in ISO 14040 and ISO 14044 (ISO 2006a, ISO 2006b). Within the building context, EN 15643 (CEN 2021) is used as the overarching framework for the sustainability

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assessment of construction works, providing the building-level assessment context in which the benchmark methodology is applied. Within this framework, the building life cycle is structured into modules A to D. Modules A to C cover the core cradle-to-grave assessment, including product and construction processes (A), the use stage with maintenance, replacements, and operational energy use (B), and end-of-life processes (C). Module D, by contrast, reports potential benefits and loads beyond the system boundary, such as recycling benefits or exported energy. The benchmark logic from ISO 21678 (ISO 2020) and the implementation guidance from IEA Annex 72 (Lützkendorf et al. 2023b) were also used as reference works.

Three benchmark values were defined for each category: target value (policy-aligned performance objective), reference value (average current performance), and limit value (upper bound). Furthermore, the benchmark was developed under consideration of three key methodological aspects:

- **Differentiation by building types:** Trigaux et al. (2021) find systematic differences between building categories, with significant variations in operational impacts between use types, and with residential buildings showing lower benchmark values as non-residential ones. In terms of embodied carbon, Röck et al. (2022a) also show significant differences in impact level, depending on building usage. Hence, differentiation according to building type is highly relevant.
- **Gross-accounting approach:** In this study, positive GHG emissions refer to all life-cycle emissions that add greenhouse gases to the atmosphere within the assessed building system, including emissions from material production, construction, replacements, operational energy use, and end-of-life processing. Negative GHG emissions refer to accounting items that reduce the reported balance, such as avoided burdens or carbon storage that occur outside the building system. Adopting a gross-accounting approach focusing on positive GHG emissions and accounting for negative emissions separately enables prioritizing intrinsic impact reduction. In practice, this translates into focusing on a cradle-to-grave assessment, including the life-cycle modules A to C according to EN 15643 (CEN 2021). Module D should not be included in the main balance, but reported separately, as recommended by Lützkendorf et al. (2023b). By excluding offsetting credits or avoided burdens such as energy exports (e.g. PV grid feed-ins) or end-of-life recycling benefits, the framework motivates the mitigation hierarchy: sufficiency → efficiency → renewables → offsets. This methodology ensures that net-zero GHG targets are achieved primary through emission reduction rather than relying on future offsets to reach net-zero targets.
- **A unified scale for new constructions and refurbishments:** In this study, refurbishment refers to interventions that retain the main building structure while improving environmental performance through measures affecting the envelope, technical systems, and, where relevant, selected component replacements. This may range from moderate upgrades to deeper energy retrofits. As recent review work shows, renovation strategies vary substantially in scope, functional unit, and assessed measures, with envelope and system upgrades among the most common interventions (Fahlstedt et al. 2024). While retaining existing structures often avoids part of the upfront emissions associated with replacement by new construction, some refurbishment measures, such as added insulation, window replacement, or new HVAC systems, can themselves involve non-negligible embodied emissions (Fahlstedt et al. 2024, Zimmermann et al. 2023). The purpose of the unified scale is therefore to enable comparison between functionally equivalent options under a common whole-life-cycle framework, consistent with the benchmark-setting approach for both new construction and refurbishment projects discussed by Lützkendorf et al. (2023b).

SYSTEM BOUNDARY AND FUNCTIONAL UNIT

The applied functional unit is one square metre of gross floor area (GFA), which includes non-conditioned and conditioned areas. The reference study period (RSP) within this study is 50 years, in accordance with the German standard. In terms of components and life cycle phases considered, a differentiation between new construction and refurbishments

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is proposed. For new constructions, the most relevant modules A1–A3, B4, B6, and C3–C4 shall be considered. For refurbishment, drawing clear system boundaries is more challenging, as underlined in (Kjær Zimmermann et al. 2022). Here, the upfront impact of the already built materials is considered outside the system boundaries. The modules considered are thus A1–A3 of the refurbished materials only, B4, B6 and C3–C4. For both new constructions and refurbishments, Module D should be reported separately, as well as biogenic carbon content. The main environmental indicator used for the benchmark is GWP_{fossil} according to (EN 15804:2012+A2:2019+AC:2021 2022), per square metre of reference area per year. The choice of GWP_{fossil} over GWP_{total} is explained in the following section.

DEFINITION OF TARGET, REFERENCE, AND LIMIT VALUES

Target values

The ISO 21678 (ISO 2020) differentiates between 3 types of target values: short-, medium-, and long-term. Short-term targets are attainable milestones usually tied to current best practices and technical/economic feasibility, whereas long-term targets express the ultimate destination defined by policy or climate goals. Both are necessary because the long-term target sets the required end state, while the short-term target creates a realistic transition path that industry, regulation, and funding can implement and tighten over time.

The long-term target raises the question of what the ultimate goal should be. As evoked in the previous section, the goal is reaching net GHG neutrality by first reducing impacts through sufficiency and efficiency, then using renewables, and finally compensating the remaining impacts. To encourage the sequence of reducing impact before compensating it, the unified, ideal, and unattainable long-term target of the impact zero was chosen. By setting zero as the ultimate target for GWP_{fossil}, striving for impact reduction is held above compensation. In this framework, no negative impact is possible, as no $GWP_{biogenic}$ and no benefits from material recycling or exported energy from module D are accounted for. These need to be accounted separately from the main scale, to enable checking whether the building is really net GHG neutral or not, in a second step.

Concerning the definition of targets, the ISO 21678 (ISO 2020) proposes different methods, from statistics to surveys, demonstration projects and theoretical calculations. While some existing studies adopt a best-in-class approach (Özdemir et al. 2022) focusing on current technical feasibility, others apply a top-down approach based on global planetary boundaries, which enables a clear link to global targets (Habert et al. 2020), while being highly sensitive to the choice of the allocation method (Priore et al. 2025).

Reference values

A central methodological decision was to anchor the reference values for embodied impacts to the average of new constructions, while deriving operational reference values from the existing building stock (including old and new buildings). This distinction is essential for establishing a unified benchmarking scale that allows for the direct and consistent evaluation of new constructions, existing buildings, and energy refurbishments within a single framework.

The rationale behind this approach is as follows:

- Operational impacts are anchored to the average performance of the existing stock, which typically consists of older and less efficient buildings. This represents an “average worst-case” scenario for the operational phase.
- Embodied impacts, on the other hand, are referenced to the average of new constructions, which generally exhibit significantly higher embodied greenhouse gas emissions compared to refurbishment projects. This again represents an “average worst-case” for embodied impacts.

By aligning both dimensions with their respective “worst-case” averages, the benchmark spans the full range of real-world building performance. As a result, any project, whether a highly efficient refurbishment or a new construction, can be positioned within this spectrum. In practice, energy-efficient refurbishments will typically achieve lower total GHG emissions, while new constructions will generally perform less favourably, allowing for transparent and meaningful comparison across all building types.

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In terms of data sources, the ISO 21678 points out toward using statistics, surveys, theoretical calculations, or demonstration project as data basis, as well as regulatory requirements and national standards. Ideally, to get a representative average, large-scale surveys of a statistically significant number of buildings should be prioritised.

Limit values

Limit values can be defined similarly to reference values, by considering maximum statistical values, or alternatively considering upper limitations set by national regulations.

COMMUNICATION CONCEPT

Context and objectives

A central consideration in developing this benchmark communication framework is determining what information to present and how to present it to facilitate meaningful interpretation during early building design stages, when design decisions can have a significant influence on its future impacts. The overarching objective is to provide a framework that is highly accessible to a broad range of stakeholders.

The benchmarking scale

To facilitate clear communication, the calculated benchmark values are mapped onto a discrete performance scale ranging from A to G, aligning with the proposal of the Energy Performance of Buildings Directive (EPBD), as shown in Figure 1. The class boundaries are defined by specific values. At the extremes, Class A represents the highest performance, bounded by a theoretical zero-emission baseline and the medium-term target, while Class G is the least ambitious, encompassing all buildings with emissions exceeding the defined limit value. Intermediate classes are delineated by strategic targets and current practices. Specifically, Class B bridges the medium- and short-term targets, while Class C captures above-average buildings bounded by the short-term target. The reference value, representative of average current practices, serves as the threshold between Class D (slightly above-average performance) and Class E (slightly below-average performance). Boundaries between classes C and D, and E and F, are derived through simple average interpolations of the surrounding values. Fragmenting the scale with these interpolated values enables a more nuanced assessment of typical "average" buildings and a more balanced distribution of the classes over the entire scale. The A-to-G classification is intended to build on the familiarity of existing energy performance certificates and consequently improve the accessibility for practitioners and non-specialist users. At the same time, it should not be interpreted as a direct equivalent to energy-based building classifications. Whereas energy certificates primarily reflect operational energy performance, the present framework assesses whole-life cycle GHG emissions, including both operational and embodied impacts. The two systems are therefore best understood as complementary: a building with strong operational energy performance may still show comparatively high life-cycle emissions due to embodied impacts, while a refurbishment may perform favourably from a WLC perspective despite more limited operational performance.

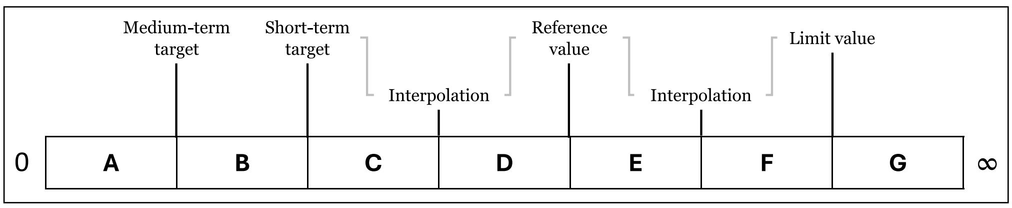

Figure 1 Definition of benchmark classes based on target, reference, and limit values.

Visualisation strategies and LCA best practices

The graphical design of the communication approach should follow established recommendations for design-stage LCA visualisation (Hollberg et al. 2021, Lützkendorf et al. 2023b). While radial or spider charts are suitable for benchmarking multiple indicators, a performance scale or stacked bar chart is the most intuitive format for visualising a single impact indicator, because they clearly display the direction of performance and distance to targets. Furthermore, this framework adopts the best-practice principles for transparent, decision-oriented communication outlined by Lützkendorf et al. (2023b), which highlight:

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- Targeted communication: Tailoring formats to meet the specific requirements of diverse actors, including planners, clients, and policymakers. For this, co-creation processes involving practitioners appear to be the most appropriate approach.
- Data transparency: Separately reporting biogenic carbon content and module D impacts to avoid misinterpretation of the data.
- Visual consistency: Utilising clear, consistent visual structures that support comparability across different projects.

Together, these elements contribute to a robust communication framework that significantly enhances the interpretability, transparency, and practical usefulness of LCA results within the building evaluation process.

CASE STUDY APPLICATION FOR GERMANY

TARGET, REFERENCE, AND LIMIT VALUES DEFINITION

To apply this framework to the German context, data was first gathered on building typologies and on target, reference, and limit values for both operational and embodied emissions. Building typologies were categorised using the framework from Hörner and Bischof (2022) for non-residential buildings (11 categories) and Stein et al. (2025) for residential buildings (grouping single- and two-family houses into one category, and multi-family houses into another).

Because these foundational studies rely respectively on large-scale surveys and robust building stock modelling, they served as the basis for determining reference and limit values for the operational impact. Specifically, average building stock emissions derived from these studies were used as operational reference values. To establish operational limit values, the maximum of the statistical distribution for non-residential buildings was used. For residential buildings, lacking comparable statistical distributions, the limit value was defined using the operational emissions of an archetypal building from the least efficient age class (pre-1978) heated by heating oil, the most common high-emitting fuel source, to depict a worst-case scenario for the end of the scale. Climatic differentiation was not introduced at this stage of the benchmark development. The proposed values should therefore be understood as national average benchmarks by building type, rather than as climate-specific thresholds.

In the absence of German-specific literature deriving operational and embodied target values from planetary boundaries, Swiss values from the SIA 390 standard were adapted (Schweizerischer Ingenieur- und Architektenverein (SIA) 2025), converting the RSP from 60 to 50 years by distributing the total impacts over the new RSP, and converting the reference floor area from the conditioned floor area to the gross floor area using a proportionality factor of 0.9, in compliance with (Bundesamtes für Umwelt (BAFU) 2016). Although the German and Swiss energy grids differ, the material and construction standards as well as the cultures and habits (Roose 2010) are sufficiently aligned to use SIA 390 as a robust initial proxy for embodied carbon targets.

Finally, due to a lack of statistically representative data for embodied emissions in German buildings, the average values for new constructions of a mix of EU buildings from the analysis of Röck et al. (2022b) were used as reference values. Embodied emission limit values were defined as the maximum of the statistical distributions for each building type within this study.

Where specific building types were unrepresented in the literature, custom assumptions were applied. A comprehensive list of these assumptions is provided in the supplementary material.

RESULTS

Embodied, operational and Whole Life Cycle benchmark values

The comprehensive benchmark values, differentiated by building typology, are presented in Figure 2 as a value table, and in Figure 3 as stacked bar charts. The WLC benchmark results from the aggregation of the operational and embodied emissions.

The resulting performance ranges show substantial variation across use categories. Residential buildings form the lower end of the scale, with the beginning of class G at 54.5 kg $CO_2e/(m^2GFA \cdot a)$ for multi-family houses and 61.4 kg $CO_2e/(m^2GFA \cdot a)$ for single- and two-family houses. The highest values occur in use categories with intensive or specialised operation, particularly Buildings for Culture and Leisure; Hotels, Boarding, Restaurants or Catering, and Production, Workshop, Warehouse or Operations, with class-G thresholds of 194.1, 181.4, and 175.5 kg $CO_2e/(m^2GFA \cdot a)$, respectively. This pattern is consistent with previous benchmark reviews, which show that residential buildings generally have lower full-life-cycle GWP benchmarks than non-residential buildings, and that the spread between building types increases when operational emissions are included (Trigaux et al. 2021, Rasmussen et al. 2022).

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	Ideal long-term target	A	Medium-term target	B	Short-term target	C	Inter-polated value 1	D	Ref. value	E	Inter-polated value 2	F	Limit value	G
Multi-family houses	op 0 emb 0 wlc 0		op 2.2 emb 5.4 wlc 7.6		op 3.3 emb 7.6 wlc 10.8		op 14.9 emb 10.3 wlc 25.1		op 26.6 emb 12.9 wlc 39.4		op 30.7 emb 16.3 wlc 46.9		op 34.9 emb 19.6 wlc 54.5	
Single- and two-family houses	op 0 emb 0 wlc 0		op 2.2 emb 5.4 wlc 7.6		op 3.3 emb 7.6 wlc 10.8		op 18.7 emb 8.8 wlc 27.4		op 34.1 emb 10 wlc 44		op 41.1 emb 11.6 wlc 52.7		op 48.2 emb 13.3 wlc 61.4	
Trade Buildings	op 0 emb 0 wlc 0		op 3.3 emb 5.4 wlc 8.7		op 6.5 emb 7.6 wlc 14.1		op 24 emb 9.4 wlc 33.3		op 41.4 emb 11.1 wlc 52.5		op 62.8 emb 12.5 wlc 75.2		op 84.2 emb 13.9 wlc 98	
Office, Administrative or Government Buildings	op 0 emb 0 wlc 0		op 3.3 emb 5.4 wlc 8.7		op 4.4 emb 7.6 wlc 11.9		op 22 emb 9.6 wlc 31.5		op 39.6 emb 11.5 wlc 51		op 60.3 emb 14.8 wlc 75		op 81.1 emb 18 wlc 99.1	
Sports Facilities	op 0 emb 0 wlc 0		op 2.6 emb 5.4 wlc 8		op 3.6 emb 7.6 wlc 11.2		op 21.4 emb 11.7 wlc 33		op 39.2 emb 15.7 wlc 54.8		op 59.2 emb 18 wlc 77.1		op 79.3 emb 20.2 wlc 99.4	
Technical and Utility Buildings (supply and disposal)	op 0 emb 0 wlc 0		op 3.3 emb 5.4 wlc 8.7		op 4.4 emb 7.6 wlc 11.9		op 25.4 emb 9.4 wlc 34.7		op 46.4 emb 11.1 wlc 57.5		op 68.3 emb 12.5 wlc 80.7		op 90.1 emb 13.9 wlc 103.9	
School, Day Nursery and other Care Buildings	op 0 emb 0 wlc 0		op 2.6 emb 5.4 wlc 8		op 3.6 emb 7.6 wlc 11.2		op 24.5 emb 10.8 wlc 35.2		op 45.4 emb 13.9 wlc 59.2		op 66.5 emb 20.4 wlc 86.8		op 87.5 emb 26.9 wlc 114.4	
Transport Buildings	op 0 emb 0 wlc 0		op 3.3 emb 5.4 wlc 8.7		op 4.4 emb 7.6 wlc 11.9		op 25.2 emb 14.9 wlc 40.1		op 46 emb 22.2 wlc 68.2		op 71 emb 24.9 wlc 95.8		op 95.9 emb 27.7 wlc 123.5	
Buildings for Health and Care	op 0 emb 0 wlc 0		op 6.5 emb 5.4 wlc 11.9		op 8.7 emb 7.6 wlc 16.2		op 32.5 emb 11.6 wlc 44.1		op 56.4 emb 15.6 wlc 71.9		op 86.5 emb 18.4 wlc 104.9		op 116.6 emb 21.3 wlc 137.8	
Buildings for Research and University Teaching	op 0 emb 0 wlc 0		op 2.7 emb 5.4 wlc 8.1		op 3.8 emb 7.6 wlc 11.4		op 28.9 emb 10.2 wlc 39		op 54 emb 12.7 wlc 66.7		op 87.5 emb 17.6 wlc 105.1		op 121.1 emb 22.5 wlc 143.5	
Production, Workshop, Warehouse or Operations	op 0 emb 0 wlc 0		op 3.3 emb 5.4 wlc 8.7		op 4.4 emb 7.6 wlc 11.9		op 35.5 emb 9.4 wlc 44.8		op 66.6 emb 11.1 wlc 77.7		op 114.1 emb 12.5 wlc 126.6		op 161.7 emb 13.9 wlc 175.5	
Hotels, Boarding, Restaurants or Catering	op 0 emb 0 wlc 0		op 6.5 emb 5.4 wlc 11.9		op 8.7 emb 7.6 wlc 16.2		op 37.4 emb 11.6 wlc 48.9		op 66 emb 15.6 wlc 81.6		op 113.1 emb 18.4 wlc 131.5		op 160.2 emb 21.3 wlc 181.4	
Buildings for Culture and Leisure	op 0 emb 0 wlc 0		op 2.6 emb 5.4 wlc 8		op 3.6 emb 7.6 wlc 11.2		op 32.2 emb 10.8 wlc 42.9		op 60.7 emb 13.9 wlc 74.5		op 114 emb 20.4 wlc 134.3		op 167.3 emb 26.9 wlc 194.1	

Figure 2 Values of class boundaries for operational (op), embodied (emb) and whole-life cycle (wlc) emissions GWP_{fossil} in kg $CO_2e/(m^2_{GFA} \cdot a)$.

As is characteristic of the current building stock, operational emissions constitute the most significant share of the total WLC values. This is especially visible for non-residential categories with long operating hours, higher ventilation and lighting requirements, cooling demand, hot-water demand, hygiene requirements, or process-related energy use. By contrast, residential buildings, particularly multi-family houses, typically benefit from lower demands for lighting, cooling, and process-related energy consumption. This dominance is further accentuated by the static calculation approach, which evaluates current conditions without considering the future decarbonization of energy grids.

Concerning embodied carbon, the findings confirm already known aspects from the literature, namely the importance of the building type, reflecting variations in structural systems, material choices, and technical equipment, (Röck et al. 2022a, Röck et al. 2022b). In the present benchmark set, higher embodied limits occur for Transport Buildings; School, Day Nursery and Care Buildings; Culture and Leisure buildings, and Research and University buildings. These use types often involve larger spans, higher structural or functional requirements, more complex envelopes, and more complex technical installations. The observed differences therefore confirm that WLC benchmarks should be interpreted within a clearly defined functional context rather than as a universal ranking across all buildings.

The applied methodology leads to performance classes of varying widths. As illustrated in Figure 3, the average classes C and D are quite broad while the more ambitious A and B are narrower. This non-linear approach is a direct consequence of the method used to define the class boundaries, with target, reference, limit, and interpolated values. It fits with the principle of diminishing returns in decarbonization: as total impacts decrease, further reductions become increasingly technically challenging. Consequently, a 1 kg CO_2e reduction is effectively weighted higher within a more ambitious performance class (e.g., Class B) compared to a lower-performance class (e.g., Class D).

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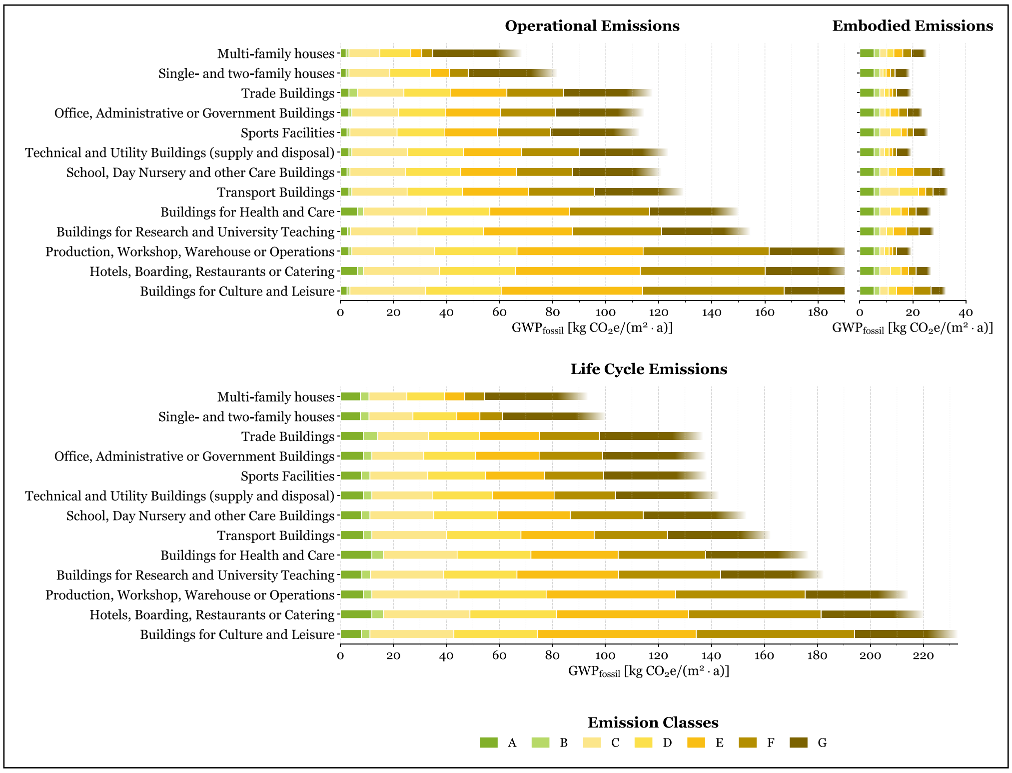

Figure 3 Benchmark classes for WLC emissions (GWP_{fossil}) differentiated by building use.

To further illustrate the balance between operational and embodied emissions, Figure 4 shows the embodied share of total WLC emissions, calculated as embodied emissions divided by the sum of operational and embodied emissions. The results highlight a clear trend: the more ambitious the WLC performance class, the more significant the embodied share becomes. In the higher-performing classes, operational emissions are strongly reduced, so the remaining embodied impacts represent a larger proportion of the total footprint: from about half to a maximum of 71% of WLC impacts for the medium- and short-term targets, depending on the building type. By contrast, embodied shares range only from 14% to 33% for the reference values, and from 8% to 36% for the limit values. This indicates that, while operational emissions dominate the current average and limit values, a focus on embodied carbon becomes increasingly decisive for achieving target classes A and B.

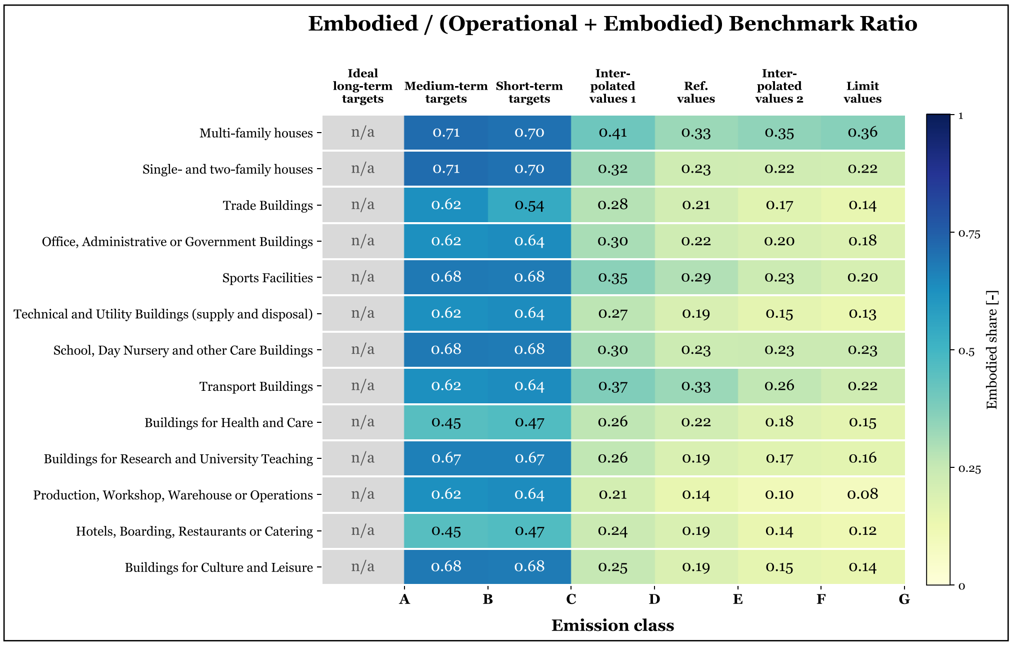

Figure 4 Embodied share of total WLC emissions (GWP_{fossil}), calculated as embodied / (operational + embodied), differentiated by building use and benchmark class boundaries.

To put these benchmarks into perspective, a comparison was made with the currently most widely used German target values from the certification scheme QNG (BMWSB 2023). For new residential buildings, the standard target lies at 24 kg CO_2e/m²a and the ambitious target at

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20 kg CO_2e/m^2a, based on net floor area. A rough conversion to gross floor area values using a 0.9 proportionality factor leads to 21.6 kg CO_2e/m^2a and 18 kg CO_2e/m^2a, both of which would correspond to the benchmark category C (better than average, but still far from the short-term target value of 11 kg CO_2e/m^2a).

Communication concept

The strategy for communicating a benchmark depends heavily on its intended application and target audience. In this study, the benchmark was developed for the LezBAU project (Fkz: 03EN1074 A, 2026), which aims to create a free, intuitive online LCA tool for the German context. The tool is designed for use in the early design phases as formalised by Lützkendorf et al. (2023a), which include strategic definition, preliminary studies and concept design. It should allow a broad audience (including architects, construction professionals, and non-experts) to quickly analyse both new constructions and refurbishment measures. Consequently, the benchmark is intended to deliver easily interpretable results, highlighting key emissions data to help users get a straightforward overall picture of the project's impacts. Created in collaboration with architects, this communication concept translates the benchmarking framework into an intuitive, multi-layered dashboard (see Figure 5, illustrating a fictive dataset). This design balances broad accessibility with the technical transparency expected by sustainability professionals.

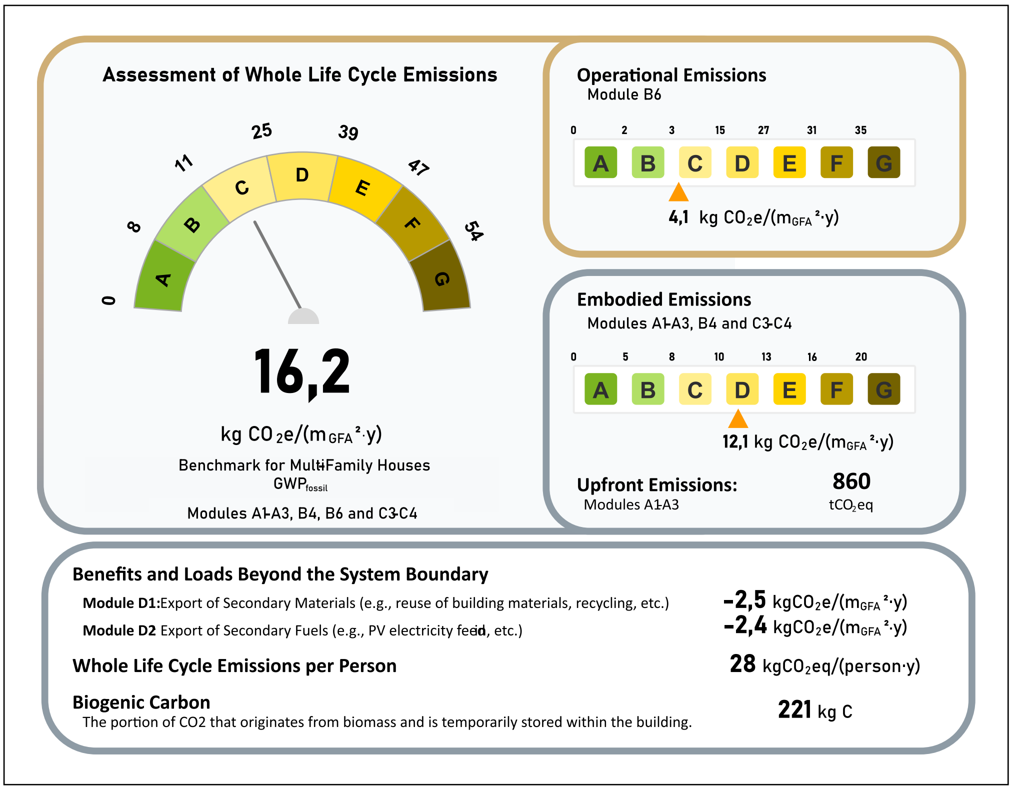

Figure 5 Benchmarking dashboard for results visualisation (fictive dataset).

The dashboard design is defined by several key features:

- Intuitive gauge-style scale: The primary WLC assessment is displayed using a speedometer-style radial gauge. This familiar analogy allows stakeholders to immediately and intuitively interpret the building's total life-cycle performance at a glance.
- Distinctive A–G scaling: The tool utilises the above-mentioned A to G performance scale with a colour gradient that echoes traditional Energy Performance Certificates (EPCs). However, it deliberately employs a different overarching shape and colour palette to ensure clear visual differentiation from operational energy ratings.
- Emission breakdown: To help directly identify hotspots and areas for improvement, the interface disaggregates the total WLC score into operational and embodied emissions, displayed on their own individual linear scales.

- Methodological transparency: The visualisation actively deters misinterpretation by explicitly stating important key scope features. This includes the precise life-cycle modules evaluated (e.g., A1–A3, B4, B6, C3–C4), the functional unit (kg $CO_2e/(m^2_{GFA}\cdot a)$), and the specific building use category the scale applies to.
- Adhering to established best-practice recommendations (Lützkendorf et al. 2023b), the framework ensures that biogenic carbon content and Module D (D1 and D2) are reported separately from the core footprint. Furthermore, it incorporates an "impact per person" metric to actively incentivize sufficiency.

DISCUSSION AND CONCLUSIONS

This study develops a transparent framework for deriving and communicating WLC greenhouse gas benchmarks for different building use types. The framework combines target, reference, and limit values in order to distinguish between policy-aligned performance, current average performance, and high-impact buildings. Its main contribution is not to present a final normative benchmark dataset, but to show how available carbon-budget and building-stock data can be translated into a usable benchmarking structure for early design support.

A first key aspect of the framework is the differentiation of WLC benchmarks by building use type. The German case study shows that benchmark values differ substantially between use categories. residential buildings show the lowest values, while categories such as transport buildings and buildings for culture and leisure show considerably higher values. This confirms that carbon performance cannot be meaningfully assessed through a single generic benchmark for all buildings. Differentiation by use type allows buildings to be evaluated within an appropriate functional context and avoids masking differences in operational demand, technical requirements, occupancy patterns, and service intensity.

A further contribution is the use of one common WLC scale for both new construction and refurbishment. This is important because climate-oriented building strategies increasingly require decisions between constructing, replacing, or renovating existing buildings. A shared benchmark logic makes these options more comparable and helps shift the assessment from isolated measures to overall life-cycle performance. At the same time, refurbishment is not a homogeneous category. Light, moderate, and deep renovations differ in embodied emissions, operational savings, technical constraints, and functional outcomes. The proposed scale should therefore be understood as a tool for comparing functionally equivalent options under clearly stated assumptions.

The results also show that operational impacts remain the dominant share of WLC emissions. This reflects current German building-stock and energy-system statistics, and it is influenced by the static calculation approach used in this study. Further investigations could focus on the dynamic modelling of future changes in climate, as well as in electricity and district heat mixes over the reference study period.

Several assumptions influence the proposed benchmark values. The choice of a 50-year reference study period follows the German case-study context and enables alignment with established national assessment practice. The method itself, however, is not limited to this time horizon. If applied in contexts using different assumptions, such as 30-year periods discussed in broader European policy contexts for residential buildings, the benchmark values would need to be recalculated. In practice, shorter RSPs increase the relative importance of embodied emissions for construction and end-of-life, whereas longer RSPs increase the influence of operational emissions and replacement cycles. The current benchmark does not differentiate between climatic zones. Future applications could address this by introducing climate-zone-specific operational benchmarks or correction factors.

The approach combines German stock models, adapted Swiss target values, and European embodied-emission datasets, that were harmonised as far as possible. Although residual differences remain regarding system boundaries, geographical scope, and data quality, such transparent proxy-based benchmarks can already support comparison between buildings, learning, and design decisions, while indicating where better empirical datasets are most urgently needed.

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Future work should validate and calibrate the proposed target, reference, and limit values using larger and more representative datasets of German buildings. Benchmark values should ideally be generated from consistent calculations across building types, energy-efficiency levels, construction systems, and technical building-services configurations. Future development should also extend the indicator scope beyond GWP_{fossil} to avoid burden shifting, either through separate indicator-specific benchmarks or through a transparent aggregated metric (e.g., eco-points (Ahbe et al. 2018, Frischknecht et al. 2006)), and should explore sufficiency-based benchmarks, for example expressed per person.

The communication concept is another contribution of the study. By translating WLC results into an A–G class structure, a dashboard, and separate embodied and operational indicators, the framework makes complex LCA results more accessible to architects, planners, and other decision-makers. The resemblance to familiar energy-class systems supports intuitive interpretation, and the two instruments can be complementary: energy certificates describe operational energy performance, while carbon-based benchmark classes address greenhouse gas emissions over the building life cycle. This complementarity creates opportunities for practical and policy use beyond the original benchmark development context of the LezBAU project (Fkz: 03EN1074 A, 2026). In particular, the proposed label and dashboard could inform renovation planning, funding schemes, and emerging instruments such as the EU Building Renovation Passports, by making embodied carbon visible alongside operational energy consumption. The separate reporting of embodied emissions, operational emissions, biogenic carbon, Module D effects, and impact per person is essential in this context, as it prevents a black-box approach and helps identify appropriate improvement strategies.

In conclusion, the study shows that WLC benchmarks can be made both methodologically transparent and practically communicable. Its main contribution lies in combining use-type-specific benchmark values, a common scale for new construction and refurbishment, the pragmatic use of currently available data, and an accessible communication concept. Although the proposed values require further validation, the framework offers a usable basis for comparing building variants, communicating carbon performance, and supporting early design and policy decisions. By connecting benchmark derivation with practical communication, the study aims at making life-cycle carbon assessment more actionable for building practice and policy.

DATA ACCESSIBILITY STATEMENT

Data repository: https://github.com/IWUGERMANY/WLC-Benchmarks-for-German-Domestic-and-Non-Domestic-Buildings.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplementary Material.** GWP Benchmarks. DOI: https://doi.org/10.66506/essp.7-012-26.s1
- **PowerPoint Slides.** PowerPoint Slides relating to this article. DOI: https://doi.org/10.66506/essp.7-012-26.s2

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COMPETING INTERESTS

The authors have no competing interests to declare.

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AUTHOR CONTRIBUTIONS

Guillaume Behem: Conceptualization, methodology, investigation, formal analysis, writing – original draft, visualisation. Julian Bischof: Conceptualization, methodology, investigation, writing – review & editing, project administration, funding acquisition.

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