BENCHMARKS FOR GREENHOUSE GAS EMISSIONS FROM BUILDING CONSTRUCTION

Results of a study with 50 buildings

Abstract

Reducing carbon dioxide (CO_2) emissions is one of the top environmental policy goals. Targets for this were agreed worldwide within the framework of the Paris Agreement of 2015. In Germany, the building sector accounts for a significant share of CO_2 emissions. While in recent years the evaluation of the operation of buildings and the associated emissions were at the forefront of scientific interest, the question of the evaluation of the buildings themselves is now increasingly being raised. In order to be able to classify and assess the building itself, there is currently still a lack of sufficient data. This is where this study comes in.

Within the framework of the statistical evaluation of 50 buildings from the DGNB pool, for which Life Cycle Assessment results were available, benchmarks for greenhouse gas emissions [kg CO_2e/m^2a] were derived. The mean value of all buildings is 8.7 kg CO_2e/m^2a, which is approx. 8% below the current reference value of the DGNB (9.4 kg CO_2e/m^2a). The group of the best performing buildings has a value of 6.5 kg CO_2e/m^2a. Overall, a wide spread of results can be observed. This can only be partially explained by the influence of various differentiating characteristics. This is a starting point for further research.

The developed benchmarks concretely support the evaluation of buildings with regard to reducing their greenhouse gas emissions. In this way, they make it possible to react and, for example, open up the possibility of comparing different planning variants with each other when carrying out a building project and selecting a low greenhouse gas variant.

1. Introduction

Background

By signing the Paris Agreement, the German government has committed itself to being carbon neutral by 2050 at the latest. In May 2021, the German government decided to intensify climate protection targets with the aim of achieving greenhouse gas neutrality by 2045. The interim objectives were also adjusted and made more stringent: By 2030, 65% (previously 55%) and by 2040 88% less CO_2 greenhouse gases are to be emitted compared to the 1990 level. This is accompanied by a reduction in the annual permissible CO_2 emissions for the individual sectors (energy, industry, transport and buildings)[1]. The climate target for 2020 envisaged a 40% reduction in greenhouse gas (GHG) emissions compared to 1990 and was narrowly achieved, partly due to the impact of the coronavirus pandemic. A closer look at the federal government's analysis reveals that the building sector is the only area that failed to meet its target. Instead of the targeted 118 million tonnes of CO_2 equivalents, 120 million were emitted.[2]

The study "*Umweltfussabdruck von Gebäuden in Deutschland*" (Environmental Footprint of Buildings in Germany) commissioned by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), which is available in German only, shows that in 2014, 40% of German greenhouse gas emissions were caused by the production, construction, modernisation and operation of residential and non-residential buildings.[3]

For the building sector, this means that major efforts must be made to achieve the politically prescribed reduction targets. To this end, both politicians and representatives of various stakeholders in the building sector are currently proposing measures to reduce greenhouse gas emissions.

In order to be able to evaluate measures at all, instruments are needed that help to assess these measures with regard to their effects on the carbon footprint. This is where this DGNB study comes in.

Objective

One of the most important substantive goals in the current debate is the reduction of greenhouse gas emissions in the life cycle of buildings. Production, maintenance and subsequent deconstruction account for an increasing share of greenhouse gas emissions in the life cycle of a building. An important factor here is the quantity of greenhouse gas emissions which can be attributed to the construction work[4] (GWP_C)[5]. In Germany, there are hardly any statistically validated values for this so far.

The aim of this study is to establish benchmarks for greenhouse gas emissions from the construction work of buildings. In order to determine a possible comparative value, greenhouse gas emissions of buildings from a large pool of life cycle-assessed buildings are used. Differentiating characteristics (=possible factors that have an influence on greenhouse gas emissions) are included in the evaluation.

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[1] Cf. https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672 on 17 June 2021.
[2] Cf. https://www.bmu.de/pressemitteilung/treibhausgasemissionen-sinken-2020-um-87-prozent/ on 17 June 2021.
[3] Cf. BBSR: BSSR Online Publication No. 17/2020, *Umweltfussabdruck von Gebäuden in Deutschland*, *Kurzstudie zu sektorübergreifenden Wirkungen des Handlungsfelds "Errichtung und Nutzung von Hochbauten" auf Klima und Umwelt*; Bonn, 2020.
[4] Construction work = building construction and technical installations.
[5] GWP = Global Warming Potential.

2. Approach and methodology

APPROACH

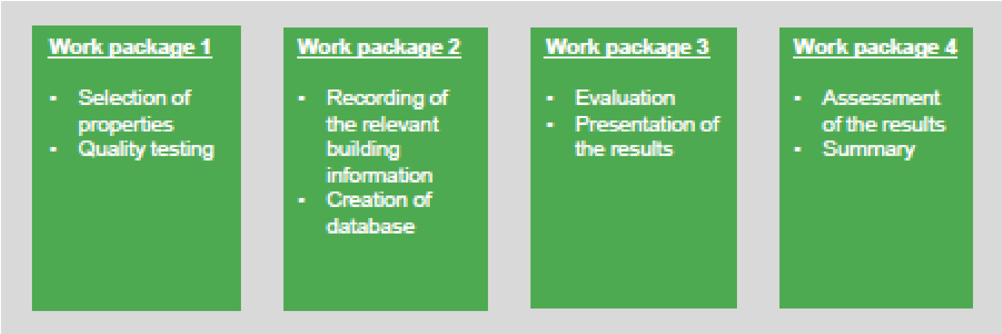

Figure 1: Overview of the work packages

The approach is divided into four work packages:

Work package 1: The first step is to identify suitable properties. To this end, an examination of the quality of the available data is carried out. The result of this work package is a list of identified properties for which the DGNB has adequate data.

Work package 2: In the following step, further relevant building information/characteristics are collected and systematically recorded. A database with carbon dioxide information and building data is now available as a basis for the evaluation.

Work package 3: The evaluation of the calculated CO_2 emissions of the construction work (construction + technical installations) and the operation under consideration of different building information/indicators as well as the derivation of CO_2 benchmarks is carried out in work package 3. The results of the investigation are documented.

Work package 4: In the last step, the results are summarised and evaluated, also with regard to the need for further research.

PRESENTATION OF THE SAMPLE

As the focus of this study is on office and residential buildings, this was taken into account when selecting buildings from the pool of certified buildings. After detailed examination - especially of the quality of the available data - 50 buildings could be considered for further processing. These are distributed by type of use as follows:

- 46 office buildings
- 4 residential buildings.

The size of the buildings ranges from 583 m² to 40,400 m² gross floor area (GFA). The buildings can be classified into three groups as follows:

- Group 1: 500 to 10,000 m² GFA: 20 properties;
- Group 2: 10,000 to 20,000 m² GFA: 19 properties;
- Group 3: 20,000 to 50,000 m² GFA: 11 properties.

In addition to the type of use, size and quality requirements for the available data, the timeliness of the data sets was also taken into account. This ensures that the available data were collected on the basis of uniform standards and calculation rules.

Determination of the differentiating characteristics

In addition to an evaluation of the entire sample, differentiating characteristics are defined and also - if available - collected and filed. These are considered as possible influencing factors in further processing and can help to explain certain deviations. This list can also be accessed in future data collections. It therefore provides a basis for further analysis.

Overview of the collected differential characteristics:

Building sizes:

- Gross building volume (GRV) [m³]
- Gross floor area (GFA) [m²]
- Net floor area (NFA) [m²]
- EnEV area [m²]
- LCA reference area [m²]
- Number of floors (total) [n]
- Number of basements [n]

Building description:

- Type of use
- Construction
- Material of the primary support structure
- Type of support structure
- Façade design
- Predominant material of the façade
- Ceilings/Components
- Floor plan structure

Building technology:

- Final energy electricity [kWh/(m²a)]
- Final energy heat [kWh/(m²a)]
- Type of heat supply system
- PV system [kWh/a]
- Primary energy demand of actual building and reference building [kWh/(m²a)]
- Percentage below EnEV requirements [%]

Building - thermal envelope:

- Opaque exterior components [kWh/(m²a)]
- Transparent exterior components [kWh/(m²a)]

Legal basis and calculation method

- Applied version of the German Energy Saving Ordinance
- Life cycle assessment method [simplified or detailed]
- Ökobau.dat database version used [year published]

General conditions of the survey

The LCA results are determined separately for operation and construction work. The data for the manufacture of the construction work of the examined buildings are collected and documented according to DIN 276 cost groups 300 and 400 on the 2nd level6 (if available). If the simplified procedure is used, the corresponding specifications of the DGNB system are taken into account7. Furthermore, the data for repair and maintenance (replacement = module B4) as well as for the end of life (module C3, C4 and D cumulated) are differentiated. Emissions from the energy demand of building operation, which corresponds to module B6, are also reported individually. Table 1 provides information on the scope of the modules according to EN 15978[8].

Life cycle stages according to DIN EN 15978	Product stage	Construction process stage	Use stage	End of life stage	Benefits and loads beyond the system boundary
Modules according to DIN EN 15978	A1 – A3	A4 – A5	B1 – B7	C1 – C4	D
Construction work/Construction	A1 Raw material supply A2 Transport A3 Manufacturing	A4 Transport A5 Construction and installation processes	B1 Use B2 Maintenance B3 Repair B4 Replacement B5 Refurbishment	C1 De-construction/Demolition C2 Transport C3 Waste processing C4 Disposal	D Reuse, recovery and recycling potential
Operation			B6 Operational energy B7 Operational water		

Table 1: The building life cycle with its life cycle stages according to DIN EN 15978 (the modules addressed here are marked in green)

3. Results of the evaluation

Standardisation

In order to be able to carry out the desired comparison of buildings within the framework of benchmarking, key metrics are usually compared. These provide a higher level of information than the comparison of the basic figures alone. In the building sector, an indication in relation to size is widely used.[9] For the following evaluation, the net floor area (NFA) is defined as the reference value.

The greenhouse gas emissions are stated as CO_2 equivalent within the framework of a life cycle assessment. This is a unit of measurement developed by the United Nations IPCC expert panel to standardise the climate impact of different greenhouse gases.[10] CO_2 equivalents are also referred to as "Global Warming Potential" (GWP) and abbreviated as "CO_2e".

Greenhouse gas emissions from the construction work (GWP_C)

For the 50 selected buildings, the results of the greenhouse potential of the construction work, which are determined within the scope of the life cycle assessment, are compiled and evaluated. All buildings are evaluated uniformly using the same life cycle assessment method. The box plot in Figure 2 shows the distribution of the underlying data. The exact measures of location are shown in Table 2 .

[6] DIN 276:2018-12: Building costs
[7] Cf. DGNB: DGNB System Criteria Set New Construction Building, Version 2018
[8] DIN EN 15978:2012-10: Sustainability of construction works - Assessment of the environmental performance of buildings - Calculation method
[9] Cf. Stoy, Quante, Lasshof: *BKI-Nutzungskosten Gebäude Statistische Kennwerte* (BKI usage costs for buildings - statistical parameters), Stuttgart, 2020
[10] Cf https://www.ipcc.ch/

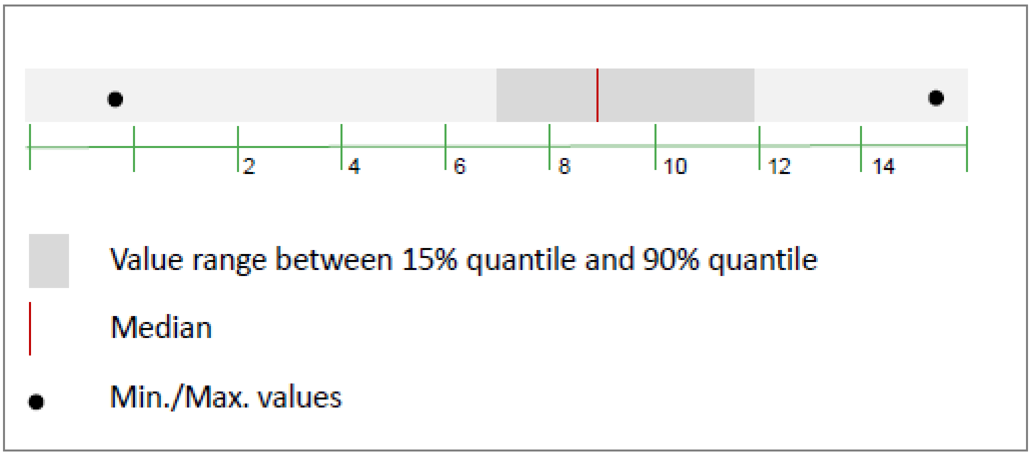

Figure 2: Statistical parameters from the analysis of the buildings (data for GWP_C [kg CO2e/m²a], n=50)

Statistical values	GWP_C [kg CO2e/m²a]
Mean value	8.7
Median	8.8
Minimum	-0.4
Maximum	15.5
15% percentile	6.5
90% percentile	11.9

Table 2: Total amount - statistical values for GWP_C (n=50)

This shows that the mean value is 8.7 and the median 8.8 kg CO_2e/m^2a. The minimum value is -0.4 kg CO_2e/m^2a and is shown as an outlier in the diagram in Figure 1. The maximum is 15 kg CO_2e/m^2a. The group of buildings with low greenhouse gas emissions (below 15% percentile) emits less than 6.5 kg CO_2e/m^2a.

Assessment according to components and life cycle modules

In the following step, it is examined which building components, sorted according to cost group 300 of DIN 276, have the greatest influence on the greenhouse gas emissions of the construction work. Suitable data are available for 43 buildings, which are therefore taken into account.

Figure 3 shows the results of the mean values for the manufacture of the components of cost group 300 for modules A1 - A3 as well as the scenarios for replacement and end of life (cumulative). The cost group with the highest share of production, also from a life cycle perspective, is cost group CG 350 (ceilings). Exterior walls and foundation are also very relevant, followed by interior walls.

The figure also shows the cost group 400 as well as the module B4 and cumulatively the modules C3, C4, D. Since the cost group 400 was only determined as a lump sum, it is only of limited significance. The relatively high share of module B4 "Replacement", in which the greenhouse gas emissions of the calculated replacement of components after their useful life are determined, is still in the order of magnitude of the production of the foundation. However, since the results cannot be assigned to the components, no specific recommendation can be derived from this. The end-of-life emissions and credits can also only be evaluated cumulatively with the available data. A greater differentiation into emissions and credits as well as an allocation to cost groups or components would provide clarity on the expected follow-up emissions after production. Thus, it can only be stated that the end-of-life of all buildings as a whole - taking into account the standardised calculation rules - have a net positive effect on the overall carbon footprint. The current discussion on a more future-oriented calculation of environmental impacts would possibly lead to results for the end of life pointing in a different direction.

If modules A 1 - A3 alone are considered, which were emitted at the time of construction completion ("upfront emissions", "investment emissions"), the mean value is 7.3 kg CO_2e/m²a.Without annual reference, this corresponds to an area-related CO_2-intensity of 365 kg CO_2e/m².

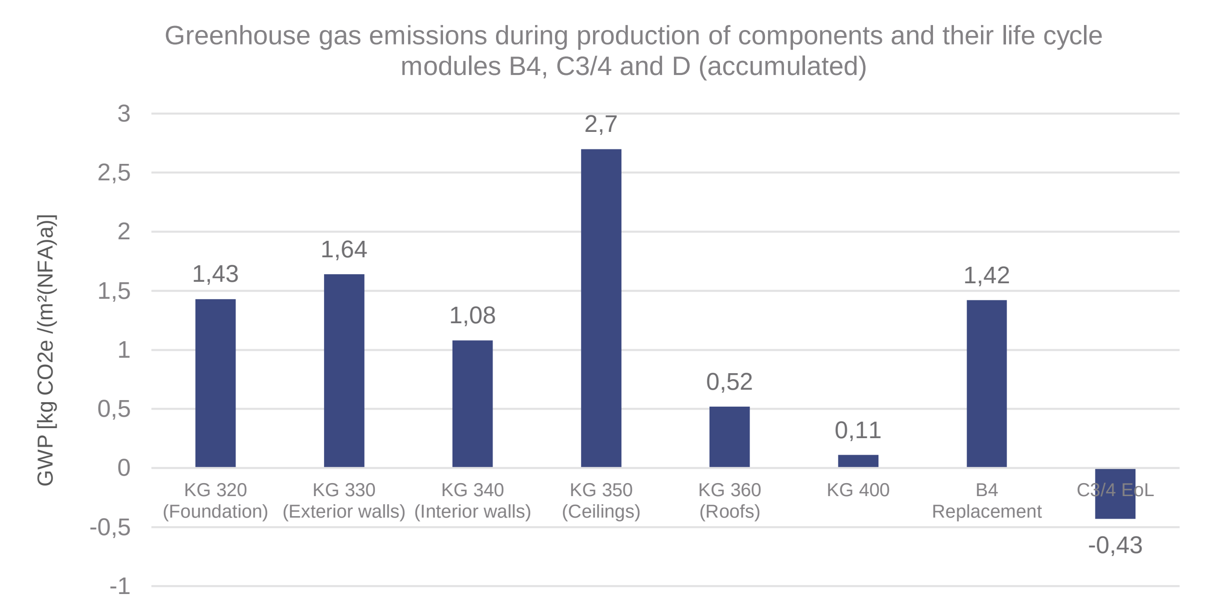

Figure 3: Greenhouse gas emissions by component (mean values, modules A1-A3, B4 and C3, C4 and D cumulated)

Modules A1 - A3 "upfront emissions" (n = 44)	GWP [kg$_{CO2e/m^2a}$]
Mean value	7.3
Median	7.4

Table 3: Mean value and median of modules A1 - A3 of the buildings available for evaluation (n = 44)

EVALUATION ACCORDING TO OTHER INFLUENCING FACTORS

In the first step the evaluation was presented over the total amount of buildings, now in a second step it is to be examined whether and how further selected factors affect the represented result. Influencing factors can be taken into account by the user in the context of benchmarking and thus support the assessment of a building with regard to its global warming potential.

Type of use

There are 46 office buildings and 4 residential buildings in the current data pool. Due to the very small amount of data for residential buildings, no further analysis is carried out for buildings with residential use. The 46 office buildings are examined with regard to the greenhouse gas emissions of the construction work (GWP_C). The results of the evaluation are presented in Table 4. Compared to the evaluation for all buildings, slightly higher values for the mean value and median are determined for the buildings with the use "office". The mean value is 9.1 kg CO_2e/m²a and thus 0.4 kg CO_2e/m²a higher than the mean value for all buildings. The median for office buildings is 9.0 kg CO_2e/m^2a, which is also somewhat higher than for all buildings (median: 8.8 kg CO_2e/m^2a). Somewhat higher values are also found for the 15% and 90% percentiles. The minimum and maximum values are identical.

Statistical values office buildings	**GWP_C [kg CO2e/m²a]**
Mean value	9.1
Median	9.0
Minimum	5.5
Maximum	15.5
15% percentile	6.6
90% percentile	12.7

Table 4: Office buildings - static values for GWP_C (n=46)

Construction method (supporting structure + material)

All 50 buildings are classified in terms of their construction and the material of the main structure. The groups wood/wood-hybrid construction (n = 3), solid construction (n = 25) and reinforced concrete skeleton construction (n = 22) are formed. The results are shown in Table 5. Due to the small number of buildings where the wood/wood-hybrid construction method was used, this construction method cannot be presented in a similar way.

Statistical values	**Solid construction GWP_C (n=25) [kg CO2e/m²a]**	**Skeleton construction GWP_C (n=22) [kg CO2e/m²a]**
Mean value	8.6	9.7
Median	8.2	9.4
Minimum	5.5	6.1
Maximum	14.1	15.5
15% percentile	6.6	7.4
90% percentile	11.1	13.8

Table 5: Buildings sorted by construction method/material, values for GWP_C

On closer analysis, some buildings stand out in particular. The two solid buildings with the highest GWP_C values are, firstly, a very tall building (with a very high proportion of ceilings) and a smaller building with a perforated façade. Without these two projects, the mean value for solid construction would be 8.1 kg CO2e/m²a, which is half a kilogram below the mean value for the group. The three skeleton buildings with similar and very high GHG emissions are all six stories and have higher than average GHG emission values for the interior walls and the roofs.

The analysis shows that there is a correlation between construction method and greenhouse gas emissions from the construction. Buildings constructed using wood or a wood-hybrid construction method have a much lower value than the other two groups. The mean value here is 2.7 CO_2e/m^2a. However, this group consists of only three buildings. This value is therefore of limited significance. The group of buildings with solid construction has a mean value that is approx. 11% lower than those with reinforced concrete skeleton construction. However, all three groups show a very high dispersion of the results, the determined standard deviation is 2.3. Figure 4 graphically represents the greenhouse gas emissions of buildings, depending on the construction method.

It can also be seen that a wood/wood-hybrid construction method does not in every case cause fewer CO_2 emissions than the other two construction methods. A closer analysis reveals that the group of the best solid and skeleton buildings (buildings within the 15% percentile value) are each 24% below the mean value. The group of the worst buildings (represented by the 90% percentile) is still between 30% and 40% above the mean value.

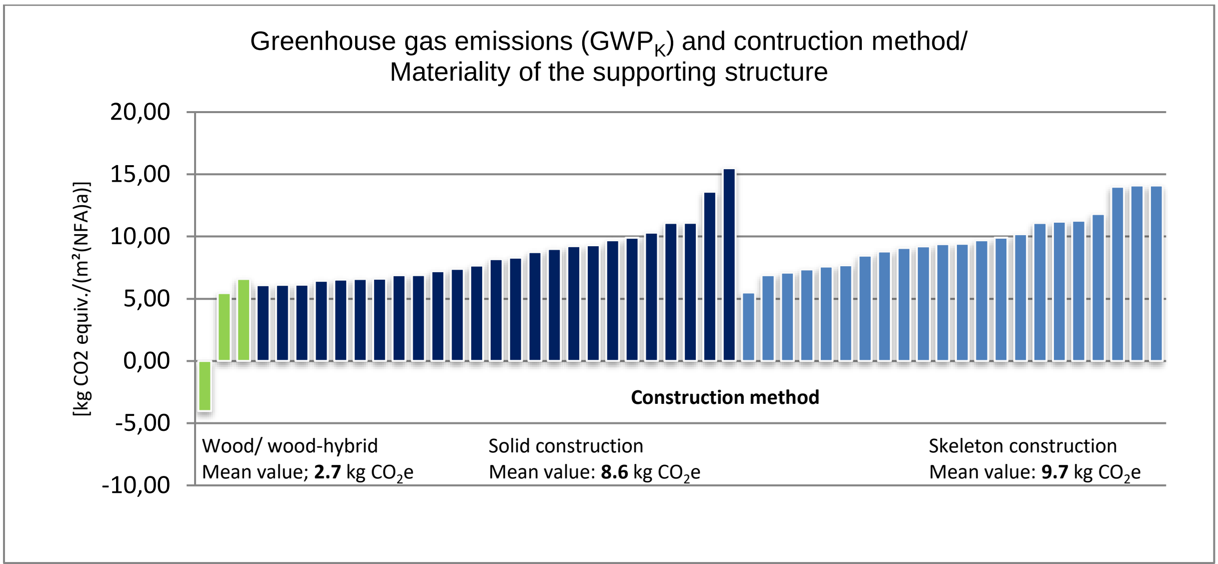

Figure 4: Greenhouse gas emissions (GWP_C) as a function of the construction method / materiality of the supporting structure (n=50)

Building operation during the use phase: Energy efficient buildings

In this step, it was investigated whether there is a connection between the greenhouse gas emissions of an energy-efficient building during its use phase and its construction work. For this purpose, the share of greenhouse gas emissions from building operation (GWP_U) in the total greenhouse gas emissions over the entire life cycle (GWP_C + GWP_U) was evaluated, taking into account the percentage below the primary energy requirements according to EnEV[11].

Figure 5 shows the ratio of construction work-related and operational greenhouse gas emissions for all buildings. Although sorting according to the date of issue of the energy certificate was implemented, no clear change can be read in the values over time.

The contribution of the construction work (GWP_C) is on average 35 % of the greenhouse gas emissions over the entire life cycle. This means that about two thirds of the greenhouse gas emissions (calculated over 50 years) are caused by the building operation (GWP_U) and about one third by the production, use and deconstruction at the end of the construction work's life. This ratio applies to the mean value, median and all percentile values examined. However, when looking individually at the group of buildings with the lowest value for GWP_U (operation), this relationship is different: This ratio is balanced for the buildings with the lowest greenhouse gas emissions during use.

[11] The study was conducted in 2020. Accordingly, the specifications of the EnEV 2014 applied. Since 1 November 2020, the German Energy Saving Ordinance (*Energieeinsparverordnung*, EnEV) has been integrated into the German Building Energy Act (*Gebäudeenergiegesetz*, GEG) and is no longer in force.

Nevertheless, a correlation between energy efficiency of the operation and GWP_C can be shown for the studied group (see Table 6). The group of least energy efficient buildings (buildings within the 15% group of lowest EnEV non-compliance) have a lower GWP_C value than the most energy efficient buildings (buildings within the 15% group of highest EnEV non-compliance). The energetically less demanding buildings have an average GWP_C value of 7.5 kg CO_2e/m^2a, which is 13% less than the mean value of all buildings. The mean value of the seven most energy-efficient buildings, on the other hand, is 1.1 kg $CO2e/m^2a$ higher and amounts to a value of 8.6 kg CO_2e/m^2a. Furthermore, a relatively high dispersion of all results was observed, which is also reflected in the standard deviations for both the value for the construction work and the value for the operation (standard deviation s for GWP_C is 3.1 and for GWP_U 9.1).

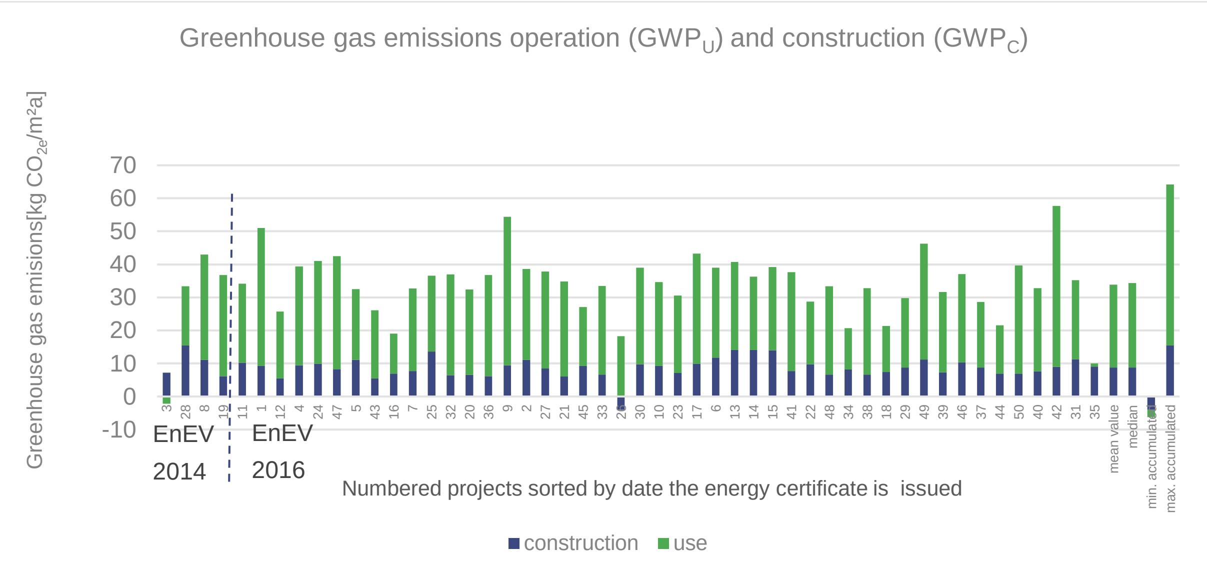

Figure 5: Greenhouse gas emissions of all buildings over the life cycle (n = 50), sorted by date of energy certificate

Statistical values	Amount below primary energy requirements according to EnEV [%]	GWP_C [kg CO_2e/m^2a]	GWP_U [kg CO_2e/m^2a]
Mean value	24%	8.7	25.1
Median	22%	8.8	25.6
Minimum	3%	-0.4	-2.2
Maximum	58%	15.5	48.7
15% percentile	38%	6.5	18.0
90% percentile	7%	11.9	33.5
Mean value GWP_C 15% lowest amount below EnEV (n=7)		7.5	
Mean value GWP_C 15% highest amount below EnEV (n=7)		8.6	

Table 6: Greenhouse gas emissions for construction work and operation considering energy efficiency (n=50)

It should be noted that for all projects only the simplified form of life cycle assessment is available. This means that the expenses for building technical systems (cost group 400) are only included in the calculation as a lump sum mark-up factor. Thus, the results cannot reflect whether energy efficient buildings have a higher GWP_C value due to higher technology use. Presumably, this value would be even higher, since at least three of the seven buildings classified as energy-efficient have PV systems installed, which are not included in the GWP_C value. An upward deviation from the mean value is therefore likely for the energy-efficient buildings with detailed life cycle assessment. This would mean that not only the less energy-efficient buildings (13% as determined here) would deviate downwards from the mean value, but also that the energy-efficient ones would deviate upwards.

Low greenhouse gas emissions during operation

The study on the correlation between buildings with low greenhouse gas emissions in operation and the greenhouse gas emissions of the construction work, concludes that there is no correlation between these two values for the buildings analysed. The nine buildings that were below the 15% percentile value of < 18 kg CO_2e/m^2a were examined. It should be noted in this analysis that the number of buildings is relatively small and that no detailed life-cycle assessment is available for the buildings.

Photovoltaic system

An evaluation with regard to the effects of a PV system is not possible as part of this study, as only the simplified form of the life cycle assessment is available for all buildings. This means that the expenses for building technical systems (cost group 400)[12] are only included in the calculation as a lump sum mark-up factor. Thus, the results cannot reflect whether energy efficient buildings have a higher GWP_C value due to higher technology use.

Date of issue of the energy certificate and date of submission

No correlation could be demonstrated between either the date of issuance of the energy certificate or the date of submission against the construction work's greenhouse gas emissions (GWP_C) values. The energy certificates of the buildings in the data pool were issued from 2015 to 2020. The analysis therefore does not allow any conclusions to be drawn as to whether the greenhouse gas emissions of the construction work increase or decrease over the period under review.

Number of floors

All 50 buildings were evaluated in terms of their number of floors. No correlation between the number of floors and the greenhouse gas emissions of the construction work (GWP_C) could be identified.

4. Results of the evaluation

PRESENTATION AND CLASSIFICATION OF THE RESULTS

In order to determine greenhouse gas emissions, the information on greenhouse gas emissions of the construction work (GWP_C value) of 50 DGNB certified buildings was systematically recorded and analysed with regard to various aspects of the study. The aspects investigated included type of use, building operation, number of floors, construction method, contribution of building components and evaluation of the time profile. Table 7 shows the results of the analysis as a function of the aspects examined (if any).

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[12] Cost group 400 according to DIN 276:2018-12: Building costs

The mean value of all buildings is 8.7 kg CO_2e/m²a and thus approx. 8% below the current reference value of the DGNB (9.4 kg CO_2e/m²a). A study by the German Federal Environment Agency determined a CO_2 equivalent of 10 - 16 kg CO_2e/m²a for new buildings. When comparing the values with this study, however, it should be noted that the underlying life cycle assessment was calculated with the actual CO_2 expenditure for cost group 400.[13]

	15% percentile	Mean value	Median	90% percentile	Number
Buildings - total	6.5	8.7	8.8	11.9	50
Manufacture of buildings (modules A1 to A3) - "Investment emissions"		7.3	7.37		44
Buildings sorted by influencing factors:					
Type of use - office	6.6	9.1	9.0	12.7	46
Construction method - solid construction	6.6	8.6	8.2	11.1	25
Construction method - skeleton construction	7.4	9.7	9.4	13.8	22
Energy efficiency (amount below EnEV), figures in %	38%	24%	22%	7%	50

Table 7: Results for greenhouse gas emissions GWP_C [kg CO_2e/m²a] total and as a function of influencing factors

The group of best performing buildings (derived from the 15% percentile value) has a GWP_C value of 6.5 kg CO_2e/m²a. It is interesting to note that buildings from all three of the construction methods mentioned here can be found in this group. Overall, a wide range of results can be observed.

Due to the data available, an evaluation with regard to the type of use is only possible for office buildings. Here, the values are slightly higher than for the buildings as a whole. However, the question arises as to whether the type of use is the main influencing factor or whether it is much more the chosen construction method of the office buildings that is the decisive factor. This cannot be satisfactorily clarified here. Further investigation is required.

The analysis of the correlation between energy efficiency (derived from the primary energy demand being below the reference value according to the Energy Saving Ordinance) and GWP_C shows that the mean value of the buildings classified as energy efficient is at the mean value of all buildings, but the buildings classified as low energy efficient have 13% lower GHG emissions from the construction than the mean value of all buildings. However, since the cost group 400 for all buildings was only included in the balances as a lump-sum surcharge, no statement can be derived from the study on the connection between a possibly higher technology expenditure of energy-efficient buildings and the associated greenhouse gas emissions.

[13] Cf. Federal Environment Agency: *Energieaufwand für Gebäudekonzepte im gesamten Lebenszyklus* (Energy use for building concepts throughout the life cycle), final report. No. 132/2019; Federal Environment Agency, Dessau, 2019.

The ratio of construction to use is on average 35% (construction work) to 65% (use). These values are thus also in the range of other studies, which show a share of 25 - 40%.[14] This ratio is balanced for the buildings with the lowest greenhouse gas emissions during use.

The number of floors could not be clearly correlated with the GWP_C values. The construction method, on the other hand, shows clear differences: Buildings where wood or wood-hybrid construction methods were used have much lower GHG emissions from construction compared to the mean value. Solid buildings have slightly lower GWP_C values than reinforced concrete buildings. Here, too, the relatively wide dispersion of the data must be taken into account when making an assessment. A case-by-case analysis shows that a wood-hybrid building is not per se better than any solid or reinforced concrete building.

When looking at the individual components, the ceilings stand out, followed by the exterior walls and the foundation. Optimisation of these parts thus has a major impact and is therefore recommended.

CRITICAL ASSESSMENT OF THE RESULTS

The following points must be included in the critical assessment of these results:

- Size and scope of the database

Some of the interim results are based on a relatively small database of 50 buildings. No general specifications should be derived from this. In addition, not all project data could be collected, which would have allowed a better resolution and further correlations. For example, there is a lack of information on the materials of the façades and the floor plan structure.

- Use of cost group 400

No findings could be provided for cost group 400 (building technical systems), as all buildings were calculated using the simplified life cycle assessment method. Higher results can be expected, as shown by several other studies.[15] With the latest publication of the DGNB certification system, instead of a 10% surcharge, a 20% surcharge is now to be implemented. This takes into account the fact that the building technical systems have a non-negligible influence on the results. Moreover, this proportion is increasing as the level of technology in buildings rises.

- Influence of the construction method

Unfortunately, the small number of wood or wood-hybrid buildings does not allow comparative statements to be made with other construction methods. A tendency towards much better results is visible, but a larger data base is needed for reliable recommendations.

OUTLOOK AND CONCLUSION

Within the framework of this study, it was possible to classify current buildings with regard to the global warming potential of the construction work. However, further detailed evaluations are still necessary in this area. Three approaches in particular should be pursued: Firstly, cost group 400 should not be taken into account as a lump sum but as part of a detailed calculation. This would make it possible to investigate possible interactions between the global warming potential of the construction work and that of its use. Secondly, the construction method should be analysed in more detail. Within the framework of this study, a connection between the construction method (depending on the material)

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[14] Cf. Federal Environment Agency: *Energieaufwand für Gebäudekonzepte im gesamten Lebenszyklus* (Energy use for building concepts throughout the life cycle), final report. No. 132/2019; Federal Environment Agency, Dessau, 2019.
[15] Cf. Federal Environment Agency: *Energieaufwand für Gebäudekonzepte im gesamten Lebenszyklus* (Energy use for building concepts throughout the life cycle), final report. No. 132/2019; Federal Environment Agency, Dessau, 2019.

and the global warming potential could only be shown in rudimentary form. Last but not least, more attention should be paid to the end of life, both in differentiating outcomes and in optimisations.

Current approaches to the "compensation" of greenhouse gas emissions of the construction work over the life cycle[16] also require detailed bases on the interrelationships between emissions from the construction work and its use. These approaches should also be considered in further research.

The presented analysis allows a classification of the respective calculated building within the framework of a benchmarking exercise. This allows a statement to be made as to whether the result determined is more in the ambitious range or in the range of buildings with relatively high greenhouse gas emissions. If such an assessment is carried out during the planning phase of a building, variant calculations can be used to identify potential for optimisation and, ideally, also implemented during the construction process. The knowledge of greenhouse emissions in the construction work and its use is indispensable for achieving the climate targets in the Paris Agreement and thus represents an important building block for the upcoming development. To act as recommended by many climate scientists would require at least to cut global emissions by 50 percent every decade. In this sense, the construction of new buildings should then emit only 4.3 kg CO_2e/m^2a. In order to still consider the time component of emissions, it would be necessary to halve modules A1 to A5. It is therefore urgently necessary to know, or at least be able to estimate, the greenhouse gas emissions of modules A4 and A5 and to set reduction targets for these as well. For a possible benchmark for modules A1 - A3, the current average value of 7.3 kg CO_2e/m^2a, or without annual reference of 365 kg CO_2e/m^2 would be suitable. A target value as recommended by the climate scientists would therefore be 3.7 kg CO_2e/m^2a or 183 kg CO2e/m² for these "investment emissions".

Since the buildings included in the determination of all benchmarks had only a few very "good" values, and the current mean value differs from the previous reference value of the DGNB by only 8%, an analysis of further "very good" buildings with low greenhouse gas emissions of the construction work would be important. Planners can support the DGNB with calculations of pioneering projects. A data collection sheet for this is currently under development and an extension to this study is planned.

[16] DGNB: DGNB "Framework for carbon neutral buildings and sites" (https://www.dgnb.de/de/themen/klimaschutz/rahmenwerk/index.php Stuttgart, 2020

Glossary

Benchmarking	Benchmarking is an ongoing process in which the products and services of a company (in this case a building) are measured against a benchmark, i.e. against a defined reference value or reference process.
CO_2 equivalent	CO_2 equivalents are a unit of mass used to standardise the climate impact of different greenhouse gases.
GWP	Global Warming Potential Is used to estimate the impact of greenhouse gases.
LCA	Life cycle analysis (also referred to as life cycle assessment) is a method for determining environmental impacts. It can be carried out for individual building materials, for building components and for the entire building (including building use). The environmental impact can be considered from production to end of life. Life cycle analysis can be used to determine the CO_2 equivalent of a building.
Median	The median divides a sample into two halves of equal size. It is also called the central value.
Mean value	The mean value is also called the average value. To calculate the mean value, all values of a data set are added and the sum is divided by the number of values.
Quantile	A quantile defines a certain part of the data set. A quantile defines how many values of a sample are above or below a certain limit.
Greenhouse gases	In addition to carbon dioxide (CO_2), the Kyoto Protocol names five other greenhouse gases: methane (CH_4), and nitrous oxide (N_2O), as well as the so-called F-gases: hydrofluorocarbons and perfluorocarbons and sulphur hexafluoride (SF_6). Since 2015, nitrogen trifluoride (NF_3) has also been included. These gases are normalised with each other by applying the so-called GWP values.

List of abbreviations

GRV Gross building volume defined according to DIN 277-1:2016-01

GFA Gross floor area defined according to DIN 277-1:2016-01

DGNB Deutsche Gesellschaft für Nachhaltiges Bauen e.V. (German Sustainable Building Council)

EnEV *Energieeinsparverordnung* (Energy Saving Ordinance) (replaced by GEG in 2020)

GEG *Gebäudeenergiegesetz* (Building Energy Act) (from 1 November 2020)

GWP_C Global Warming Potential of the construction work/ construction + technical installations)

GWP_U Global Warming Potential of use

LCA Life cycle assessment

kg Kilogram

NFA Net floor area defined according to DIN 277-1:2005-02 (as of January 2016: DIN 277-1:2016-01)

List of tables and figures

Appendix

Project #	Main use	Construction method	Amount below PE req. of EnEV (%)	Area class (GFA)	GWP_C	GWP_U	Number of floors	Base ment	KG320 (Founda tion)
1	Office	Skeleton construction	26%	500 - 10000	9.2	41.8	5	1	1.86
2	Office	Solid construction	36%	20000 - 50000	11.1	27.5	18	2	1.09
3	Office	Solid construction	44%	500 - 10000	7.2	-2.2	4	1	1.48
4	Office	Skeleton construction	28%	500 - 10000	9.4	29.9	7	1	2.40
5	Office	Skeleton construction	20%	500 - 10000	11.1	21.4	8	1	3.02
6	Office	Skeleton construction	48%	500 - 10000	11.8	27.2	5	1	1.07
7	Office	Solid construction	10%	10000 - 20000	7.7	25.1	7	1	2.20
8	Office	Solid construction	51%	500 - 10000	11.1	31.9	2	0	
9	Office	Skeleton construction	29%	20000 - 50000	9.4	45	10	3	
10	Office	Solid construction	39%	10000 - 20000	9.3	25.3	7	1	1.85
11	Office	Skeleton construction	7%	500 - 10000	10.2	24	7	2	
12	Office	Skeleton construction	34%	10000 - 20000	5.5	20.2	10	4	
13	Office	Skeleton construction	19%	20000 - 50000	14.1	26.6	6	1	0.44
14	Office	Skeleton construction	27%	10000 - 20000	14.1	22.2	6	1	0.44
15	Office	Skeleton construction	20%	10000 - 20000	14	25.2	6	1	0.44
16	Residenti al	Solid construction	32%	10000 - 20000	6.9	12.1	10	1	0.15
17	Office	Solid construction	30%	20000 - 50000	9.9	33.4	7	1	1.04
18	Residenti al	Solid construction	45%	500 - 10000	7.4	14	7	1	0.47
19	Office	Solid construction	40%	10000 - 20000	6.1	30.7	9	2	
20	Office	Solid construction	17%	10000 - 20000	6.5	25.9	8	1	
21	Office	Solid construction	21%	10000 - 20000	6.1	28.8	6	0	0.34
22	Office	Solid construction	6%	500 - 10000	9.7	19	9	2	
23	Office	Skeleton construction	31%	10000 - 20000	7.1	23.5	4	1	0.41
24	Office	Skeleton construction	29%	10000 - 20000	9.9	31.1	7	1	0.59
25	Office	Solid construction	36%	500 - 10000	13.6	23	3	0	2.21
26	Residenti al	Solid wood construction	4%	500 - 10000	-4.0	18.3	3	0	2.04
27	Office	Skeleton construction	12%	10000 - 20000	8.5	29.4	8	1	1.28
28	Office	Solid construction	20%	10000 - 20000	15.5	17.9	19	2	1.84
29	Office	Skeleton construction	23%	500 - 10000	8.8	21	5	1	1.98

30	Office	Skeleton construction	21%	10000 - 20000	9.7	29.3	8	1	1.74
31	Office	Skeleton construction	0%	20000 - 50000	11.3	23.9	9	2	1.93
32	Office	Solid construction	30%	10000 - 20000	6.4	30.6	8	1	0.69
33	Office	Solid construction	7%	10000 - 20000	6.6	26.9	7	1	4.34
34	Office	Solid construction	6%	500 - 10000	8.2	12.5	5	1	0.85
35	Office	Skeleton construction	0%	500 - 10000	9.1	0.9	8	3	1.65
36	Office	Solid construction	24%	20000 - 50000	6.1	30.7	6	0	0.33
37	Office	Solid construction	9%	500 - 10000	8.8	19.9	6	1	1.36
38	Office	Solid construction	25%	10000 - 20000	6.6	26.2	6	1	0.50
39	Office	Skeleton construction	15%	10000 - 20000	7.3	24.3	7	1	1.16
40	Office	Skeleton construction	n.v.	500 - 10000	7.6	25.2	6	1	1.30
41	Office	Skeleton construction	20%	20000 - 50000	7.7	30.0	7	1	0.41
42	Office	Solid construction	n.v.	20000 bis 50000	9.0	48.7	6	1	2.14
43	Residenti al	Wood-hybrid construction	20%	500 - 10000	5.5	20.6	10	1	0.73
44	Office	Solid construction	58%	500 - 10000	6.9	14.6	3	0	1.05
45	Office	Solid construction	38%	20000 bis 50000	9.2	17.8	9	2	2.54
46	Office	Solid construction	8%	20000 bis 50000	10.3	26.8	9	3	3.46
47	Office	Solid construction	18%	500 - 10000	8.3	34.2	2	0	1.82
48	Office	Wood-hybrid construction	15%	500 - 10000	6.6	26.8	6	0	0.89
49	Office	Skeleton construction	3%	10000 bis 20000	11.2	35.1	8	1	2.51
50	Office	Skeleton construction	10%	20000 bis 50000	6.9	32.8	8	1	1.48

Table 8: Core information of the analysed properties

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