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Existing benchmark systems for assessing global warming potential of buildings – Analysis of IEA EBC Annex 72 cases

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Abstract. Life cycle assessment (LCA) is increasingly being used as a tool by the building industry and actors to assess the global warming potential (GWP) of building activities. In several countries, life cycle based requirements on GWP are currently being incorporated into building regulations. After the establishment of general calculation rules for building LCA, a crucial next step is to evaluate the performance of the specific building design. For this, reference values or benchmarks are needed, but there are several approaches to defining these. This study presents an overview of existing benchmark systems documented in seventeen cases from the IEA EBC Annex 72 project on LCA of buildings. The study characterizes their different types of methodological background and displays the reported values. Full life cycle target values for residential and non-residential buildings are found around 10-20 kg $CO_2e/m^2/y$, whereas reference values are found between 20-80 kg $CO_2e/m^2/y$. Possible embodied target- and reference values are found between 1-12 kg $CO_2e/m^2/y$ for both residential and non-residential buildings. Benchmark stakeholders can use the insights from this study to understand the justifications of the background methodological choices and to gain an overview of the level of GWP performance across benchmark systems.

Keywords: Buildings, LCA, Benchmarking, Global Warming Potential

1. Introduction

After decades with a primary focus on reducing operational energy demand of buildings, the use of LCAs is increasingly being applied to evaluate the life cycle environmental performance of buildings. In particular, the urgent need to curb greenhouse gas emissions and the associated global warming potential (GWP) of all human activities has led to several life-cycle oriented initiatives from building stakeholders, such as public authorities, industry organizations, as well as research. In most cases, the initiatives about evaluating and improving a building's GWP performance are voluntary. However, authorities in several countries are currently implementing or preparing legal binding regulations including limit values for GWP from individual buildings[1]. The performance evaluation of individual building projects is made in relation to specific benchmarks, i.e. reference points against which comparisons can be made. These benchmarks are often specific to a national or sub-national context, determining the method, data and tools that apply for an evaluation to be representative and fair across several building projects[2]. Despite differences between benchmarking systems, a range of general learning about methodological choices and points-of-attention exists. To enable more widespread creation and implementation of GWP benchmarks for buildings, core learnings from existing benchmark systems may provide valuable inspiration and knowledge for benchmark developers.

More than 50 international experts in the Annex 72 international research project “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (2017-2022) of the IEA EBC (International Energy Agency Energy in Buildings and Communities Programme) have worked on harmonized methods, tools, processes, and reporting formats for LCA in buildings [3]. A part of this work dealt with a thorough analysis of existing benchmarking schemes, providing detailed insights of benchmarking systems in practice.

The aim of this paper is to provide benchmark developers with core insights and recommendations for generating new benchmarks by:

1) Providing an in-depth overview of systems characteristics, methodological choices, and points of attention from existing GWP benchmark
2) Establishing an overview of the GWP benchmark values currently in use

2. Methods

The analysis of system characteristics and methodological choices from existing GWP benchmarks for buildings is based on detailed information provided from 17 Annex 72 cases, representing benchmark values from Australia (AU), Belgium (BE), Canada (CA), Switzerland (CH). Czech Republic (CZ), Germany (DE), Denmark (DE), Spain (ES), France (FR), Hungary (HU), Netherlands (NL), Norway (NO), New Zealand (NZ) and Sweden (SE). The data collection was done by use of a spreadsheet template structured to communicate the type of benchmark system, reference units, system boundaries and methods, as well as actual benchmark values. Benchmark values can be in the format of limit, reference or target values, and the data collection for this study is based on implemented benchmarks, as well as on cases expressing best-practice and reference values, i.e. performance values representing the state of the art. In both cases, for reference values as well as for benchmark values, the core part of considerations about method is comparable.

The benchmark cases represent the main categories of residential and non-residential buildings. Within residential buildings there are single-family houses as well as multi-family houses. Within non-residential buildings there are offices, schools, retail, nurseries, health care centers and others. Hence a large spread in use type. The majority of the building cases behind the benchmarks are built in the period of 2010-2020, although a few cases are 5-10 years older.

Following the data collection of each benchmark system, expert sessions were conducted to further explore the methodological choices in play, and to uncover the issues and problems that the experts saw as part of the benchmark development. Expert sessions were conducted at two occasions as part of the scheduled, semi-annual, Annex 72 expert meetings. Feedback on the topics of reference unit, system boundaries, and calculation rules were recorded in minutes, and form the background of the discussion points in this paper. It is important to note that several of the Annex 72 benchmarks documented here are still under development, especially in the cases where regulations are currently being prepared. An in-depth Annex 72 report about existing benchmarks will be published late 2022.

In the mapping of GWP benchmark values in use, part of the data was from the filled-in spreadsheet templates. All reported benchmark values were harmonized to net floor area, by use of a conversion factor of 0.8 [as in 4,5] for the cases originally reported in gross floor area.

3. Results and discussion

3.1. Benchmark system characterization

Table 1 presents the basic characteristics of the Annex 72 benchmark cases. Based on the mapped characteristics, a number of core methodological choices for the generation of benchmarks are unfolded below.

3.1.1. Archetypes or real building cases as background source? The two main sources to derive benchmarks based on a bottom-up approach are the use of archetypical buildings (based on building models) and the use of real building cases. Each of these sources have pros and cons in terms of being representative. As explained by Flyvbjerg [6], a random selection of cases (of real buildings in this context) may avoid systematic bias. However, the size of the sample is crucial for generalization. In the case of archetypes, a building case may quite accurately represent the archetypical, or the 'most common', type of building and be used as a baseline. However, environmental impacts from materials as well as energy use can vary notably depending on the exact design choice, hence diverging considerably from the results of the defined archetype. As seen from the Annex 72 cases in Table 1, several of the archetypical approaches further diversify the samples by varying important parameters such as climate zone and material use. The possibility of controlling the variation, e.g. concerning climate zones, can be seen as an explicit advantage of the archetypical model approach. In contrast, it is more difficult to control the variations of a sample of real buildings. However, the use of real buildings for benchmark derivation could ensure a more accurate representation of reality.

3.1.2. Which type of reference unit to choose? The prevalent way of defining the functional equivalent in the Annex 72 benchmark cases is based on reference units to assess the impacts per m^2 floor area distributed over a reference study period of 50-60 years. Table 1 further specifies the provided definitions of the m² floor area for the different cases. A notable diversity is apparent, mainly centred on variations of gross, net and heated floor areas (GFA, NFA and HFA respectively). However, since there is no common terminology or standards on calculating the different types of floor area, this varies across countries.

A central argument about the use of m^2 floor area as reference unit is the relation to existing schemes and regulations. In particular, the energy regulations for building operation are tied to specific ways of defining reference areas of GFA, NFA or HFA. Using the heated/conditioned floor area as a reference unit for embodied impacts is convenient, because the operational energy relates to this area anyway. Further, harmonizing impacts from a building over the heated/conditioned floor area is more closely related to the user perspective. This is because the heated/conditioned floor area is where the human activities take place whereas non-conditioned spaces are for parking, storage etc. In this line of argument, additional m^{2}s in non-conditioned spaces serve a somewhat secondary function.

Using the GFA as a reference unit may be seen as more closely tied to the inventory of materials used in the whole building. However, the inclusion of large non-conditioned spaces, e.g. basements, has been seen to generate inconveniently large differences across projects, which makes it difficult to evaluate them within the same levels of performance per m^2.

From a practical perspective it is more convenient to operate a benchmark system with just one reference unit. However, reporting results with more than one reference unit (e.g. HFA and GFA) can potentially ensure that secondary qualities of the buildings are also taken into account. To ensure more focus on the user perspective, it is recommended to also evaluate results on a per-user basis. This expands the perspective from evaluating eco-efficiency onto evaluating sufficiency, which is closer related to the aspects of planetary boundaries.

Table 1 (next page). Basic characteristics of the Annex 72 benchmark cases. Life cycle stages per module as defined by EN 15978. Scope of building elements included defined as (S) structure; (F) foundation; (I) internal elements; (B) building services

Case	Based on	Background	Reference unit	m^2 specification	Reference study period	Life cycle stages included	Building scope
AU	Typical building in varying climate zones	Academic purpose	Impacts/m^2/year	Internal floor area including garage	50	A1-A5, B2, B4, B6$^{1-2}$, C1-C4	SFIT
BE	Statistics based on 35 archetypes	Research project on environmental benchmarks	Impacts/m^2/year	Heated floor area	60	A0-A5, B2, B4, B6$^{1-3}$, B8, C1-C4	SFIT
CA	Statistics based on 10 buildings	Research pilot project	Impacts/m^2	Gross Internal Floor Area	60	A1-A5, B2, B4, C1-C4	SFI
CH	Statistics based on real building Goals of '2000 Watt society'	SIA Technical bulletin 2040 SIA energy efficiency path	Impacts/m^2/year	Energy Reference Floor Area	60	A1-A3, B4, B6$^{1-2}$, C1-C4	SFIT
CZ	Embodied: Statistics based on 200 buildings Operational :Statistics based on archetypes in 400 variations	SBToolCZ	Impacts/m^2/year	Gross Internal Floor Area	50	A1-A3, B6^1	SFI
DE1	Statistics based on 19 real buildings	Bewertungssystem Nachhaltiger Kleinwohnhausbau (BNK)	Impacts/m^2/year	Gross Internal Floor Area (NRF)	50	A1-A5, B1-B5, B6^1, C1-C4	SFIT
DE2	Statistics based on 100+ real buildings	DGNB certification system 2018	Impacts/m^2/year	Gross Internal Floor Area	50	A1-A3, B2, B4, B6^1, C3-C4, D	SFIT-
DE3	Statistics based on archetypes in 150 variations	Bewertungssystem Nachhaltiges Bauen (BNB) 2015	Impacts/m^2/year	Gross Internal Floor Area (NRF)	50	A1-A3, B2, B4, B6^1, C3-C4	SFIT
DE4	Statistics based on archetypes in 50 variations	Qualitätssiegels Nachhaltiges Gebäude (QNG) 2021	Impacts/m^2/year	Gross Internal Floor Area (NRF)	50	A1-A3, B4, B6^{1+3}, C3-C4, D	SFIT-
DK	Statistics based on 60 real buildings	Academic purpose. Study specific (resembles the DGNB-DK approach)	Impacts/m^2/year	Gross Floor Area	50	A1-A3, B4, B6^1, C3-C4	SFIT-
ES	Statistics based on 7 real buildings	Academic purpose.	Impacts/m^2	Gross Internal Floor Area	50	A1-A5, C1-C4	SFIT
FR	Statistics based on archetypes in 20.000+ variations	Equer, www.izuba.fr	Impacts/m^2/year	Net Internal Floor Area	100 50	A1-A5, B4, B6$^{1-3}$, B7,C1-C4, D	SFIT
HU	Statistics based on archetypes in 6000 variations	Academic purpose	Impacts/m^2/year	Heated Internal Floor Area	50	A1-A5, B3, B4, B6^1, C1-C4	SFIT
NL	Statistics based on 5 residential archetypes Statistics based on 5 real office buildings	Milieu Prestatie Gebouwen	€/m^2	Gross Internal Floor Area	75 50	A1-A5, B1-B5, C1-C4	SFIT
NO	Statistics based on 129 real buildings	ZEN Case: GHG emission requirements for material use in buildings	Impacts/m^2/year	Heated floor area	60	A1-A3, B4, B8	varies
NZ	Statistics based on 66 real buildings	Whole-building whole-of-life framework / LCAQuick	Impacts/m^2/year Impacts/occupant	Treated floor area Gross floor area Net lettable floor area	90 60	A1-A5, B2, B4, B6$^{1-3}$, B7, C1-C4, D	SFIT
SE	Statistics based on 68 real buildings	Research work for national authorities	Impacts/m^2	Gross floor area Heated floor area	N/A	A1-A5	SFIT(-)

3.1.3. Which type of reference study period to choose? Concerning the reference study period (RSP), all cases reported in the Annex 72 examples use a reference study period of 50-60 years for at least one of the building types in focus (see Table 1). FR, NZ and NL furthermore apply a longer reference study period of 75-90 years for residential buildings. The longer reference study periods such as 75-120 years can be characterized as emphasizing the technical service life of the building. Arguments for a longer study period are to avoid programmed obsolescence and be in line with e.g. the Eurocodes requiring durable structures [7]. A central argument for using a shorter RSP, such as 30 years, is the alignment with the shorter time span used in life cycle costing. Further, the use of 30 years may be seen as representing a generational perspective, i.e. the consequences (impacts) of choices (concerning the specific building) are dealt with within the temporal perspective of one generation. The opposite is the case for longer service lives, such as 120 years, in which impacts are distributed over an extended time period, spanning multiple generations [8].

Arguments for RSPs around 50-60 years include the opportunity to cover 1 to -3 replacement cycles of the materials and components that are more frequently replaced, e.g. windows and technical systems. This type of lifespan definition may thus be seen as a compromise solution between a one-generation perspective and taking into account the durability of the building design.

No general recommendations can be made for the choice of RSP to a benchmark system, because this choice is context dependent and value-based. Regardless of the chosen RSP for a specific benchmark system, however, it is important to transparently communicate how the RSP relates to the expected service life of the building. This explanation of method choices versus service life projections could counteract misconceptions among benchmark users and industry.

3.1.4. Which life cycle stages to include? Table 1 displays the life cycle stages included in the reported cases of the Annex 72. Worth noting is that the only stage included in all systems is the product stage (modules A1-A3). 12 of the 15 cases further include the B4 replacement module and 12 include the waste treatment/disposal modules (C3-C4). 10 systems include the initial A4-A5 transport and construction modules. Nine systems include the B6 operational energy use, although it differs to which extent the scope of B6 is delimited, i.e. including only regulated, operational energy use (B6.1) or also including non-regulated energy use (B6.2) and user-specific energy use (B6.3). Three of the reported systems include module D, the benefits and loads beyond the system boundary. Of these, DE2 and FR integrate the impact of module D into the final results, whereas NZ reports module D separately. Further, in the CH and NO cases, user transport is also included as a B8 module, i.e. the estimated personal transport related to the users of the building.

Ultimately, the choice of life cycle stage modules for a benchmark system depends on the purpose and context of application. However, some important points of attention should be noted for consideration in the creation of benchmarks:

- The inclusion of the modules for production (A1-A3), transport to site (A4), and construction (A5) are related to emissions and resource use that are taking place right now. These current emissions are in focus in several countries aiming for ambitious GHG reductions via building regulations, such as Sweden.
- Inclusion of the replacement module B4 is critical, especially in the case of highly energy efficient and/or net zero emission buildings. Frequently replaced materials and components in the building may significantly affect the life cycle impacts. This is for instance the case for several components of the technical installations.
- Energy use (B6) generally has a large impact on the overall results of a building LCA. It should be carefully specified which part(s) of the energy use is included. Recent definitions, included in the context of the revision of EN 15978 standards, provide the basic descriptions for declaring this.
- Inclusion of EoL modules C3-C4. In the cases where the nationally applied impact assessment data for the production of materials include the storage of biogenic carbon (e.g. wood), it is

crucial to have the mass balances restored in a life cycle perspective. Hence, the inclusion of modules C3-C4 is needed to counterbalance the uptake of carbon during the production.

- Module D. If the cut-off allocation approach of the EN 15978 is used for the background data, standards require values from module D always to be reported separately. Otherwise, there is a risk of double-counting the potential benefits occurring between systems, except if e.g. a 50/50 method is applied [9].

Benchmark developers are recommended to display module-based subsets of the benchmark values as guiding values for building designers. These guiding values encompass up-front embodied GWP (modules A1-A5), operational GWP (module B6), use stage embodied GWP (modules B1-B5) and end-of-life GWP (modules C1-C4).

3.1.5. How much of the building scope to include? The completeness of the inventory model affects the final results. In general, the more complete the model, the higher the resulting potential impacts and resource uses from the assessed building (see e.g. [10]). The specific regulatory and practice context can influence the material scope applied. For instance, if ease-of-application for benchmark users is important for the benchmark system, a limited scope of inventory can be applied. Simplifications of this kind include for instance:

- A scope including only the building shell. Because the information about the building shell is often easily available via mandatory energy demand calculations
- Disregarding technical systems. Because there is limited availability of generic data on technical aggregates and distributions systems

However, disregarding whole categories of building elements/components, such as the technical equipment (e.g. HVAC), may seriously bias results and underestimate the actual impacts of the buildings. In cases where foreground data is sparse, e.g. amounts of technical installations per m^2 building, these elements are sometimes added to the building model with default values.

In Table 1, the reported inventory scopes of the Annex 72 cases are presented. 11 of the 15 reported systems include space delimiting building elements as well as technical services. One of the 11 explicitly states the limitation of only central technical aggregates being included. 3 of the 15 do not include technical installations and services. The NO case reports a mixed inventory scope from the sample behind the reported benchmark values.

The exact description of included building elements is also challenged, on a more general level, by the lack of standardized classification of building decomposition terminology [11]. Although this may be standardized on national levels, in-practice use may diverge from this due to company workflows, for instance concerning digital building models [12]. This may lead to diverging perceptions of what is actually included in a system, and thus complicates the correct application of a benchmark system by the users. Confusion may especially concern the inclusion/exclusion of: fixtures and fittings, sealings and beadings, concealed cables/wirings, pipes and ducts, plumbing and drainage, fixed furniture.

Benchmark developers must provide detailed descriptions of the inventory scope, for benchmark users to apply assessments correctly within a specific benchmark system.

3.1.6. Which scenarios and calculation rules to apply? Scenarios and assumptions are relevant in the detailed modelling of life cycle stage modules, specifically in the cases where no representative data exist. For modules A1-A5 in the Annex 72 cases, the reported assumptions concern the distances and transport modes for A4, transport to construction site. The assumptions about distances lie in a span of 50-800 km. At least two systems (NZ and SE), furthermore include assumptions, and provide default values for module A5, construction and installation.

For the embodied part of module B, the assumptions are primarily relevant concerning scenarios for replacements, i.e. module B4. Several of the reported systems refer to national or local guiding values for service life of materials and elements. Same goes for the reported assumptions for end-of-life modules C and D.

Calculation rules include, but are not limited to:

- Factor-based corrections, for instance applied on generic data. E.g. the LCIA-results are multiplied with an uncertainty factor of 1.3 if generic data is used instead of product-specific EPDs
- Default scenarios and assumptions that should be applied if no better data exist
- Exceptions from the declared method. E.g. replacements of materials B4 should not be modeled if happening within 20 years from the end of the service life of the building
- Cut-off rules for modeling. E.g. building elements making up less than 5% of the life cycle impacts can be disregarded from the model

Specifications of scenario assumptions and calculation rules in a benchmark system are needed for the benchmark user to apply the method correctly.

3.2. Overview of GWP benchmarks in use

Figures 1a and 1b present an overview of embodied and full life cycle GWP benchmarks within the Annex 72 cases, as specified in Table 1. Note that this means a methodological diversity in terms of different system boundaries, included life cycle stages, reference study period, etc. Only reported values for new constructions are included in Figures 1a and 1b. Reported values are displayed for limit, reference and target values. Median benchmark values across limit-, reference- and target values are marked by a vertical line. Median benchmark values from the similar study of 23 benchmark systems by Trigaux et al [4] are additionally marked by dashed vertical lines in figures 1a and 1b for comparison.

Embodied GWP values from the Annex 72 cases (Figure 1a) span approximately 1-12 kg $CO_2e/m^2/y$ for both residential and non-residential. Full life cycle GWP values from the Annex 72 cases (Figure 1b) span approximately 5-90 kg $CO_2e/m^2/year$, i.e. notably more than for the embodied benchmarks in Figure 1a. This larger span indicates that the emission factors used for the operational energy demand vary widely between countries. For embodied GWP as well as for full life cycle GWP, the mapped values indicate that limit-, reference, and target values for residential buildings overall are slightly lower than for non-residential buildings. This pattern is comparable to previous reviews of GWP benchmarks for buildings. It is not possible to point to a certain parameter causing non-residential buildings to yield these higher values, but it is likely related to more intense use (e.g. new schools and retail with more technical installations and replacement needs) and higher operational energy demands.

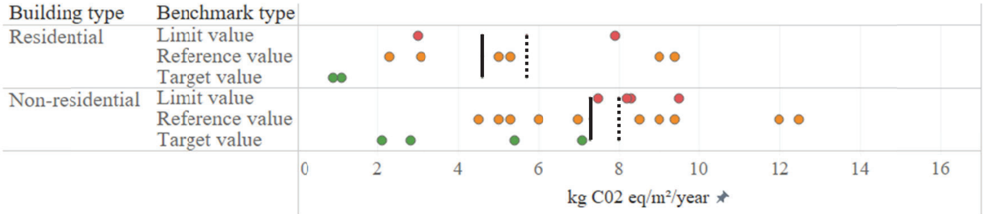
Furthermore, the median GWP values from the Annex 72 cases appear comparable with the statistical median of benchmark systems found in Triguax et al [4], although the embodied values from the Annex 72 cases are slightly lower and full life cycle values slightly higher than said review. However, GWP values representing the full life cycle are bound to decrease following updates of operational requirements, i.e. improving the energy efficiency of buildings. Hence, the Annex 72 cases represent conditions for operational energy requirements up to 2020. The aspect of changing energy performance requirements serves as a reminder of how important it is to update the benchmarks regularly.

Note further that reported benchmark systems are not directly comparable since they rely on different backgrounds in terms of methodology (e.g. scope and data) and in terms of physical context (e.g. climate zone, building culture). For instance, the New Zealand case covers three different climate zones and three different residential building types. Hence, there are overlaps between the reported limit and target values. However, the harmonized values from the collection of Annex 72 case studies of existing benchmarks indicate, for each case, what is seen as reference value for typical new buildings. Details of several of the Annex 72 cases further show how far the reference and target values are situated from each other, indicating the performance gap that the local construction industry has to deal with to reduce GHG emissions.

Even though several systems include target values as part of the GWP benchmark system, the majority of the reported values are reference values, reflecting the current state-of-art. In a future with additional focus on GWP mitigation, target values are crucial pointers for the building industry and should be applied broadly. Furthermore, target values based on planetary boundaries and remaining GWP budgets are only found in few of the existing benchmark systems (e.g. the CH case), but should be implemented to a much larger degree to curb GWP from the building and construction activities [13].

Only few benchmark cases for refurbished buildings exist so far, and more refinement of methods are needed to provide the incentives for increased renovation rates. The benchmarking in refurbishment and renovation cases could be set at the same level as benchmarks for new buildings, as refurbished buildings may benefit from the reuse of existing building components. Benchmarks for refurbishment could also be separate values, as found in the CH system. Refurbishment benchmarks could be used to evaluate a property by comparison with lowest and highest GWP. Providing this information when renting or selling the property would encourage owners to engage in low-GWP renovation.

a) Embodied impacts



b) Full life cycle impacts

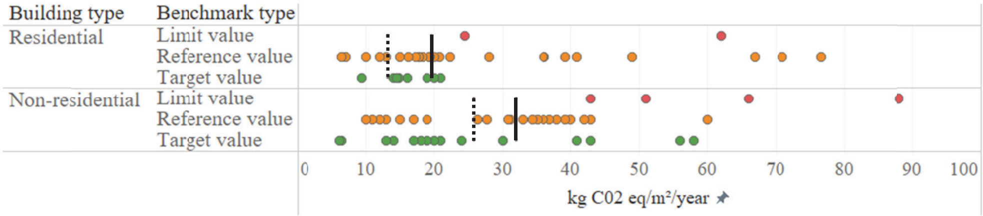


Figure 1a and 1b. GWP values reported from the Annex 72 benchmark cases for embodied (a) and full life cycle (b) impacts. Median benchmark values across limit-, reference- and target values marked by a vertical line. Median benchmark values from the benchmark review study of Trigaux et al [4] marked by dashed vertical lines for comparison.

4. Conclusion

Under the auspices of the IEA EBC Annex 72, a comprehensive, international research effort has resulted in several reports on LCA benchmarks for buildings, to be published in the late fall of 2022. This study provides an in-depth overview of the methodological choices and values within 17 benchmark cases from the international IEA EBC Annex 72 project. Justifications and considerations in play for GWP benchmark creation are explained for the choices of reference unit, scope of life cycle stages, inventory and calculation rules. The study shows the differences and similarities within benchmark systems for buildings, and leads to a set of recommendations for furthering the uptake of benchmarks in the building industry.

Benchmark developers are recommended to ensure that benchmarks are created from representative buildings or archetypes. Reference units are recommended to represent different functions of the building, both in terms of heated/gross floor area as well as user-efficiency (e.g. kg CO_2e/user). In the choice of life cycle stages, benchmark developers are recommended to construct overall benchmark values covering the full life cycle, in order to avoid burden shifting. Additionally, benchmark developers are recommended to put forward partial values for guiding building designers on subsets of the overall benchmarks, for example partial values for the upfront GWP from production and construction stages. Concerning methodological choices for the inventory scope and the calculation rules, absolute transparency is recommended to ensure consistency in the way benchmark users apply the system.

A mapping of the GWP limit, reference and target values for the 17 Annex 72 cases further provides benchmark actors with insights into the current state-of-art for GWP benchmark systems. The reported benchmark values are found to differ notably, especially for the full life cycle benchmarks (5-90 kg CO_2e/m^2/year).

The large variations seen in GWP values from existing benchmark systems are partly due to differences in benchmark types, i.e. limit, reference, best-practice and target values. However, the variations also emphasize the uniqueness of each system; the specific methodological choices as well as the background data and the tools employed. The configuration of each system needs to be meticulously replicated by the benchmark users to ensure consistency; hence it is of utmost importance that benchmark systems are described in detail, preferably following the reporting format of ISO 21678:2020. For future developments, a stronger focus on benchmarks and target values tailored from the remaining global GWP budgets should be prioritized.

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