Towards embodied carbon benchmarks for buildings in Europe

#2 Setting the baseline: A bottom-up approach

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Towards embodied carbon benchmarks for buildings in Europe
#2 Setting the baseline: A bottom-up approach

Project name	Towards EU embodied carbon benchmarks for buildings
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Disclaimer

In this report, the widely used term 'embodied carbon' is applied. It is considered to be synonymous with 'embodied GHG emissions' herein. The data and values presented below include both CO2 and non-CO2 GHG emissions, the reference unit applied is kilogram CO2e (equivalent) expressed per m^2, per capita, or m^2 and year, respectively.

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Executive summary

Rationale – Why is this important?

"Embodied carbon" consists of all the greenhouse gas (GHG) emissions associated with the materials and construction processes used throughout the whole lifecycle of a building[1]. While past efforts have mostly focused on increasing energy efficiency in buildings operations, recent research on the GHG emissions across the full life cycle of a building highlights the increasing importance of embodied GHG emissions in relation to producing and processing construction materials.

The "Towards Embodied Carbon Benchmarks for buildings in Europe" project was set up by Ramboll Build AAU - Aalborg Universitet with the support of the Laudes Foundation. The objective is to improve our understanding of embodied carbon in buildings and to set framework conditions for reducing it. In order to do so, the project explores the concept of embodied carbon baselines, targets and benchmarks for buildings in Europe.

To understand where we need to go and what level of effort is needed to get there, we first need to understand where we are today. Therefore, this report focuses on understanding the baseline, with the aim of informing both policymakers and building design professionals about the current level of embodied carbon in new buildings across Europe.

Methodology – What did we do?

This report presents a baseline analysis based on building life cycle assessment (LCA) data from five European countries.

The countries were selected on the basis of criteria concerning geographical representation across the EU, as well as on the availability and quality of data across different building typologies. The case studies were obtained from various national data partners as shown in Table 1. They provided data on whole life cycle embodied carbon, as obtained through conducting an LCA, as defined in the relevant European standard EN 15978, albeit using the methods, data and tools specific to their respective countries.

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[1] Embodied carbon, therefore, includes the following stages (acc. to the related standard EN 15978): Material extraction (A1), transport to manufacturer (A2), manufacturing (A3), transport to site (A4), construction-installation process (A5), use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transport to end of life facilities (C2), waste processing (C3), and disposal (C4). Additional information on embodied carbon, how it relates to operational emissions, as well as how to assess and effectively reduce it, is available in the guidelines established by the IEA EBC Annex 57 - Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction.

Table 1: Main five pilot countries and related data partners.

Country	No. of cases	Data partner(s)
Belgium	105	KU Leuven
Denmark	72	AAU BUILD, Ramboll
Finland	59	Ministry of Environment, One Click LCA, Granlund
France	486	Ministry for Ecological Transition, CSTB
Netherlands	47	NIBE, W/E advisors, DGBC
Total	769	'EU-ECB dataset'

To account for differences in the data, e.g. variations in the assessment methods used and the scope of the studies included, as well as limitations on data sharing due to confidentiality concerns, pre-processing and harmonisation steps were undertaken as part of this study in order to ensure that the data could be analysed consistently and a meaningful comparison could be made.

In this report, the full life cycle embodied carbon baselines are analysed for different types of building use **(i.e. residential and non-residential buildings), building use subtypes (e.g., single family houses, multi-family houses, terraced/row houses, office or commercial, etc.), as well as for different types of building structures (e.g. timber frame, massive timber, massive concrete or brick, etc.). Furthermore, the contribution made** by the different life cycle stages and the different building parts to the full life cycle embodied carbon was also analysed, as well as the variation in embodied carbon values for different countries and different assessment scopes, i.e. life cycle stages and building parts included.

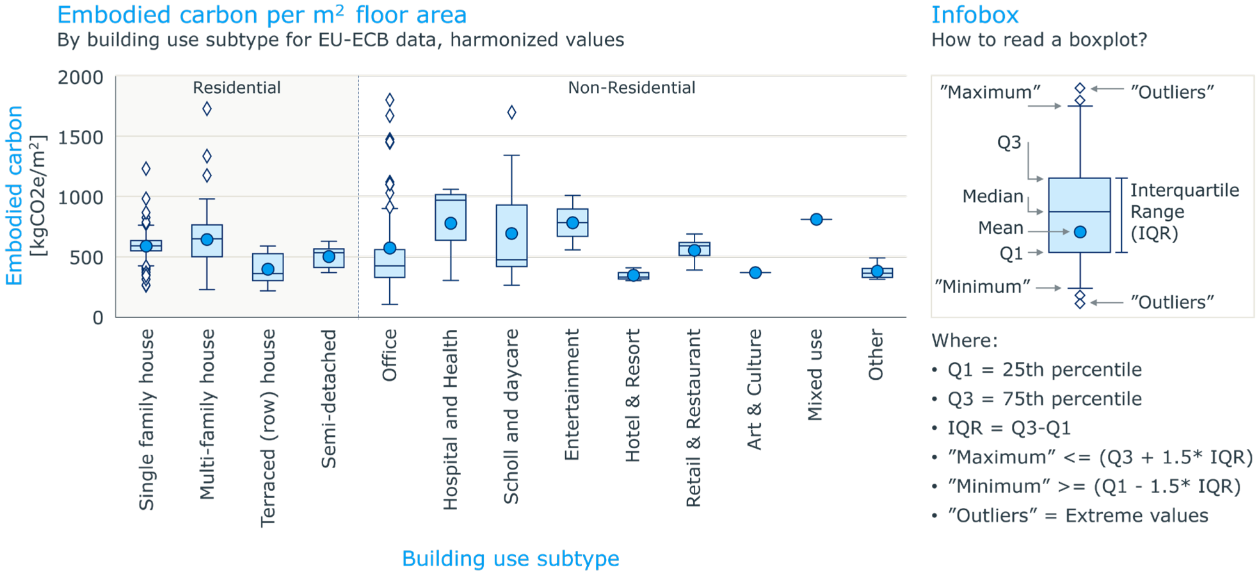
Results – What did we find?

With the support of our data partners, the study compiled a total of 769 building LCA studies, as shown in Table 1. Embodied carbon data was reported at both building-level and, in a detailed manner for some countries and specific cases, the data was disaggregated for different life cycle stages and building parts.

The main findings of our analysis show that, for residential buildings, full life cycle embodied carbon values range from around 400 to 800 kg CO2e/m^2 with a mean value of around 600 kg CO2e/m^2. For non-residential buildings, the study observes a wider spread of embodied carbon values, ranging from around 100 to 1,200 kg CO2e/m^2, with mean values, again, of around 600 kg CO2e/m^2.

Per capita values for residential buildings show a mean value for full life cycle embodied carbon of around 32 t CO2e/cap, with values ranging from 5 to almost 60 t CO2e/cap. For non-residential buildings, values range from around 2 to 35 t CO2e/cap, with a mean value of around 20 t CO2e/cap. As shown in Figure 1, considerable differences between embodied carbon for different subtypes of building use (e.g. different types of residential buildings such as SFHs, MFHs, etc.) can be observed.

Figure 1: Harmonised full life cycle embodied carbon per m^2 for different building use subtypes [kg CO2/m^2]



It is important to note that these average values and ranges are based on studies from different countries, with differences in assessment methodologies, e.g., regarding the life cycle stages and the building elements included, and the LCA background data used. An in-depth analysis which considers these different aspects is provided in the report showing, amongst other elements, that the embodied carbon baseline is even higher for the studies with 'complete' scopes.

Conclusions – What does this mean?

This report provides an in-depth analysis and discussion of the various relevant results of the life cycle of embodied carbon present in buildings across the EU. In this summary, the following aspects should be highlighted:

- **Understanding the baseline for embodied carbon in buildings is important**, as it is the basis required to be able to establish performance benchmarks, and it is also a starting point for developing roadmaps to reduce the whole life cycle carbon in buildings across Europe. Understanding the baseline is, therefore, crucial for informing and shaping both national requirements and decarbonisation strategies, and is particularly important within the context of European initiatives, such as Level(s) sustainability reporting and the EU taxonomy for sustainable activities, amongst others.

- **Firstly, the embodied carbon in new buildings is significant across the full life cycle**, even if buildings are branded "highly efficient" or "sustainable", which is the case for many buildings that are part of the baseline analysis dataset. The following is a simplified example to highlight the scale of emissions: **For a newly built 1000 m² building, on average around 600 t CO2e embodied carbon is emitted across the full life cycle**. This is almost 100 times the personal carbon footprint of one EU citizen in 2019[2].

- **Secondly, the majority of embodied life cycle carbon - around 2/3, or close to 400 t CO2e on average - is emitted upfront**, i.e. during the building production and construction (life cycle stages A1-A5). This highlights the need to focus both the discussion and reduction efforts on upfront carbon emissions rather than (future) end-of-life scenarios and potential benefits. The ongoing discussion around the latter is often used to exaggerate uncertainty issues in the life cycle assessment of buildings, and hence detracts from the **importance and urgency of acting on upfront embodied carbon emissions today**.

- **Thirdly, there is no straightforward solution to reducing embodied carbon in buildings, but multifaceted strategies need to be applied** which combine, for example, material-efficiency when designing structural systems, the use of low-carbon building materials and energy systems, as well as a general consideration of occupational density and sufficiency principles in building design to reduce the required floor area and hence material consumption, among others. Furthermore, the conscious **application of (fast-growing) bio-based construction materials** (such as timber, bamboo, straw or hemp) for building construction and renovation **offers the potential for a temporal fixation of the biogenic carbon** taken up during plant growth.

- **Fourthly, differences between per-m² versus per-capita values for full life cycle embodied carbon suggest that the building typology and design, as well as occupational patterns, have a substantial influence**. These observations are in line with findings from previous studies in the field of building energy efficiency, which included **rebound effects** where a lowering of energy consumption per m² coincided with increased m² per capita, leading to an overall levelling of, or even increase in, energy consumption, especially in residential buildings. To account for similar rebound effects and trade-offs, **both reference units** should be used to express the embodied and whole life cycle carbon performance of buildings **to effectively monitor and reduce life cycle embodied carbon per capita**.

- **Lastly, while the study was able to compile and analyse a variety of LCA studies for different building (sub)types, it also found limitations in data** availability, differences in building LCA methods, and varying levels of documentation for the different case studies.

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[2] Eurostat estimates that the total carbon footprint of EU-27 was equal to 6.7 tonnes of CO2 per person in 2019. (https://ec.europa.eu/eurostat/statistics-explained/, Accessed: 23.12.2021) – A detailed analysis of embodied carbon per m² as well as per capita for different building types is provided in the results section of this baseline report.

Call to action – What should we do?

A series of recommendations emerges from these conclusions:

- **Firstly, data gaps should be closed through stricter requirements regarding the documentation for building LCA studies, supplemented with the use of building archetypes models. For this, we recommend establishing clear and harmonised standards for the assessment methodology and the documentation for building LCA studies** both across the EU, as well as within Member States. Documentation requirements should cover both a comprehensive description of the building system and its properties (i.e. a detailed description of functional units and related life cycle inventory), as well as detailed documentation on the assessment methodology used and LCA results obtained for individual life cycle stages and building parts (i.e. detailed life cycle impact assessment results).

- **Additionally, we recommended moving beyond ad-hoc data compilation and analysis and suggest the establishment of an openly accessible, central database on the whole life carbon performance of buildings across the EU**. Existing initiatives like the EU's Level(s) programme could provide a good basis for developing related documentation standards, and for ensuring the involvement of relevant stakeholders and the long-term success of an open data platform.

- **Thirdly, methods and analytical tools for understanding embodied carbon should be developed further**, including the contribution from different life cycle stages, building parts and materials, as well as other environmental impacts. Similarly, methods for inferring missing values need to be advanced further and could include machine learning.

- **Lastly, benchmarks for reducing embodied carbon are needed**, which consider the timing of emissions and scope of the results in this assessment. To express the potential influence and reduction potential of building design, regarding both building materialisation as well as layout and patterns of use, benchmark values should be expressed in both CO2e/m^2 and CO2e/capita in parallel.

Contents

1. Introduction

As the effects of the accelerating climate and ecological crises are becoming evident, the need for transformational climate action is rising. Based on decades of climate science and driven by the increasing pressure from civil society, policymakers in the European Union (EU) and beyond are making bold claims to reduce greenhouse gas (GHG) emissions for their respective regions and activities.

Building construction and operation are amongst the most significant activities driving current GHG emissions, representing 37% of global GHG emissions [1]. At the same time, increasing the energy efficiency of both existing and new buildings, as well as shifting to sustainable construction practices, are considered to be major opportunities for decarbonising the economy in the coming decades.

While past efforts have mostly focused on increasing energy efficiency in building operation, recent research on GHG emissions across the full life cycle of buildings highlights the increasing importance of embodied GHG emissions, in relation to producing and processing construction materials. “Embodied carbon” refers to all the greenhouse gas (GHG) emissions associated with materials and construction processes throughout the whole lifecycle of a building[3].

These embodied emissions in buildings are rarely addressed in policy strategies and instruments. However, if embodied carbon is not included in building decarbonisation targets, a failure to meet global decarbonisation targets is highly likely. This is because the total climate impact of buildings would remain only partly addressed. Thus, the need and potential for reducing embodied emissions requires attention and alignment as part of European and global efforts to combat climate change. Against the backdrop of increasing efforts to understand and reduce the whole life cycle of carbon in buildings, the project “Towards Embodied Carbon Benchmarks for the European Building Industry” was set up.

In particular, setting a performance system for embodied emissions at the building level can provide relevant guidance for policymakers and the building industry. Developing the foundations of such a performance system for new buildings has been the objective of the project “Towards Embodied Carbon Benchmarks for buildings in Europe”, set up by Ramboll and Build AAU - Aalborg University, with the support of the Laudes Foundation. This includes a baseline of current embodied carbon levels in new buildings, as well as consideration of the available carbon budget for these emissions. Together with a review of data availability and quality, these elements form the basis of a performance system in the form of benchmarks for reducing embodied carbon.

This project focused on the European Union (EU). This is due to its position as a pioneer in GHG emission reduction policies with instruments such as the Energy Performance of Buildings Directive, the Taxonomy for Sustainable Activities and the EU Climate Transition Benchmark Regulation. Additionally, the life-cycle perspective of buildings is receiving increased policy awareness. These instruments and initiatives will have an increased impact on the building industry. This project seeks to inform the current debate involving policymakers and industry alike and to stimulate the development and application of benchmarks for embodied carbon in the EU and beyond.

The series of reports produced as part of this project provides insights and developments on the following questions:

1. What data is available on embodied carbon in the EU?
2. Where are we now? What is the current status of embodied carbon in new buildings?
3. Where do we need to be? What level of embodied carbon is aligned with the available carbon budget?
4. How can we close the gap? How can benchmarks to reduce embodied carbon be set?

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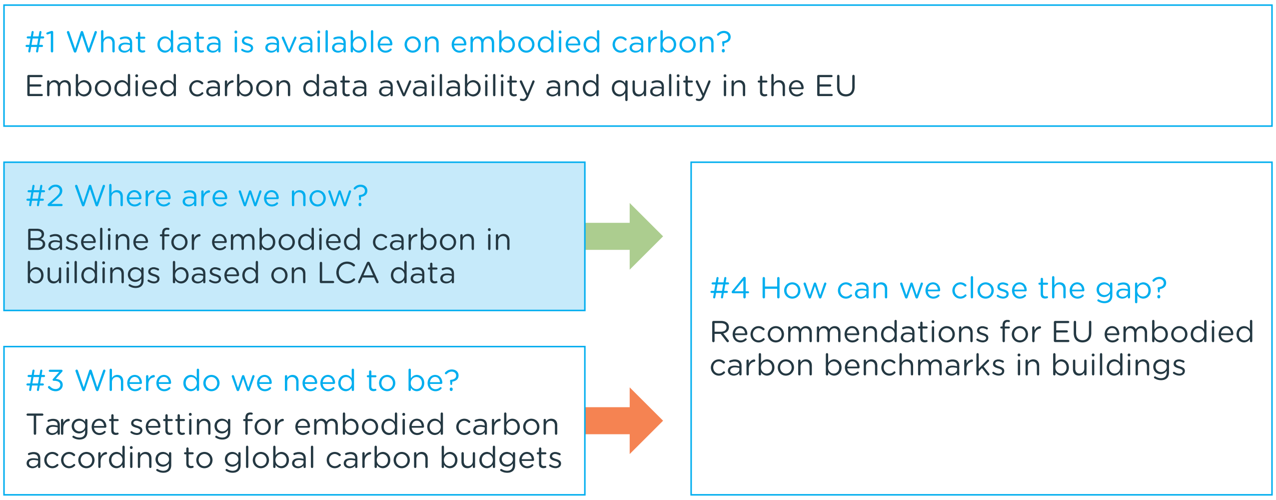
[3] Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, use phase, maintenance, repair, replacement, refurbishment, deconstruction, transport to end of life facilities, processing, disposal.

Figure 2: Overview of the series of reports produced under the "Towards Embodied Carbon Benchmarks for buildings in Europe" project



This particular report, the first in the series, aims at providing insights regarding embodied carbon baselines for new buildings across Europe. The objective is to provide an understanding of the current situation for embodied carbon across the whole life cycle of buildings, based on the data collected for building case studies from different European countries. The cases, obtained from various national partners, provide building-level data on whole life cycle embodied carbon, which were assessed using LCAs as defined in the relevant standard EN 15978, and using methods, data and tools from the respective countries.

A global meta-study by Röck et al. 2020 [2] investigated this matter, based on the analysis of hundreds of building life cycle assessment (LCA) studies. The meta-study reveals a trend of increased embodied GHG emissions for new buildings (Figure 3) and highlights the relevance of understanding and reducing the embodied GHG emissions in buildings in order to enable effective climate change mitigation: "While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases. Furthermore, this study analyses GHG emissions at time of occurrence, highlighting the 'carbon spike' from building production. [...] Considering global GHG reduction targets, these results emphasise the urgent need to reduce GHG emissions of buildings by optimising both operational and embodied impacts." [2]

Figure 3: Global trends in life cycle GHG emissions from buildings, showing a relative and absolute increase of embodied GHG emissions in new advanced buildings (as in [2], Figure 3.a).

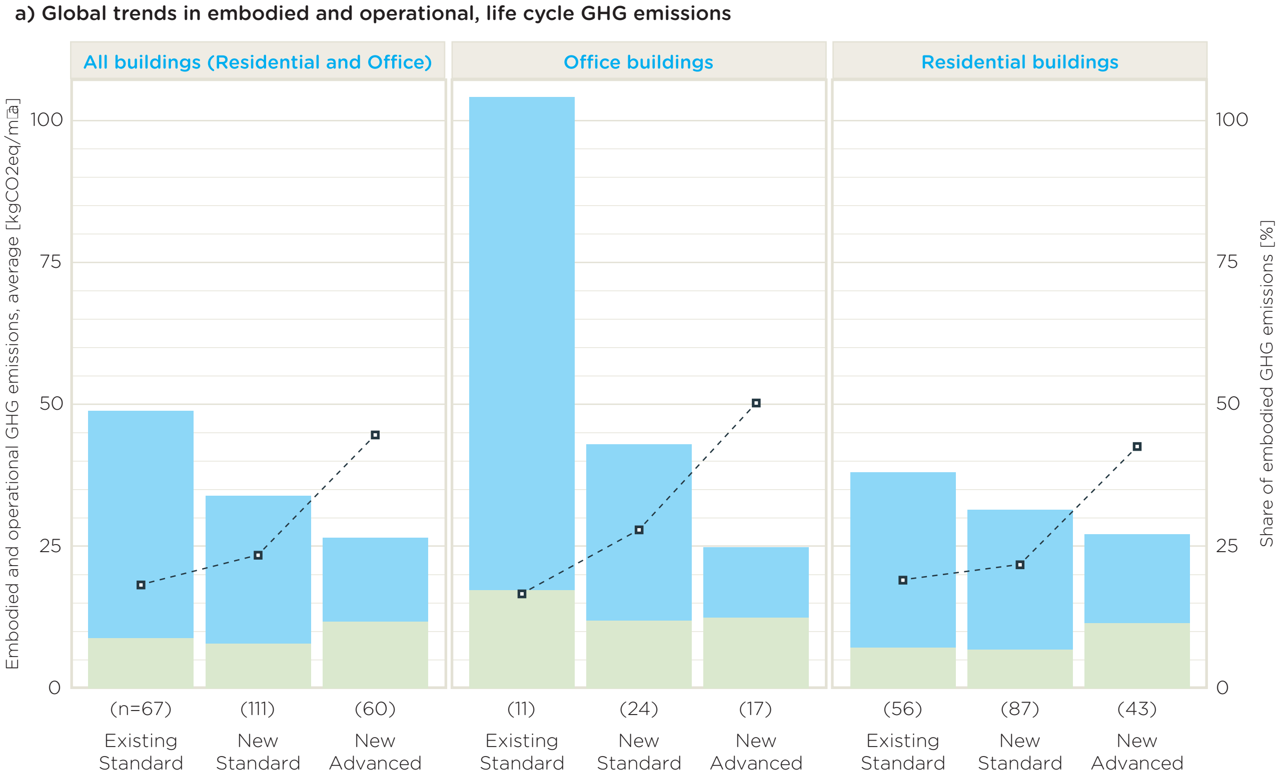


Figure 3 presents the results of the meta-study regarding the whole life cycle of GHG emissions for buildings in different energy performance classes (Existing standard; New standard; New advanced). The stacked bar charts show results for both embodied (red) and operational (blue) emissions, respectively. The dashed line expresses the relative share of embodied GHG emissions [%] within whole life cycle emissions and highlights the evolution and increasing share of embodied emissions for new buildings. The three boxes distinguish results based on subsets of the data for different building use types (Left box: residential buildings and offices, centre box: office buildings, right box: residential buildings).

Based on these results, this report aims at providing insights into the following research questions:

1. What is the baseline for whole life cycle embodied carbon (EC) for buildings in Europe?
   a. What are EC baselines for different building types per m^2 and per capita?
   b. What is the contribution to EC from different life cycle stages or building parts?
   c. What is the variation of EC considering differences in building design and methods?
   d. What are the indicative pathways for reducing buildings' EC by 2030, 2050?

Disclaimer: In this report, the widely used term 'embodied carbon' is applied. The term is considered synonymous with 'embodied GHG emissions'. The data and values presented in the following consider both CO2 and non-CO2 GHG emissions.

2. Methods and materials

2.1 Data status screening

As a first step in this study, and to identify potential partners and data sources, relevant stakeholders across Europe were contacted and interviewed on the state of building LCA methods, tools and data, as well as on the building-level benchmarks and targets, in their respective countries. An overview of the findings from country screening and data status across European countries is provided in Figure 4. One of the main goals and outcomes of the screening process was the identification of five countries where data partners would be able and willing to provide a relevant sample of building LCA data as a basis for analysing the baseline for embodied carbon benchmarks in the European building industry. A threshold of 50 cases per country was aimed at to enable meaningful analysis based on a diversity of building types and related variations in materialisation and building technologies, as well as methodological approaches.

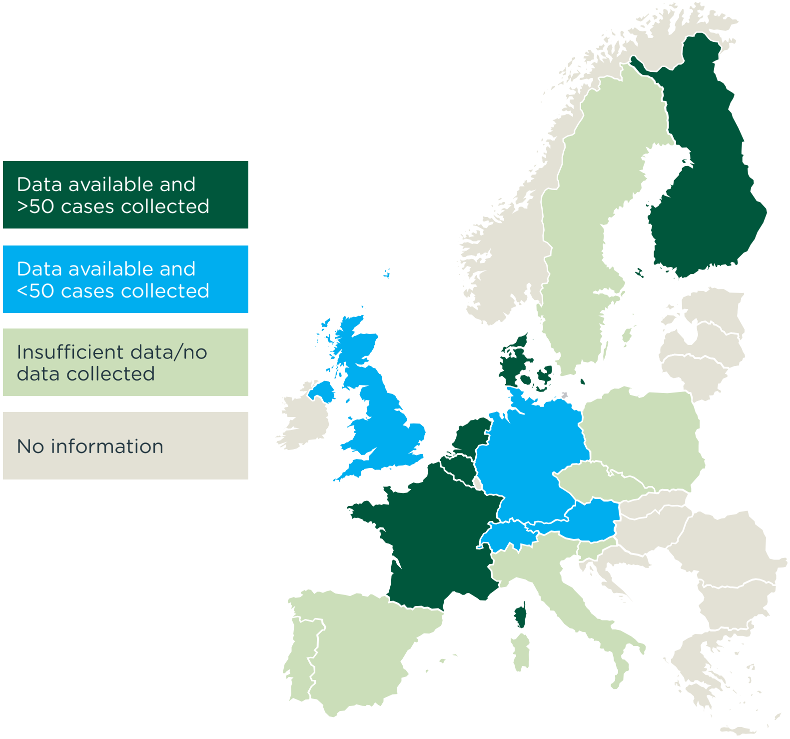


Figure 4: Overview of status from building LCA data screening and collection across European countries.

The lessons learnt from this data status analysis process have been provided as an additional output of the study. The report describes the overall data situation in the different countries in relation to the building LCA data collection and analysis used in this project, as well as the insights into the status of LCA methods, LCA-based regulation of buildings, and key actors and contact persons identified in the respective regions.

2.2 Data sources and partners

This report provides embodied carbon baselines based on building LCA data from the five European countries which were each able to provide around 50 cases for the analysis. The threshold of 50 cases was determined by the project team to gain an initial understanding of data availability and to enable meaningful statistical analysis to be undertaken on a suitable number of cases in terms of diverse types of building use, structure, etc. The data screening process enabled the five countries and related data partners listed in Table 2 to be identified.

Table 2: Main five pilot countries and related data partners

Country	No. of cases	Data partner(s)
Belgium	105	KU Leuven
Denmark	72	AAU BUILD, Ramboll
Finland	59	Ministry of Environment, One Click LCA, Granlund
France	486	Ministry for Ecological Transition, CSTB
Netherlands	47	NIBE, W/E advisors, DGBC
Total	769	'EU-ECB dataset'

Beyond these five countries, which serve as the core partners in this baseline study, data from other sources and partners across Europe were also identified and obtained, which were then used to inform our understanding of the current state of embodied carbon benchmarks, as well as the potential future steps for this initiative.

Amongst the other data obtained were cases provided by national partners in Austria, Germany, Switzerland and the United Kingdom. Furthermore, the study identified, implemented and analysed data from existing databases on embodied and whole life cycle carbon, such as: The Carbon Leadership Forum (CLF) Embodied Carbon Benchmark Study[4]; the Royal Institution of Chartered Surveyors' (RICS) Building Carbon Database[5]; the building LCA meta-study data[6] by Röck et al. [2] established in the context of the IEA EBC Annex 72 project on assessing life cycle related environmental impacts caused by buildings [3]. These data have not been included in the analysis presented in this report, but, where available, will be published as part of the EU-ECB dataset to be available for future studies.

Data from these various sources and countries were obtained and processed, with the analysis focusing on the data from the five pilot countries specified in Table 1. The data compiled from these sources is henceforth referred to as the 'EU-ECB dataset'.

2.3 Data processing and harmonisation

The baseline presented in this study is based on the analysis of existing LCA data on building cases from different countries. This required differences in the data to be considered, e.g. variations in assessment methods and scope of studies, as well as limitations in data sharing due to confidentiality concerns. Therefore, substantial pre-processing and harmonisation was undertaken in order to ensure that the data could be analysed consistently. To improve the comparability between the studies, harmonisation procedures were also undertaken, for example to harmonise the reference study period (RSP) for the various studies to a common timeframe of 50 years. Furthermore, statistical approaches for inferring missing data in order to improve the completeness and size of the dataset were also implemented, for example: raising the value of the data for further use in research and practice, on the basis of the observed contribution from different life cycle stages or buildings parts.

Further information on the methods and materials used, such as an overview of the attributes on which information was collected through our data collection template, the data structures, steps and scripts applied for processing, as well as the formulae applied to harmonise the embodied carbon emission values, is provided in the "Supplementary Methods" section.

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4. Available via https://carbonleadershipforum.org/embodied-carbon-benchmark-study-1/
5. Available via https://wlcarbon.rics.org/Default.aspx
6. Related publication available open access via https://doi.org/10.1016/j.apenergy.2019.114107

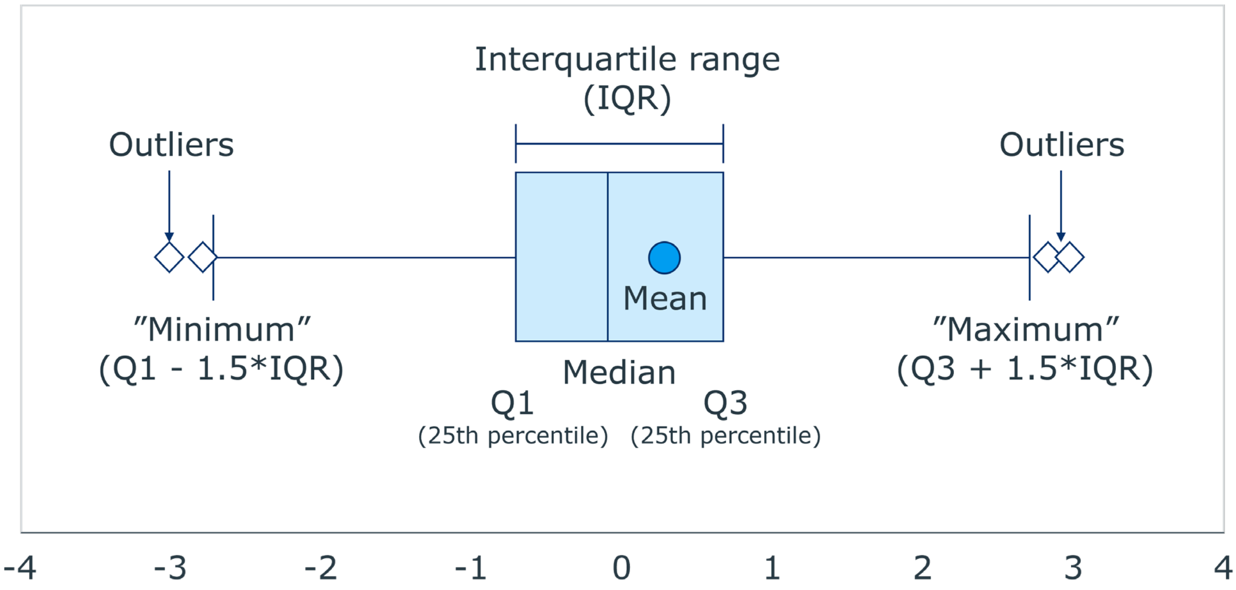
3. What are the current levels of embodied carbon?

3.1 General remarks on embodied carbon baselines

The results of our analysis of the embodied carbon baselines are presented in the section below. They are divided into different, relevant categories, for example: different types of building use or structural system. Furthermore, this chapter presents an analysis of the contribution made by the different life cycle stages or building parts to a building's whole life cycle of embodied carbon.

The reference unit applied for presenting the embodied carbon baseline is CO2 equivalent per m^2 gross floor area (kg CO2e/m^2) or capita (kg CO2e/cap), respectively. These values express the harmonised totals of embodied whole life cycle carbon over the harmonised timeframe of 50 years. The decision to present harmonised totals rather than annualised values (e.g. kg CO2e/m^2/year), as is often the case, is based on our understanding of the importance of taking into consideration the timing of emissions – a piece of information which is obstructed in annualised values, as these suggest a spread of emissions across the building life cycle. However, as will be shown in the following section, **embodied carbon emissions mostly occur upfront**, i.e. in the production of the construction materials used in a new building.

Figure 5: Infographic explaining the boxplot representation and its elements (e.g. median, mean, 1st and 3rd quartiles)



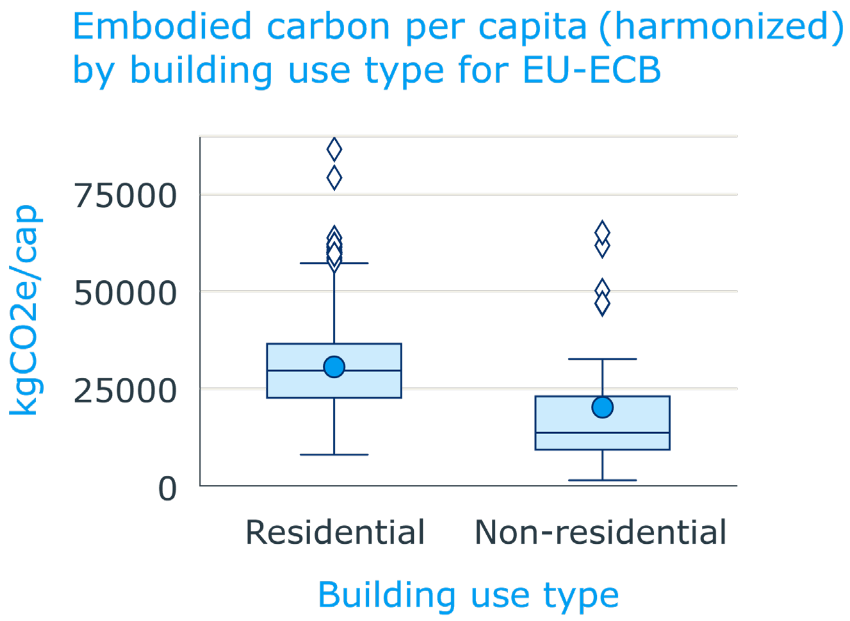
The figures presented in Figure 5 above are mostly boxplots which follow established conventions. The line in the box represents the median value, i.e. the middle value of cases in the dataset. A single white-filled circle represents the mean value, i.e. the statistical average of values in the dataset. It was chosen to show both median and mean as these can differ substantially, depending on the composition and skewedness of a given dataset. The box boundaries indicate the interquartile range (IQR), limited by the first and third quartile, i.e. 25th and 75th percentile, respectively. The upper and lower whisker show values up to Q1 and Q3 minus/plus 1.5 times IQR, respectively. Data points outside of this range are considered extreme values ("outliers") and are shown as individual rhombic shapes.

While the main part of the report focuses on presenting the results based on the combined EU-ECB dataset, so as to not overload the report, the additional analyses of the embodied carbon baseline, for example per country, or considering the differences in the scope of the studies, or the influence of different construction materials, as well as the annualised baseline values, are provided in the "Supplementary Results" section.

3.2 Baseline for different types of building use

3.2.1 Life cycle embodied carbon per m^2

Figure 6: Harmonised life cycle embodied carbon per m^2 gross floor area by building use type based on the EU-ECB dataset



Firstly, the whole life cycle embodied carbon baseline is analysed for different types of building use, based on the combined EU-ECB dataset, which includes data from five countries, as presented in Table 1. Figure 6 presents the full life cycle embodied carbon (EC) baseline for residential and non-residential buildings, respectively. **It shows that EC values for residential buildings range from around 400 to 800 kg CO2e/m^2 with a mean value of around 600 kg CO2e/m^2. For non-residential buildings, a wider spread of EC values can be observed, ranging from around 100 to 1200 kg CO2e/m^2, with mean values of around 600 kg CO2e/m^2**. The reason for the large variance in the non-residential building results is likely, among other aspects, to be due to the wide difference in building sub-types grouped together in this category.

Figure 7: Harmonised life cycle embodied carbon per m^2 gross floor area by building use subtype based on the EU-ECB dataset

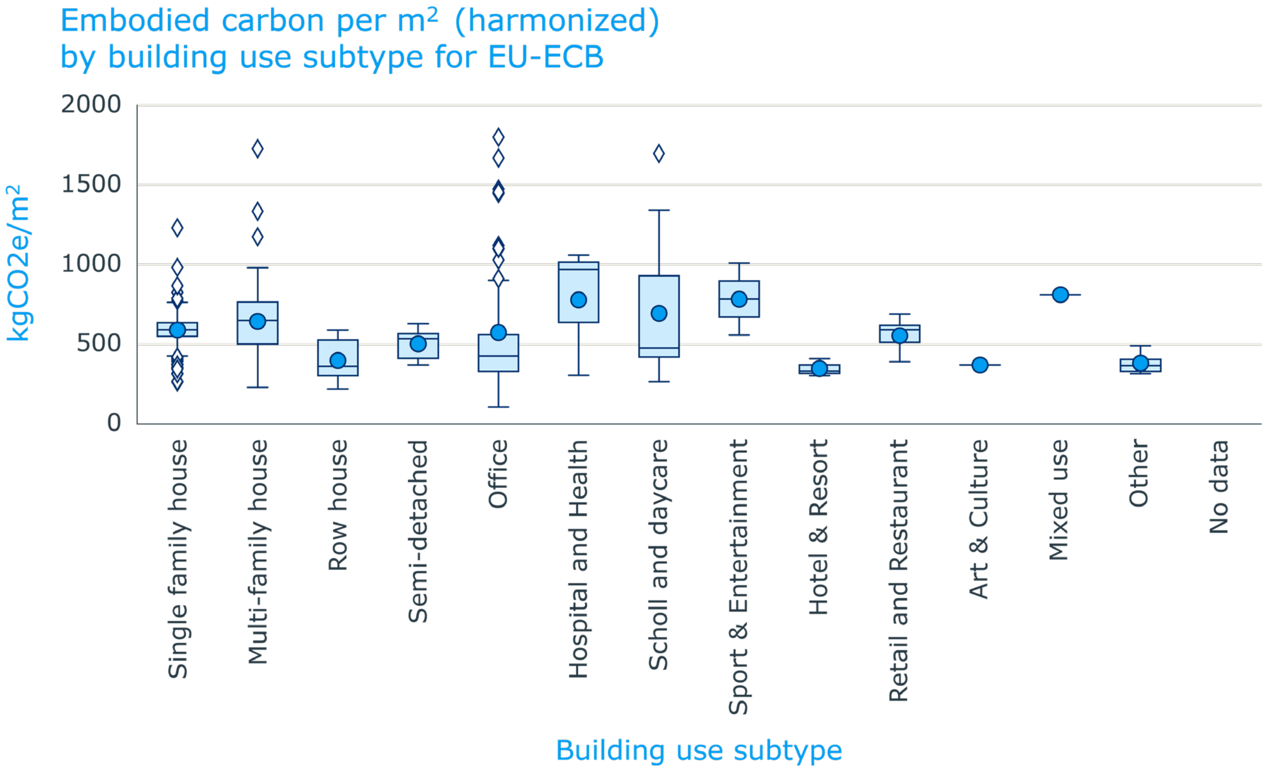


Figure 7 presents the life cycle embodied carbon baseline for different subtypes of building use. The first four categories presented on the horizontal axis represent residential building types. Out of these, the highest per-m^2 values are found for multi-family houses, with a mean value of around 700 kg CO2e/m^2. The lowest per-m^2 values are observed for terraced (row) houses, with mean values of around 400 kg CO2e/m^2. The other categories on the horizontal axis represent non-residential building types. For these, the highest per-m^2 values can be observed for 'hospital and health' and 'sport and entertainment' buildings, with mean EC values of around 800 kg CO2e/m^2 for both. 'Office' buildings weigh in with a mean EC value of around 600 kg CO2e/m^2, while displaying a large variation of EC values with multiple outliers. A wide spread and high values are furthermore observed for 'school and daycare' buildings, with a mean value of around 750 kg CO2e/m^2.

Detailed analyses of EC baselines for different types and subtypes of building use in the different countries, as well as tables presenting the related descriptive statistics, are provided in the "Supplementary Results" section.

3.2.1 Life cycle embodied carbon per capita (number of users)

To further investigate the influence of different types of building use and the related differences in occupational density, the study collected information on the number of users in the respective buildings in order to calculate the embodied carbon baseline per capita. In this approach, an estimated number of users was specified for each individual case study, based on the number of beds for residential buildings. For non-residential buildings, the indicators used for the number of users were the number of working desks (office buildings), patient beds (hospitals) or number of students or children cared for (schools and daycare), respectively. Again, the harmonised total of embodied carbon is presented across the whole life cycle, as obtained through analysing the building LCA cases from the main five countries (Table 1).

Figure 8: Harmonised life cycle embodied carbon per capita by building use type based on the EU-ECB dataset

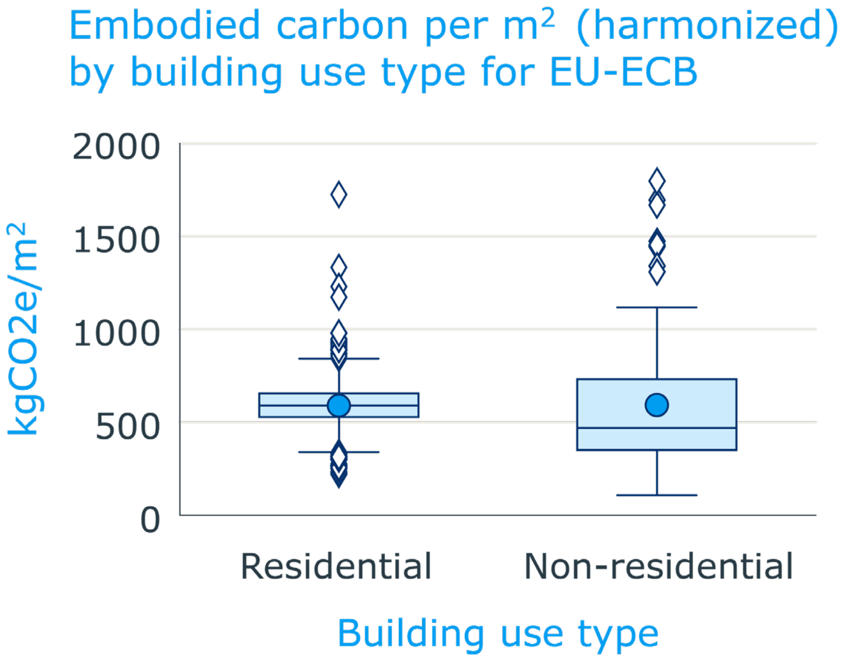


Figure 8 presents the embodied carbon baseline per capita for the different building types. For residential buildings it shows a mean value of around 32 t CO2e/cap, with values ranging from 5 to almost 60 t CO2e/cap. For non-residential buildings, values range from around 2 to 35 t CO2e/cap, with a mean value of around 20 t CO2e/cap.

Figure 9: Harmonised life cycle embodied carbon per capita by building use sub-type based on the EU-ECB dataset

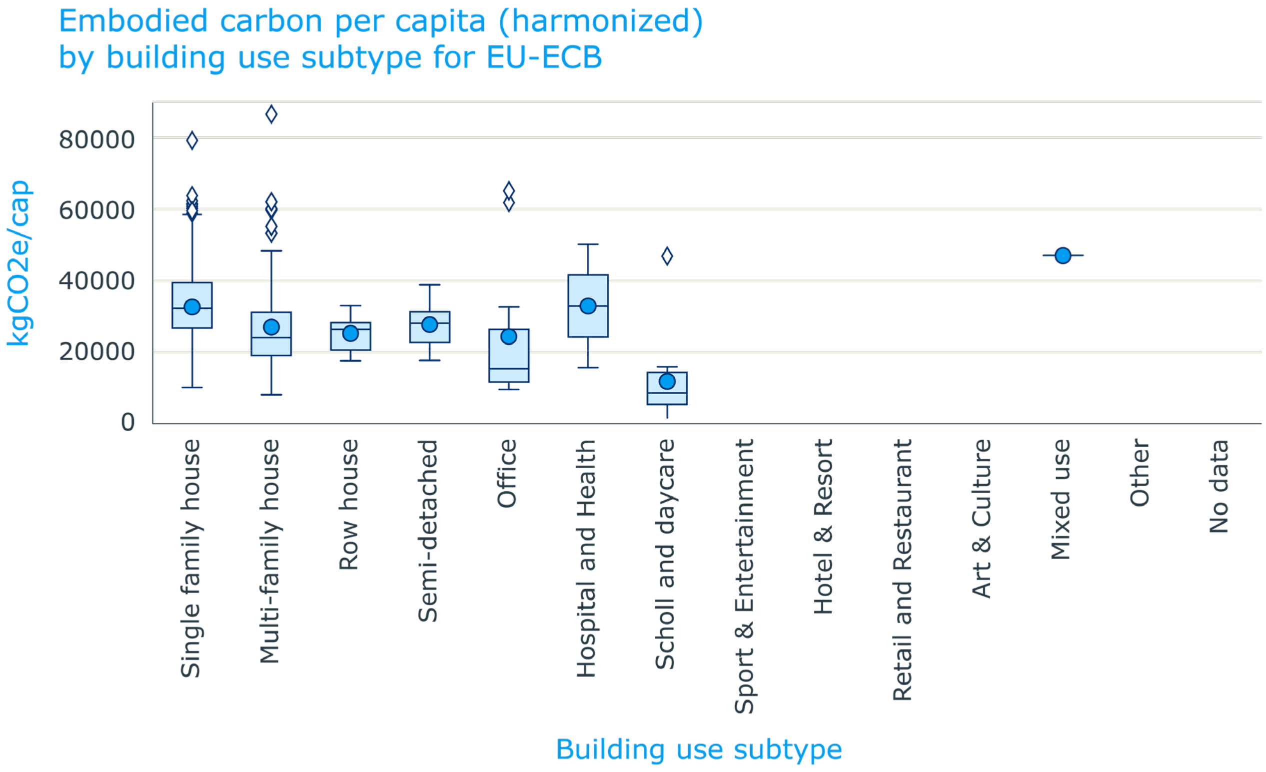
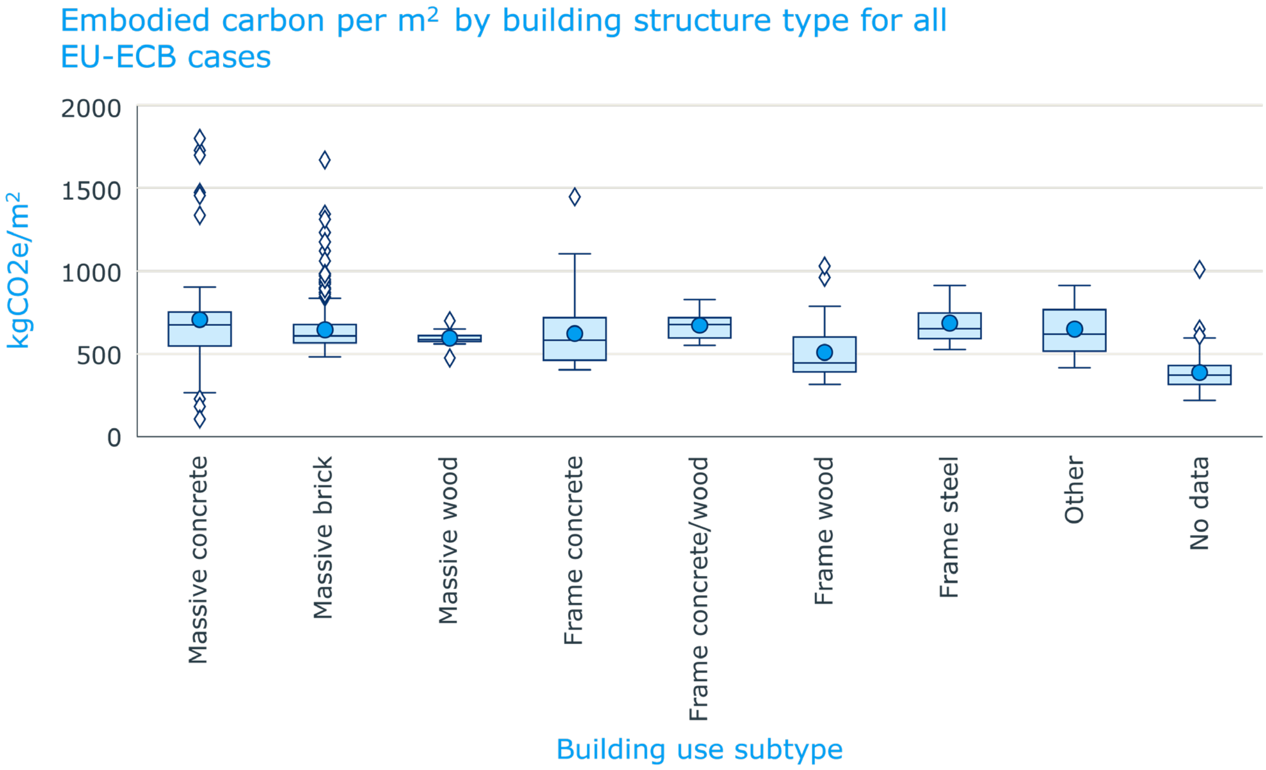


Figure 9 shows the analysis of EC baselines per capita for different building use subtypes. It reveals several substantial differences to the per-m^2 analysis. **On a per capita basis, the EC baseline for residential buildings is lowest for multi-family houses and terraced/row houses**, with a mean value of around 26 t CO2e/cap and 24 t CO2e/cap, respectively. **Single family houses show the highest life cycle embodied carbon amongst the residential buildings** with a mean value of around 33 t CO2e/cap. The range of EC values per capita for the different building types, and the differences observed from the per-m^2 baseline, highlight **the significant influence of the number of users in the respective house/apartment on the per-capita type of metric**.

Information on per capita values for non-residential buildings is only available for very few subtypes, due to limitations in providing valid estimates of the number of users for the different buildings. As shown in Figure 9, the mean per-capita value is around 24 t CO2e/cap for office buildings; around 33 t CO2e/cap for hospital and healthcare buildings; and a remarkably low value of approximately 10 t CO2e/cap for school and daycare buildings, respectively. The low values for school and daycare building might be related to the high occupational density (users per m^2) in those buildings, when compared to other non-residential and residential building types.

3.3 Baseline for different types of structures and materials

Figure 10: Harmonised life cycle embodied carbon per m^2 by type of building structure based on the EU-ECB dataset



To improve understanding of the influence the different types of building structures and materials have, the plot shows embodied carbon values per m^2 in Figure 10. The categories displayed on the horizontal axis are combinations of the type of structural system (massive, frame) and the main structural material (steel, concrete, brick, wood), respectively. Comparable values for all massive options are observed, with **massive concrete buildings showing the highest mean value – around 750 kg CO2e/m^2 - as well as the widest spread, ranging from approximately 250 to 900 kg CO2e/m^2**, with outliers approaching 1850 kg CO2e/m^2. Massive brick cases display a mean of around 700 kg CO2e/m^2, with various outliers ranging up to 1700 kg CO2e/m^2. **Values for massive wooden buildings show only minor variations, with a mean of around 600 kg CO2e/m^2**. For frame type structure buildings, Figure 10 again shows a wide variation for concrete frame buildings, ranging from around 400 up to 1200 kg CO2e/m^2, with the mean being around 650 kg CO2e/m^2. **The lowest**

life cycle embodied carbon values per m² are observed for wood framed buildings, with a mean value of around 500 kg CO2e/m², and ranging from 300 to 800 kg CO2e/m². Somewhat surprisingly, the cases of hybrid concrete/wood framed structures show a mean value of around 700 kg CO2e/m², comparable with that of massive concrete structure buildings. Similarly, the mean value for cases of steel framed structures is around 700 kg CO2e/m², comparable to that of cases of hybrid concrete/wood framed structures and massive concrete structures. Cases that could not be clearly identified due to missing information were categorised under 'other' or 'no data' and do not fall outside of the familiar range of values observed from the known types of structures and materials.

Overall, the analysis suggests that frame structures alone do not necessarily lead to lower embodied carbon values on average when compared to massive structures. Cases using wood as their main structural material in both massive and frame systems lead to the lowest values for the respective type of structural system, showing mean values of around 100 to 200 kg CO2e/m² lower than other material options for massive and frame cases, respectively. The lowest embodied carbon mean values are therefore observed for the wood framed cases. A detailed overview of the life cycle embodied carbon mean values for buildings with different types of structure, in the different countries, is provided in Table 3.

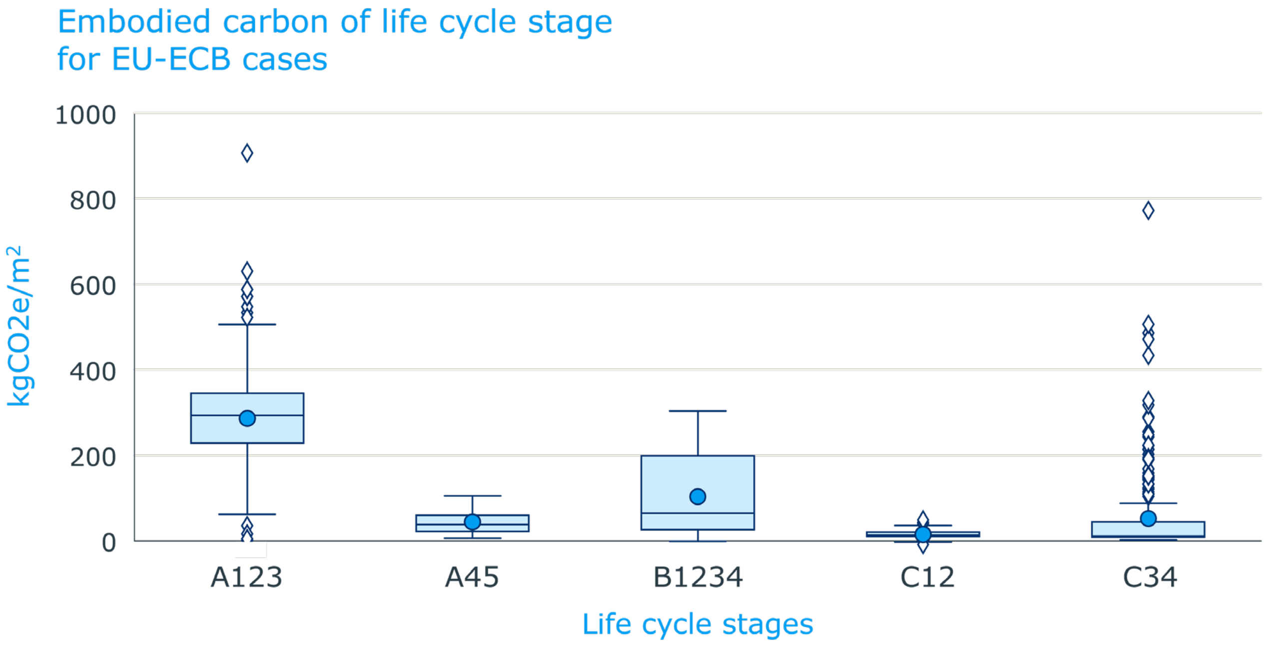
Table 3: Life cycle embodied carbon (mean) for buildings with different types of structure [kg CO2e/m²]

Metric \ Type of structure		BE	DK	FI	FR	NL	EU-ECB
mean	All structures	591	352	497	661	389	591
	frame concrete	-	-	516	759	-	622
	frame concrete/wood	-	-	-	672	-	672
	frame steel	-	-	610	912	-	685
	frame wood	464	-	395	610	-	509
	massive brick	655	-	-	643	-	645
	massive concrete	-	318	655	806	-	707
	massive wood	-	-	475	600	-	595
	No data	-	359	509	-	389	388
	other	-	-	517	913	-	649

Further analyses on the baseline for different types of structures and materials for the different countries in the EU-ECB dataset are presented in the "Supplementary Results" section.

3.4 Contribution from different life cycle stages

Figure 11: Harmonised embodied carbon per m² for different life cycle stages (A123, A45, B1234, C12, C34), based on the EU-ECB dataset



In order to provide further insights into the timing of embodied carbon emissions along the building life cycle, the study investigated the contribution from different life cycle stages. The definition of the life cycle stages is based on EN 15978. Embodied carbon emissions are hence disaggregated as occurring during: the production stage (A1-3); the construction process stage (A4-5); the use stage for use, cleaning, maintenance, and replacement (B1-4); and the end-of-life stage, differentiated into the deconstruction process and transport (C1-2) and waste processing and disposal (C3-4). This way of looking at embodied carbon emissions enables us **to understand which amounts of carbon emissions are occurring 'upfront' for new building production and construction**, i.e. A1-3 and A4-5, at certain points in time during the use phase (B1-4), or at the end of the service life (C1-2, C3-4), respectively. Benefits and loads beyond the system boundary (module D), while requested to be documented in our data collection, were not represented in the visualisations, largely due to the methodological discussions on how to model these and the related wide variation in the results values and their general availability, remaining unsettled.

Figure 11 presents these embodied carbon emissions for the different life cycle stages. It shows that **the largest contribution of embodied carbon emissions occur during the production stage (A1-3), with a mean value of around 300 kg CO2e/m²**, and ranging from around 70 to 520 kg CO2e/m². **The second largest proportion of embodied carbon emissions occur during the use phase (B1-4), with a mean value of around 120 kg CO2e/m²**, which represents the total of emissions from cleaning, maintenance, replacement activities taking place over a 50-year reference study period. Similar to emissions from the production phase (A1-3), the use phase embodied carbon emissions (B1-4) show a large variation in the values from 0 to around 350 kg CO2e/m², which most likely depends on parameters such as the type of building use, the structural system and the material choices, as well as the climate and weather conditions. It is further relevant to note that there were variations in the scope of the studies regarding the individual life cycle modules considered in the use stage, i.e. not all the studies covered all the modules of the use stage (B1-4), with, for the most part, aspects such as cleaning or maintenance potentially being missing. In extreme cases, the embodied carbon emissions occurring during the use stage (B1-4), reached the average level displayed during the production stage (A1-3). The other life cycle stages represented minor contributions to the whole life cycle embodied carbon emissions. The construction process stage (A4-5) shows a mean value of around 40 kg CO2e/m². For the end-of-life stage, deconstruction and transport (C1-2) show a mean value of less than 20 kg CO2e/m², and waste processing and disposal (C3-4) indicate a mean value for emissions of around 60 kg

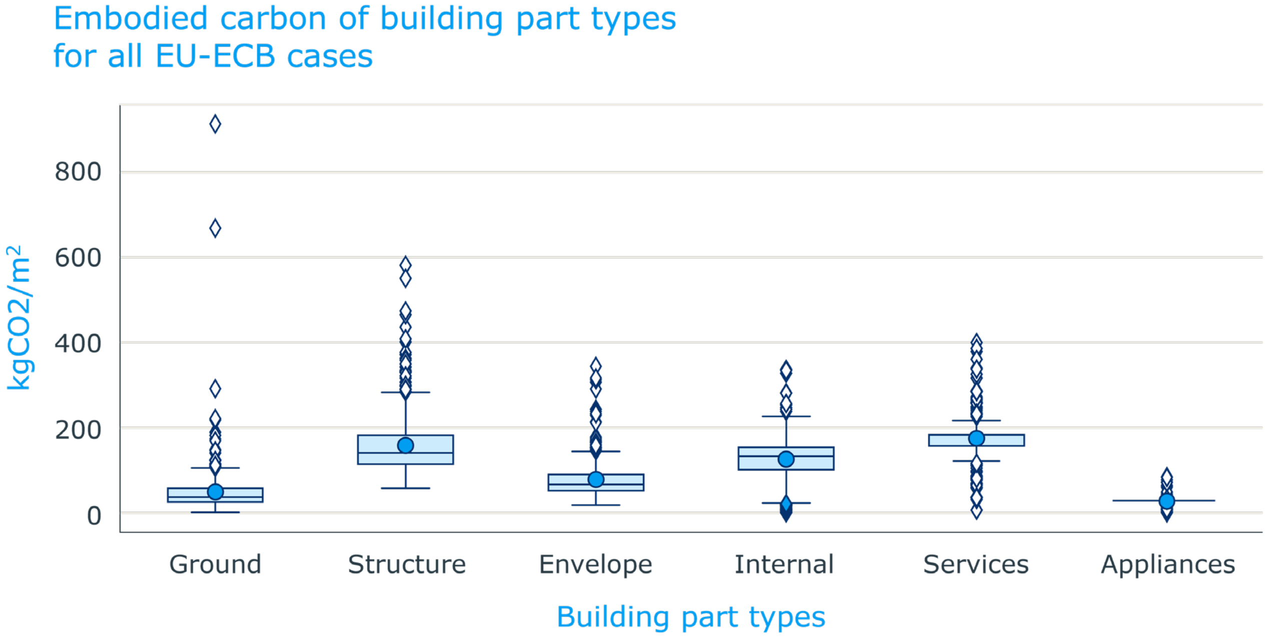
Table 4: Mean contribution to full life cycle embodied carbon [kg CO2e/m²] from different life cycle stages

	Production stage	Construction process	Use stage	End of life stage NL	
	A1-3	A4-5	B1-4	C1-2	C3-4
Absolute (mean)	300	40	120	20	60
Relative (mean)	56%	7%	22%	4%	11%

Further analyses of the contribution made by the different life cycle stages, e.g. for different building types, are provided in the "Supplementary Results" section.

3.5 Contribution from different building parts

Figure 12: Harmonised full life cycle embodied carbon per m² for different building parts



Alongside the interest in 'when' embodied carbon emissions occur (i.e. the life cycle stages), another goal of this study was to understand 'where' the main contributors are in terms of the contribution made by the main building parts. Figure 12 shows the embodied carbon per m² for different building parts.

Table 5 shows the mean contribution from different building parts to the full life cycle embodied carbon in both absolute and relative terms.

Table 5: Mean contribution to life cycle embodied carbon emissions [kg CO2e/m²] from different building parts

	Ground	Load-bearing structure	Envelope	Internal	Services	Appliances
Absolute (mean)	50	170	110	150	190	40
Relative (mean)	7%	24%	15%	21%	27%	6%

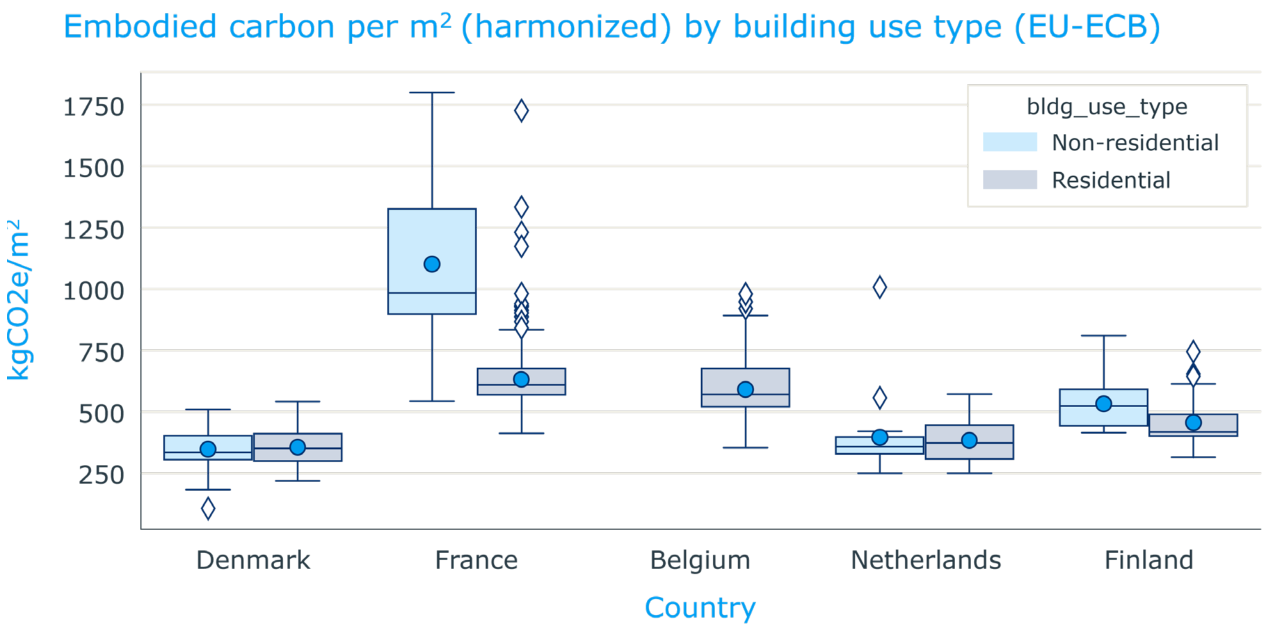
Figure 12 shows the embodied carbon per m² from the different building part groups (Ground, Load-bearing structure, Envelope, Internal, Services and Appliances). It shows that a major contribution to the life cycle embodied carbon emissions, on average, stems from the technical services (e.g., heating, cooling, domestic hot water and sewage systems), with a mean value of around 190 kg CO2e/m², ranging from 170 to 230 kg CO2e/m². Major contributions are further observed from the load-bearing structure (e.g. structural frame, walls, floors), with a mean value of around 170 kg CO2e/m² and ranging from 50 to 320 kg CO2e/m², as well as internal elements (e.g. partition walls, floor and wall finishes), with a mean value of around 150 kg CO2e/m² and ranging from 30 to 250 kg CO2e/m². The envelope (e.g. external insulation, windows) contributes approximately 110 kg CO2e/m², with a core range from 20 to 170 kg CO2e/m². Building parts related to the ground (e.g. foundation, basement), show an average contribution of around 50 kg CO2e/m², ranging from close to 0 to 120 kg CO2e/m². Appliances (e.g. kitchen equipment, laundry washing machines) fairly consistently contribute around 40 kg CO2 CO2e/m².

It is important to note that this contribution analysis is based on the data obtained from France, where proxy values are being used to close data gaps in the case of information being missed for certain buildings parts, such as the technical systems and appliances. These proxy values purposely over-estimate the contribution of said building parts to create an incentive to specifically include said elements in the detailed assessment.

Further analyses on the contribution made by the different building parts for the different types of building use, including the differences in the variation of the respective emissions values, are presented in the "Supplementary Results" section.

3.6 Variation for different countries

Figure 13: Harmonised life cycle embodied carbon per m² by building use type for the five different countries in the EU-ECB dataset



The baselines presented in the previous sections draw on the data from the combined EU-ECB dataset, i.e. data from the five main countries as described in Table 1. Figure 13 shows the embodied carbon emission baseline values per m^2 for the main types of building use in the respective country datasets side by side.

What immediately stands out in Figure 13 are the high values displayed for non-residential buildings in the data from France. These show a mean value for full life cycle embodied carbon emissions of around 1100 kg CO2e/m^2, ranging from 550 to more than 1800 kg CO2e/m^2. This is considerably higher than the values observed for non-residential buildings in the data from Denmark or the Netherlands, which display mean values of between around 350 to 400 kg CO2e/m^2, respectively. The data on non-residential buildings from Finland suggests a slightly higher mean value close to 550 kg CO2e/m^2, ranging from 450 to 850 kg CO2e/m^2. The building cases obtained for Belgium do not include non-residential buildings.

For residential buildings, the picture is more consistent, even though differences between the country sets prevail to some degree. The values for residential buildings in the datasets for Denmark and the Netherlands display comparable mean values of between around 350 to 385 kg CO2e/m^2, respectively, and values ranging from around 200 to 650 kg CO2e/m^2 for both. Values for residential buildings in Belgium and France are of a comparable magnitude and are a bit higher, with mean values of around 590 to 635 kg CO2e/m^2 and a range of 400 to 850 kg CO2e/m^2. The variation of average values between the different countries is therefore around 250 kg CO2e/m^2. Residential buildings in Finland show mean values of just above 450 kg CO2e/m^2, ranging from around 400 to 650 kg CO2e/m^2. Table 6 gives an overview of the number of cases and the specific mean values for the main building use types from the different countries.

Table 6: Life cycle embodied carbon for different building use types per country [kg CO2e/m^2], where count is the number of cases in each data subset and mean is the average embodied carbon from said subsets.

Metric \ Type of structure		BE	DK	FI	FR	NL	EU-ECB
mean	Non-residential	-	34	31	27	18	110
	Residential	105	38	28	434	29	634
	All types	105	72	59	461	47	744
mean	Non-residential	-	348	532	1102	397	593
	Residential	591	356	457	634	385	591
	All types	591	352	497	661	389	591

The variation observed between the countries is comparable to that which was found for the mean full life cycle embodied carbon emission values for the different building use subtypes (variance of up to ~650 kg CO2e/m^2) or for the different types of structural systems and materials (~250 kg CO2e/m^2), respectively.

It is expected that the variation of values observed for the different countries occurs due to multiple aspects, such as: differences in building design choices (e.g. common types of structural systems and main construction materials in the respective country), differences in the composition of the datasets (e.g. regarding the number of cases for different building types, as well as the number of cases in total), and also due to differences in the assessment methodology used, and the background data and tools applied in assessing life cycle carbon emissions in the respective countries.

Further analyses of baselines and contributions, differentiated by each individual country in the EU-ECB database, are provided in the “Supplementary Results” section for both the original and harmonised embodied carbon emission values.

3.7 Variation for different scopes

In aiming to understand the drivers of the variation even further, the study investigated the potential influence of the building assessment scope regarding the life cycle stages and the building parts covered in the respective case studies. The values presented below are based on cases that include different life cycle stages, considering: production (P); construction process (C); cleaning, maintenance and replacement (M), deconstruction and transport (D); as well as waste processing and disposal (W). The abbreviations used in the building parts scope refer to the different building parts, namely: ground (G), load-bearing structure (L), envelope (E), internal elements (I), technical systems (S), and appliances (A).

Table 7 shows the mean harmonised total of life cycle embodied carbon emissions for each life cycle stage and building parts scope combination, based on the combined EU-ECB dataset. Table 8 shows how the full life cycle embodied carbon values from each of these combinations compare to the 'full scope', i.e. GLEISA-PCMDW, studies of the same building type. The ratios are based on the harmonised mean values per m^2, as presented in Table 7.

Table 7: Life cycle embodied carbon (mean) for different building use types and scopes of life cycle stages (LCS) and buildings parts (harmonised) [kg CO2e/m^2]

	Non-residential		Residential	
Parts \ LCS	Full life cycle scope (PCMDW)	Limited life cycle scope (PMW)	Full life cycle scope (PCMDW)	Limited life cycle scope (PMW)
Full parts scope (GLEISA)	819.80	264.69	618.19	-
w/o Ground (LEISA)	810.00	-	481.63	-
w/o Internal (GLESA)	-	-	599.19	-
w/o Appliances (GLEIS)	523.18	349.19	575.49	356.67
w/o Internal & Appliances (GLES)	-	404.50	-	-
w/o Services & Appliances (GLEI)	-	-	-	343.00

Table 8: Ratio [%] of life cycle embodied carbon for different building use types and scopes of life cycle stages and buildings parts when compared to 'full scope', i.e. GLEISA-PCMDW, based on harmonised mean values per m^2

	Non-residential		Residential	
Parts \ LCS	Full life cycle scope (PCMDW)	Limited life cycle scope (PMW)	Full life cycle scope (PCMDW)	Limited life cycle scope (PMW)
Full parts scope (GLEISA)	100%	32%	100%	-
w/o Ground (LEISA)	99%	-	78%	-
w/o Internal (GLESA)	-	-	97%	-
w/o Appliances (GLEIS)	64%	43%	93%	58%
w/o Internal & Appliances (GLES)	-	49%	-	-
w/o Services & Appliances (GLEI)	-	-	-	55%

Overall, Table 7 shows that the embodied carbon emission mean values tend to increase the more complete the scope of the assessment is. Average values for embodied carbon emissions herein range from around 350 to 820 kg CO2e/m^2 for non-residential buildings and around 345 to 620 kg CO2e/m^2 for residential buildings, respectively. As would be expected, the scope combination with the highest mean value stems from the cases with a 'full scope', i.e. the PCMDW-GLEISA combination. However, there are also some unexpected results. For non-residential cases, a large difference is observed between cases that do and do not include appliances (A), where the mean values show 64% EC compared to the full scope cases. For residential cases, the results show a large difference between GLEISA and LEISA cases for residential buildings of around 19%, which suggests that such a difference could stem from including, or not, the ground structure (G) in the assessment (while in non-residential cases this seems to have a negligible influence of only 1%). For residential cases, besides the aforementioned large influence from the ground structure, a very small variation is observed in the different building parts scopes. The studies seem to cover 93% and 97% compared to the full scope when including internal elements and appliances, respectively. In general, the results show a large difference between the studies of different life cycle scopes. For studies with the GLEIS building parts scope, the mean values are 20% to 35% for PMW below the related PCMDW cases of non-residential and residential buildings, respectively. It is noted that these differences could stem from our definition of the life cycle stage M, which was assigned once one of the related processes (maintenance, cleaning, and replacement) was within the scope of the study. Therefore, studies which did not include the replacement of building parts may still have had this scope assigned to them, but they yielded substantially lower results. Furthermore, it was difficult to compare the other PMW scoped studies, as only 1-2 of the studies with this life cycle scope were available per building parts scope.

The findings of this analysis suggest that **the scope of the building case studies, regarding building parts and life cycle stages included in the assessment, considerably alters the outcome**. In order to identify the influence of the difference in that regard, we recommend defining documentation standards for the building LCA studies that do consider and request, not only information regarding the scope of the studies, but also the provision of detailed, disaggregated carbon emission values for the individual building parts and their different life cycle stages. Having more data with this level of detail and disaggregation would enable us to gain an increased understanding and better benchmarking of the contribution from the different buildings parts and life cycle stages. It could also support the application of machine learning methods to infer missing values and thus close ongoing data gaps.

Further information regarding the data and number of cases underlying this analysis of the influence made by the scopes is available in the "Supplementary Results" section.

4. How can these results be interpreted?

4.1 Contextualising the results with other studies

4.1.1 Life cycle embodied carbon in new buildings

Figure 14: Comparison of life cycle embodied carbon benchmarks with existing reference values by country and sources for residential buildings (top) and non-residential buildings (bottom), respectively.

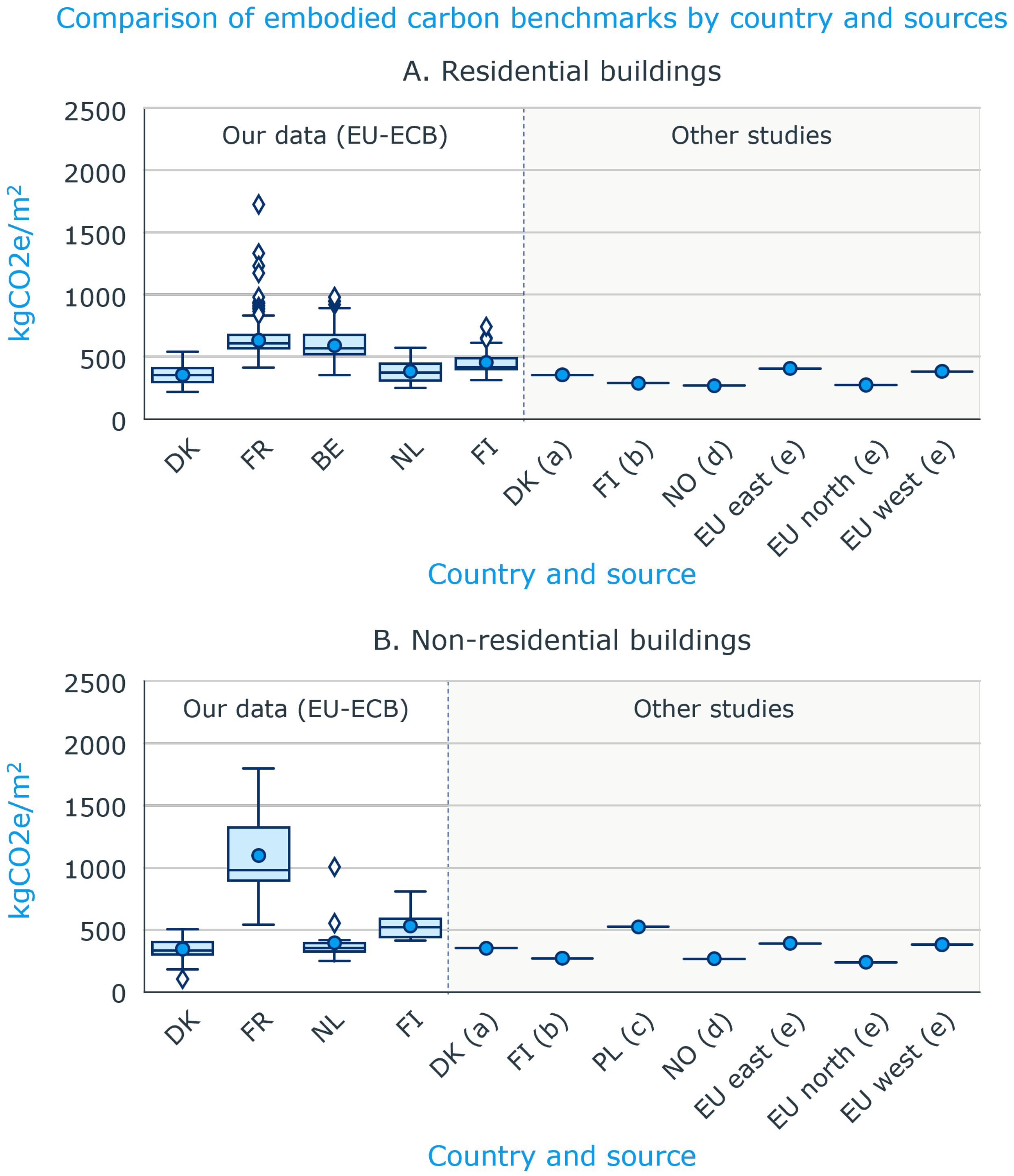


Figure 14 plots the results of our analysis of the life cycle embodied carbon values, as found based on the EU-ECB data, in comparison to benchmarks and reference values found in other studies for different countries. This analysis aims to compare the results for different countries with values from other studies on the same country or region. Figure 14 shows that for residential buildings (top), reference values from other studies are comparable to our (mean) results. This is particularly the case for our results for Denmark (DK), which are very similar to those in the existing study by Zimmermann et al.[4]. This was expected as the majority of Danish cases in our sample are from that same study, albeit with additional cases from other Danish data partners. Our results for Finland (FI) indicate significantly higher results than were presented in the existing study by OneClickLCA[5]. Here again, our sample is based on data from multiple Finnish data partners which might explain the difference in results, potentially due to a variation in the comprehensiveness of the assessment scopes. Our results for residential buildings from France, (FR), Belgium (BE), and the Netherlands (NL) do not have direct reference values to compare for the respective country, but reference values for different EU regions from another OneClickLCA study [6] suggest that the NL results are in line with the reference values for Western Europe (EU west). At the same time, the mean values for both France and Belgium in our analysis are considerably higher than the values obtained from said study for both Northern Europe (EU north) and Western Europe (EU west). Various reasons could have led to this difference. **For the cases from France and Belgium particularly, the data from these cases were very comprehensive in terms of the life cycle stages and building parts covered, and so this could explain the higher results in comparison to the reference study, which only provided a comparably limited scope assessment**.

For non-residential buildings, the mean values in our results are comparable to the reference values from other studies for Denmark and the Netherlands. For Finland, again, our results are considerably higher than the values from the reference study. The outstanding results are those for non-residential buildings in France. These are far above the values found in any of the other country or study on the respective region (EU west). The related section 3.5 discusses the potential reasons for the higher values from France.

Finally, Table 9 provides details on the studies used to contextualise the embodied carbon results as shown in Figure 14. The reference values for Norway and Poland do not have a direct comparison. Nevertheless, the related studies have been added for reference and to inform other benchmarking efforts in the future.

Table 9: Overview of other studies used to contextuale the embodied carbon results

Abbr.	Country	Title	Reference
a)	DK	Zimmermann et al., Klimapåvirkninger fra 60 bygninger SBi 2020:04, 2020	[4]
b)	FI	OneClickLCA, Carbon Footprint Limits for Common Building Types, 2021	[5]
c)	PL	Komerska et al., Preliminary Study on the GWP Benchmark of Office Buildings in Poland Using the LCA Approach, 2020	[7]
d)	NO	Kjendseth Wiik et al., Klimagasskrav til materialbruk i bygninger, 2020	[8]
e)	EU	OneClickLCA, Embodied carbon benchmarks for European buildings, 2021	[6]

4.1.2 Embodied carbon in renovating existing buildings

The data collection and analysis in this study focused on the life cycle embodied carbon emissions of newly constructed buildings. In the context of the European renovation wave and the general need to revalue and further develop existing buildings stocks, there is an increased interest in understanding embodied carbon from retrofitting. We want to highlight a recent report by the European Academies Science Advisory Council (EASAC) on the 'Decarbonisation of buildings for climate, health and jobs' [9]. Therein, with regard to embodied carbon in both new building construction and building renovation, the author states:

> "Studies of embodied GHG emissions in buildings (Rasmussen et al. 2018; Moncaster et al. 2019; Ylmén et al. 2019; Lausselet et al. 2021) have shown that typical values of **embodied GHG emissions per square metre of floor area for new buildings lie between 250 and 400 kilograms of carbon dioxide equivalent per square metre (kg CO2eq./m2)**, whereas the operating GHG emissions from existing buildings typically lie between 30 and 50 kg CO2eq./m2 per year (Odyssee-Mure 2018). The studies also show that the addition of **embodied emissions caused by the renovation of an existing building**, depending on the nature and depth of the renovation works and the materials used, **is typically less than 50% of the embodied emissions for a new building (i.e. less than 125–200 kg CO2eq./m2)**. It can be much lower if the renovation focuses, for example, on insulation and heating or cooling system improvements without major structural changes (Brown et al. 2014)." [9]

The report further suggests that the payback period, within which the embodied GHG emissions, caused by the renovation, break even with the otherwise higher operational emissions, "can typically be less than about 3 years" [9].

4.2 Limitations of this study

4.2.1 Representativeness of the samples

The data samples collected and analysed in this study are not representative of the building stock in a given country. The threshold for the number of cases to be provided per country was set at only 50 buildings. Several of the national data partners provided considerably more cases, with cases per country ranging from 47 to 486, respectively (see Table 1). The distribution of the number of cases from different countries necessarily influences the results when analysing the combined EU-ECB dataset. In particular, the high number of cases from France will have over-proportionally influenced the EU-ECB results. The results obtained overall, as well as per country, can therefore only give an initial indication of the common levels of embodied carbon in the different building types in the different countries.

In addition to the results presented in the body of this report, which to a large degree build on the analysis of the combined 'EU-ECB dataset', in-depth analyses per country are also provided in the "Supplementary Results" section.

4.2.2 In/consistency of assessment methods

The collection and analysis of building LCA data from different European countries was expected to reveal differences in the applied assessment methods. As expected, the study identified various methodological differences, e.g. regarding the scope of building parts considered; the scope of life cycle stages considered; the LCA background data used for modelling the building LCA; and reference study periods (RSP), among others. Differences in RSPs were anticipated and mitigated by applying a harmonisation procedure to reduce the influence of this aspect on the embodied carbon results - see section 2.3 Data processing and harmonisation. The potential influence of the difference in the scope regarding building parts and life cycle stages is analysed and discussed in section 3.4 (Contribution from different life cycle stages) and 3.5 (Contribution from different building parts), respectively. We are, furthermore, aware of methodological differences regarding the modelling of end-of-life emissions in the different countries which, however, have not been documented and analysed in further detail.

5. Conclusions and outlook

5.1 Conclusions

From the analysis presented above, the following conclusions can be drawn:

- **Whole life cycle embodied carbon baseline:** The baseline for whole life cycle embodied carbon emissions ranges from around 400 to 800 kg CO2e/m^2 with a mean value of around 550 kg CO2e/m^2 for residential buildings, and from around 100 to 1200 kg CO2e/m^2 for non-residential buildings, with a mean value of 450 kg CO2e/m^2.

- **Embodied carbon baseline per capita:** The analysis of embodied carbon emissions per capita shows, for residential buildings, a mean value of around 32 t CO2e/cap, with values ranging from 5 to almost 60 t CO2e/cap. For non-residential buildings values range from around 2 to 35 t CO2e/cap, with the mean value being around 14 t CO2e/cap. Relevant differences in embodied carbon per capita are observed across different building (sub)types due to occupational patterns.

- **Baseline for different building (sub)types:** the conclusions, regarding which building (sub)type has the highest embodied carbon emission intensity, change when using a per-capita perspective over the established per-m^2 metric. Such is the case for multi-family houses, which show higher per-m^2 values than single family houses, but display the lowest values out of all the residential building types in a per-capita perspective, due to their occupational density being higher than compared with single family houses. However, this analysis is currently based on a simplified approach of calculating occupational density from the estimated number of users. A refined understanding of the number of users and full-time equivalents might change perspectives in future research.

- **Baseline for building cases from different countries:** This study analysed building LCA data from five European countries, which were each able to provide around 50 cases or more for the analysis. The variation observed between the countries is comparable to what the study found for the mean full life cycle embodied carbon emission values for different building use subtypes (variance of up to ~650 kg CO2e/m^2) or for the different types of structural systems and materials (~250 kg CO2e/m^2), respectively. It is assumed that the variation in the values observed for the different countries occurs due to multiple aspects, e.g. in relation to local context and site, building design decisions, as well as differences in assessment methodology, amongst others.

- **Baseline for different structural systems and materials:** The analysis of the embodied carbon emissions baseline for the different types of structural systems and materials reveals important differences. Frame structures do not necessarily lead to lower embodied carbon values on average when compared to massive structures. Cases using wood as their main structural material, in both massive and frame systems, lead to the lowest values for the respective type of structural system, showing mean values of around 100 to 200 kg CO2e/m^2 lower than other material options for massive and frame cases, respectively.

- **Contribution from different life cycle stages:** The investigation into the contribution from the different life cycle stages shows that the largest contribution of embodied carbon emissions occur during the production stage (A1-3), with mean values of around 300 kg CO2e/m^2 (56% of whole life cycle embodied carbon emissions), ranging from around 70 to 520 kg CO2e/m^2. The second largest proportion of embodied GHG emissions occurs during the use phase (B1-4), with mean values of around 120 kg CO2e/m^2 (22%), which represents the total emissions from cleaning, maintenance, replacement activities occurring over a 50-year reference study period. Both the production stage (A1-3) and use stage (B1-4) embodied carbon emission values show a large variation, which likely depends on the type of building use, the structural system and the material choices.

- **Contribution from different building parts:** the analysis of the contribution from different building parts reveals that the main contributors to whole life cycle embodied carbon emissions, on average, are technical services (e.g. heating, cooling, domestic hot water and sewage systems) and structural elements (e.g. structural frame, walls, floors), with a mean value of around 190 kg CO2e/m^2 (ranging from 170 to 230 kg CO2e/m^2) and 170 kg CO2e/m^2 (ranging from 100 to 320 kg CO2e/m^2), respectively. Substantial contributions are further observed from internal elements (e.g. partition walls, floor and wall finishes), with a mean value of around 150 kg CO2e/m^2 (ranging from 30 to 250 kg CO2e/m^2).

5.2 Recommendations

- **Close data gaps with building archetypes until large datasets are available for each country:** From the experience with data collection and analysis for this project, and until large and representative dataset are available for each country, we recommend the application of representative building archetypes and their assessment using LCA to analyse the representative levels of embodied carbon in existing and new building types. In this study, the data obtained from the Belgium data partners were based on LCAs for the building archetypes from the TABULA/EPISCOPE project[7]. This approach of using representative archetypes (e.g. as defined for building energy or material modelling) should be investigated further with regard to its suitability for LCA-based modelling of embodied carbon values in future benchmarking studies.

- **Define extended documentation requirements for building LCA:** From the experience with data collection and analysis for this project, we recommend defining greater documentation requirements for building LCA cases, which further develop the current data collection template, i.e. ask for documentation regarding the scope of the assessment, as well as the provision of detailed, disaggregated information for the building context and geometry, individual building parts and respective life cycle stages. This would greatly benefit the ability to understand and interpret the results. Initiatives such as the EU Level(s) framework could provide a good opportunity for implementing said documentation requirements across the EU.

- **Harmonise reporting to improve comparability and consistency within and across EU countries:** To improve the situation regarding both availability and comparability of buildings LCA data, the regulation and requirement of building LCA across EU countries is essential. Countries should ensure compliance with EN standards and seek methodological consistency regarding the scope of building parts, life cycle stages, background data and reference study periods, at least at country level. Therefore, if a country regulates on the LCA of buildings, it should specify the LCA requirements.

  Attempts to harmonise the building LCA methods across Europe (and beyond) should consider the usability of the building LCA results in comparative analysis and benchmarking. Alignment should be sought at European level regarding the building parts and life cycle stages to be considered in full building LCA, to improve comparability across countries.

  Common formats for documenting building LCA results, as well as related methodological aspects and building descriptions, should also be sought. Recent developments such as the European Level(s) initiative could provide a good basis for this, albeit the level of detail in the reporting on building properties, as well as the life cycle inventories and LCA results, should be improved.

  In the context of harmonising LCA methods and benchmarking, particular attention should be paid to the developments and methodological requirements in the building LCA standard EN 15978, as well as to the latest findings and recommendations from the international IEA EBC Annex 72 project on 'Assessing life cycle related environmental impacts caused by buildings' [3]

- **Develop methods and analytical tools to understand embodied carbon:** Our analysis of LCA data shows that better methods and tools are needed. We recommend:

  Developing the methodology further for systematically analysing embodied carbon hotspots in buildings, investigating the contribution made by the different life cycle stages, building parts and materials, as well as other environmental impacts in the future.

  Developing the methodology further for inferring missing values, and identifying the influence of individual parameters on driving embodied carbon results. In the current analysis, the baselines were analysed for subsets of the data, based on different parameters (e.g. building use type), which do not, however, include a variation in the other parameters (e.g. type of structure). The application of methods like machine learning could enable an improved understanding of parameter influence.

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[7] Building archetypes developed under the framework of the Intelligent Energy Europe projects TABULA and EPISCOPE. Using the common TABULA concept as a starting point, the project partners developed national building typologies representing the residential building stock in their countries. Further information available at: https://episcope.eu/

Advancing the comparison with existing studies to consider detailed building characteristics (geometry, type of use, energy performance, etc.) to establish a framework for contextualising the results of full life cycle embodied carbon assessment studies, and building LCA results in general.

- **Develop benchmarks considering the timing of emissions and the scope of the assessment:** Our study points at a number of recommendations for setting benchmarks, including:

  Taking into account the timing of emissions when setting benchmarks to reduce embodied carbon, e.g. by expressing total emissions per life cycle stage in addition to mere annualised whole life cycle totals. This is because most embodied carbon emissions are generated "upfront" and should, therefore, be accounted for at the time they are emitted.

  Considering the scope and assessment methodology applicable to the respective situation for defining appropriate targets and benchmarks. Scope and methodology here may involve the life cycle stages and building parts considered, as well as whether process-based or input-output-based LCA background data[8] was used, among other things. Benchmarks should aim to provide values for 'full scope' assessments. Correction factors and proxy values could be applied to account for missing elements in incomplete studies (as is the case in the French methodology, which provides proxy values with an added safety margin for studies missing technical systems in their original inventory).

  To express the potential influence and reduction potential of building design regarding both building materialisation, as well as layout and patterns of use, benchmark values should be expressed in both CO2e/m^2 and CO2e/capita, in parallel.

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[8] Types of life cycle inventory analysis approaches, as described in Helal et al. [REF - https://doi.org/10.1088/1755-1315/588/3/032028]: "Life cycle inventory (LCI) analysis consists of listing the inputs and outputs associated with a service or product and is an integral part of a life cycle assessment (LCA). There are three broad approaches for compiling an LCI: • process analysis, which is a bottom-up approach where a product is studied according to the series of processes that represent its life cycle; • environmentally extended input-output analysis (EEIOA), which is a top-down approach where economy-wide input-output tables are studied to quantify the material and non-material inputs and outputs required throughout the entire supply chain associated with production; and • hybrid analysis, which combines the first two approaches by merging process data with macroeconomic data to avoid the inherent truncations in the process approach and the high levels of aggregation in the EEIOA approach."

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APPENDIX

SUPPLEMENTARY DATA

Data availability

The data compiled, processed and analysed in this study are available open access via https://doi.org/10.5281/zenodo.5895051.

Code availability

The scripts used for the processing, analysis and visualisations presented in this study are available open access via https://doi.org/10.5281/zenodo.5895051.

SUPPLEMENTARY METHODS

Methodology overview

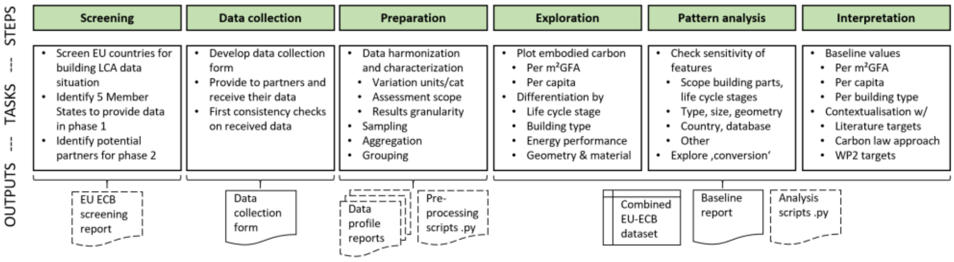


Figure 1: Methodology overview of steps, tasks and related outputs.

The analysis of embodied carbon (EC) baselines and the related research questions are investigated in six main steps, as presented in Figure 1. First, a screening of EU countries for partners and potential sources of building LCA data to inform the EC baseline analysis. Second, the data collection, starting from the definition of the relevant parameters and the collection of data from partners and sources identified in the screening process. Third, data preparation for the purpose of data harmonisation and characterisation, feature engineering and identification of the suitable data sample. Fourth, data exploration, i.e. the explorative analysis of the dataset to understand the data – distributions, correlations, missing values, etc. – and provide first insights into the EC baseline expressed for different reference units (e.g., per m² floor area, or per capita) as well as differentiated for different building parts and life cycle stages. Fifth, the analysis of patterns in the data. This step aims at analysing the sensitivity of EC results to the contribution made by different parameters, e.g., related to building design or assessment methodology. Sixth, the interpretation of EC baselines for different countries and different building types as well as contextualisation with carbon reduction targets.

Parameters and data collection

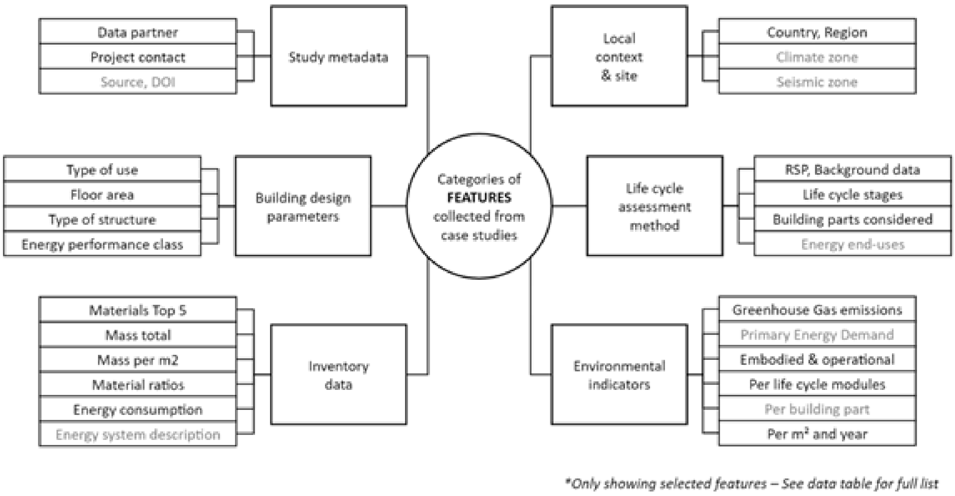


Figure 2: Overview of categories and features parameters collected from case studies.

As a first step, ahead of the actual data collection, we defined the categories and parameters relevant to be collected and analysed, as outlined in Figure 2, based on the parameters documented by the authors of the meta-study of Röck et al. [3]. To facilitate data collection along pre-defined categories and parameters, and ensure consistency of units and data types, a data collection template (DCT) was developed and provided to data partners for collecting their data. The common structure of the data collection template is key to enable automated data processing workflows and analyses.

Data processing and cleaning

To process and analyse the data obtained through the data collection from national partners and other data sources, a workflow is developed utilising Python scripts for data processing, to prepare and export the combined and cleaned EU-ECB datasets as well as for analysis of baselines and patterns.

In some cases, databases have been received in their native format instead of the developed DCT. In such cases the data is pre-processed individually using tailormade Python scripts to transform the data and fit it to the format of the DCT.

The pre-processing steps include removing rows with invalid data, translating and regrouping data into common formats and categories from the DCT and collecting all data sources into one combined dataset.

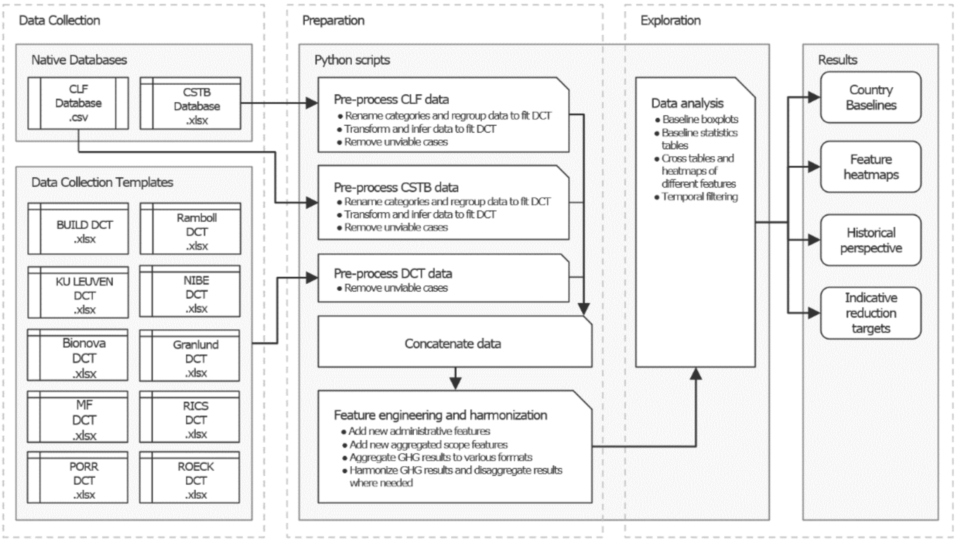


Figure 3: Flowchart of the data collection, preparation and analysis workflow for the different data sources.

Harmonization and disaggregation

With the combined dataset, new parameters are introduced based on the collected data to enable a broad range of analyses. Data is transformed, aggregated and/or disaggregated depending on the available data of each case, to ensure consistent categorical data and to transform all LCA results into a harmonized format, such that they can be used for meaningful comparison.

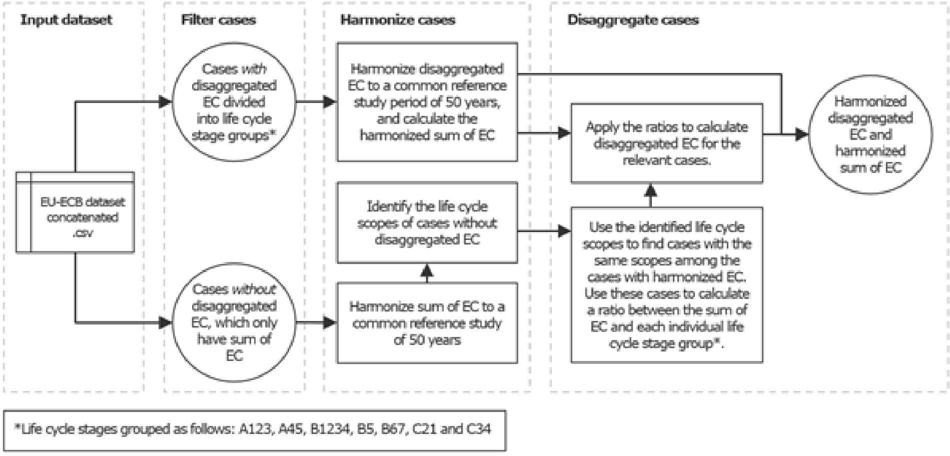


Figure 4: Conceptual presentation of the harmonization and disaggregation process.

In this step we harmonize embodied emission values to a common reference study period (RSP) of 50 years per m² gross floor area (GFA).

For the data collected in this project (EU-ECB), we already collected the data per m² GFA and per year (kg $CO_2e/m^2GFA/a$), based on the RSP of the respective case. Hence, the harmonisation of net floor area (NFA) to GFA is not required. However, harmonisation of the reference study periods is still needed to improve comparability.

The approach applied in this project for harmonizing EC values, builds on the disaggregated emission data collected per life cycle stage. Therein, we first calculate the total of carbon emission across the full life cycle of the respective case (harmonized total of EC), considering the factor between original RSP of the case study (RSP_case) and the RSP for harmonization (RSP_harm) when scaling the carbon emissions in the use stage (life cycle stage B). In a second step we annualize values using the harmonized RSP (RSP_harm). The values for life cycle stages A and C are not scaled, as the total of emissions in these life cycle stages is not affected by the RSP of a given study.

The formulas applied for harmonization of emission values to a common reference study period (RSP) are presented in the following:

Harmonized totals of EC (per LCM)

- *GHG_A123_m2_harm = GHG_A123_m2a * RSP_case*
- *GHG_A45_m2_harm = GHG_A45_m2a * RSP_case*
- *GHG_B1234_m2_harm = GHG_B1234_m2a * RSP_case * (RSP_harm / RSP_case)*
- *GHG_B5_m2_harm = GHG_B5_m2a * RSP_case * (RSP_harm / RSP_case)*
- *GHG_B67_m2_harm = GHG_B67_m2a * RSP_case * (RSP_harm / RSP_case)*
- *GHG_C12_m2_harm = GHG_C12_m2a * RSP_case*
- *GHG_C34_m2_harm = GHG_C34_m2a * RSP_case*

Harmonized annualized EC (per LCM)

- *GHG_A123_m2a_harm = GHG_A123_m2_harm / RSP_harm*
- *GHG_A45_m2a_harm = GHG_A45_m2_harm / RSP_harm*
- *GHG_B1234_m2a_harm = GHG_B1234_m2_harm / RSP_harm*
- *GHG_B5_m2a_harm = GHG_B5_m2_harm / RSP_harm*
- *GHG_B67_m2a_harm = GHG_B67_m2_harm / RSP_harm*
- *GHG_C12_m2a_harm = GHG_C12_m2_harm / RSP_harm*
- *GHG_C34_m2a_harm = GHG_C34_m2_harm / RSP_harm*

Where:

- *GHG_A123_m2_harm = Cumulative embodied GHG emissions in life cycle stage A, product stage (life cycle stages A1-3) (”upfront carbon spike”), based on harmonized RSP [kg* CO_2e/m^2*]*
- *GHG_A45_m2_harm = Cumulative embodied GHG emissions in construction process stage (Life cycle stages A4-5) (”upfront carbon spike”), based on harmonized RSP [kg* CO_2e/m^2*]*
- *GHG_B1234_m2_harm = Cumulative embodied GHG emissions during the use phase, for maintenance, repair and replacement (Life cycle stages B1-4), based on harmonized RSP [kg* CO_2e/m^2*]*
- *GHG_B5_m2_harm = Cumulative embodied GHG emissions of retrofit (Life cycle stages B5) (only for few cases) [kg* CO_2e/m^2*]*
- *GHG_B5_m2_harm = Cumulative operational GHG emissions of building in use (Life cycle stages B6-7) [kg* CO_2e/m^2*]*
- *GHG_C12_m2_harm = Cumulative embodied GHG emissions of deconstruction process stage (Life cycle stages C1-2), based on harmonized RSP [kg* CO_2e/m^2*]*
- *GHG_C34_m2_harm = Cumulative embodied GHG emissions of end-of-life processing (Life cycle stages C3-4) , based on harmonized RSP [kg* CO_2e/m^2*]*

- *_m2 = Cumulative embodied/operational GHG emissions across full life cycle*
- *_m2a = Annualized embodied/operational GHG emissions*
- *_capita = GHG emissions per capita, based on the documented number of users*
- *_harm = Values based on harmonized RSP*

In the harmonization process we recalculate the values for embodied carbon total across the full life cycle, based on the harmonisation of values for embodied carbon from individual life cycle stages.

Feature engineering

Summary of building parts scope

Problem: Data has variation in the scope of building parts covered

Approach: Summarize information on building parts included in the study in one aggregated indicator. Syntax for the indicator is a string-code using the letters of building sections included in the study.

- *Ground (1) (i.e. substructure, foundation, basement walls, etc.)*
- *Load-bearing structure (2) (i.e. structural frame, walls, floors, roofs, etc.)*
- *Envelope (3, 4) (i.e. openings, external finishes, etc.)*
- *Internal (4) (i.e. partitions, internal finishes, etc.)*
- *Services (5,6) (i.e. mechanical, electrical, renew. energy, etc.)*
- *Appliances (7,8) (i.e. fixed facilities, mobile fittings, etc.)*

Code examples:

1. *GLEISA = All standard elements considered = full scope (plus some 'other')*
2. *GLE-- = Structure, Foundation and Envelope, no internal elements or technical services*
3. *--E-S = Envelope and building services*

Related parameters:

- Aggregated indicators by building section (one-hot, 1 or 0) for Ground (1), Structure (2), Envelope (3, 4), Internal (4), Services (5, 6), Appliances (7, 8)
- Aggregated indicator as described in example (GLEISA)

Summary of life cycle stages scope

Problem: Studies collected have differences in scope regarding life cycle stages/life cycle modules covered. To be able to compare results we have to identify the scope and cluster buildings accordingly.

Approach: We summarize life cycle stages covered by the studies in various aggregated indicators. The indicators are string-code using the following syntaxes to describe the scope regarding life cycle stages and life cycle modules, following the respective standard for building LCA EN 15978:

Life cycle stages (one parameter for each)

- *A (Product stage & Construction process stage)*
- *B (Use stage, differentiating embodied and operational)*
- *C (End-of-life stage)*
- *D (Benefits and loads beyond the system boundary)*

Aggregated code example (one parameter holding the concatenated string):

- *ABC- = Whole life cycle assessment (A-C), not considering mod D.*
- *A--- = Cradle to gate/site assessment (A), not covering use, EoL, No mod D.*
- *A-C- = Cradle to grave (A+C), but not covering use phase, no mod D.*

Life cycle modules (one parameter for each)

- *A1-3: Production*
- *A4-5: Construction process*
- *B1-4: Maintenance, repair, replacement*
- *(B5: Refurbishment)*
- *(B6-7: Operational energy & water use)*
- *C1-2: Deconstruction, transport*
- *C3-4: Waste processing and disposal*

Aggregated code examples (one parameter holding the concatenated string):

- *PCMDW = All life cycle modules covered*
- *PMW = Only covering: Production; maintenance, repair, replacement; waste processing and disposal*

SUPPLEMENTARY RESULTS

Baseline for different types of building use (harmonized RSP)

Baseline results for the collected data from the combined EU-ECB dataset, as well as the five pilot countries individually, are presented here for residential and non-residential buildings, respectively.

Baseline for different building use types (residential, non-residential)

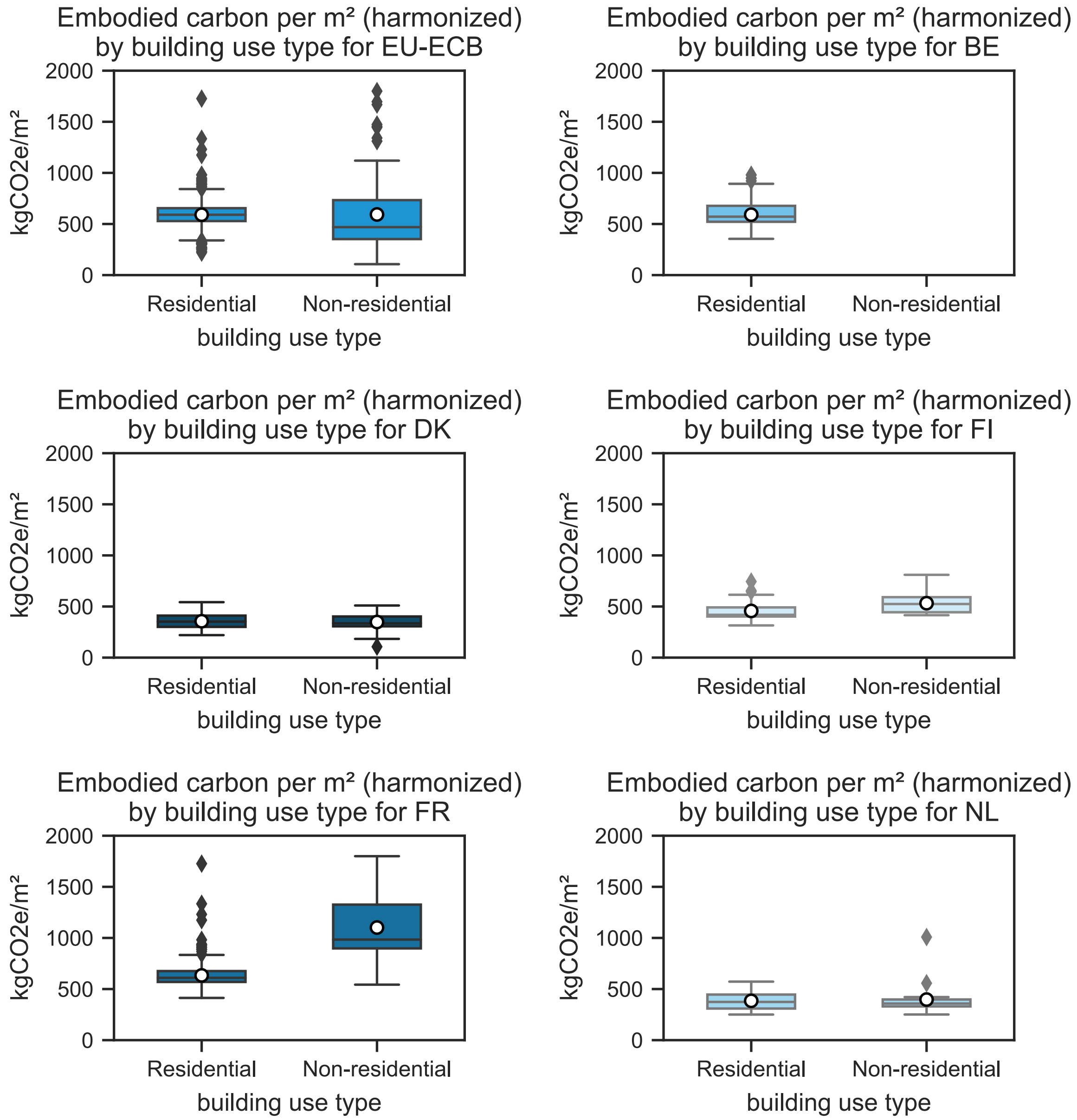


Figure 5: Overview of harmonized, whole life cycle embodied carbon per m² and year [kg/m²/a] for the combined EU-ECB dataset as well as for the main five countries.

Baseline for different building use subtypes

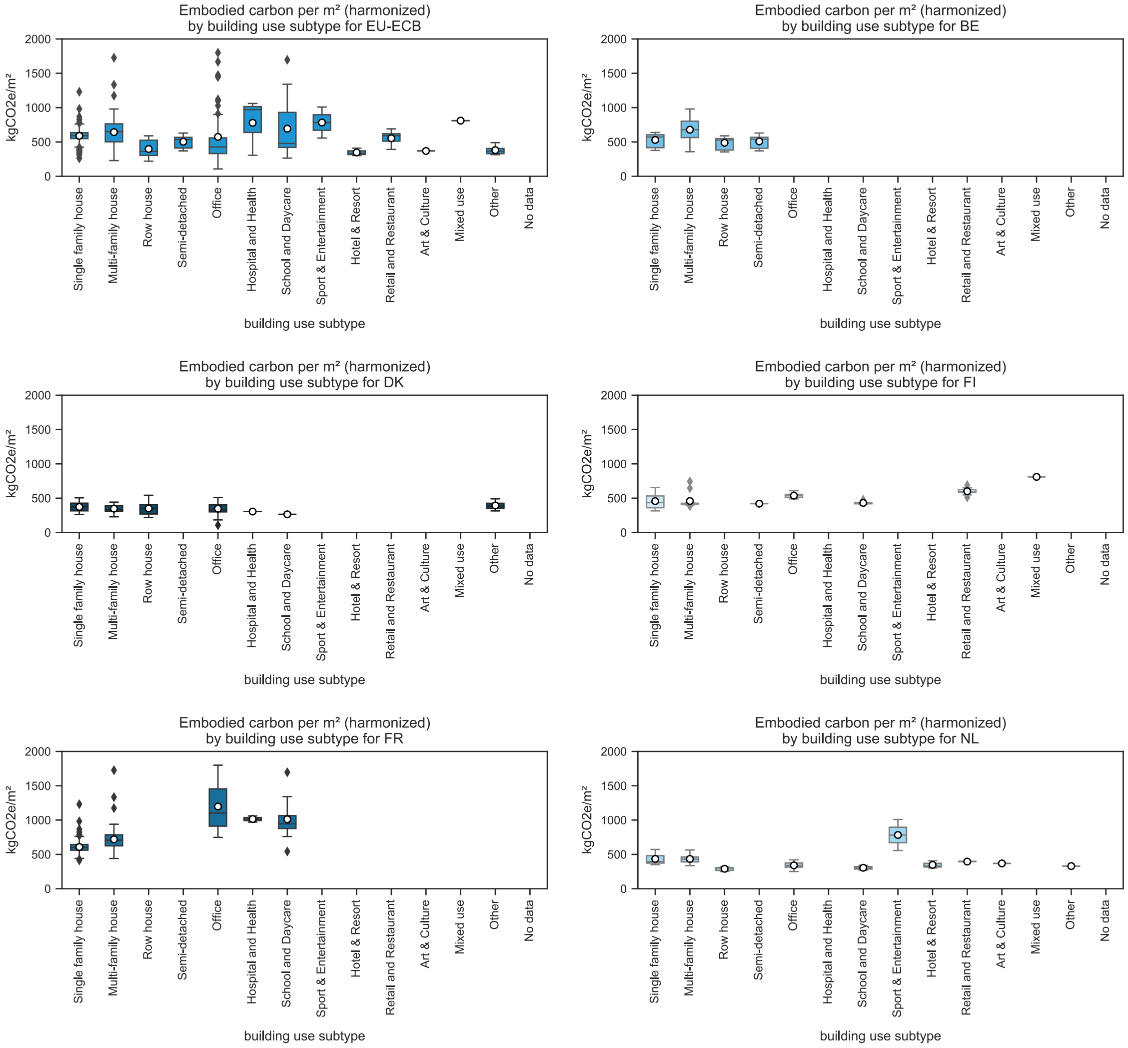
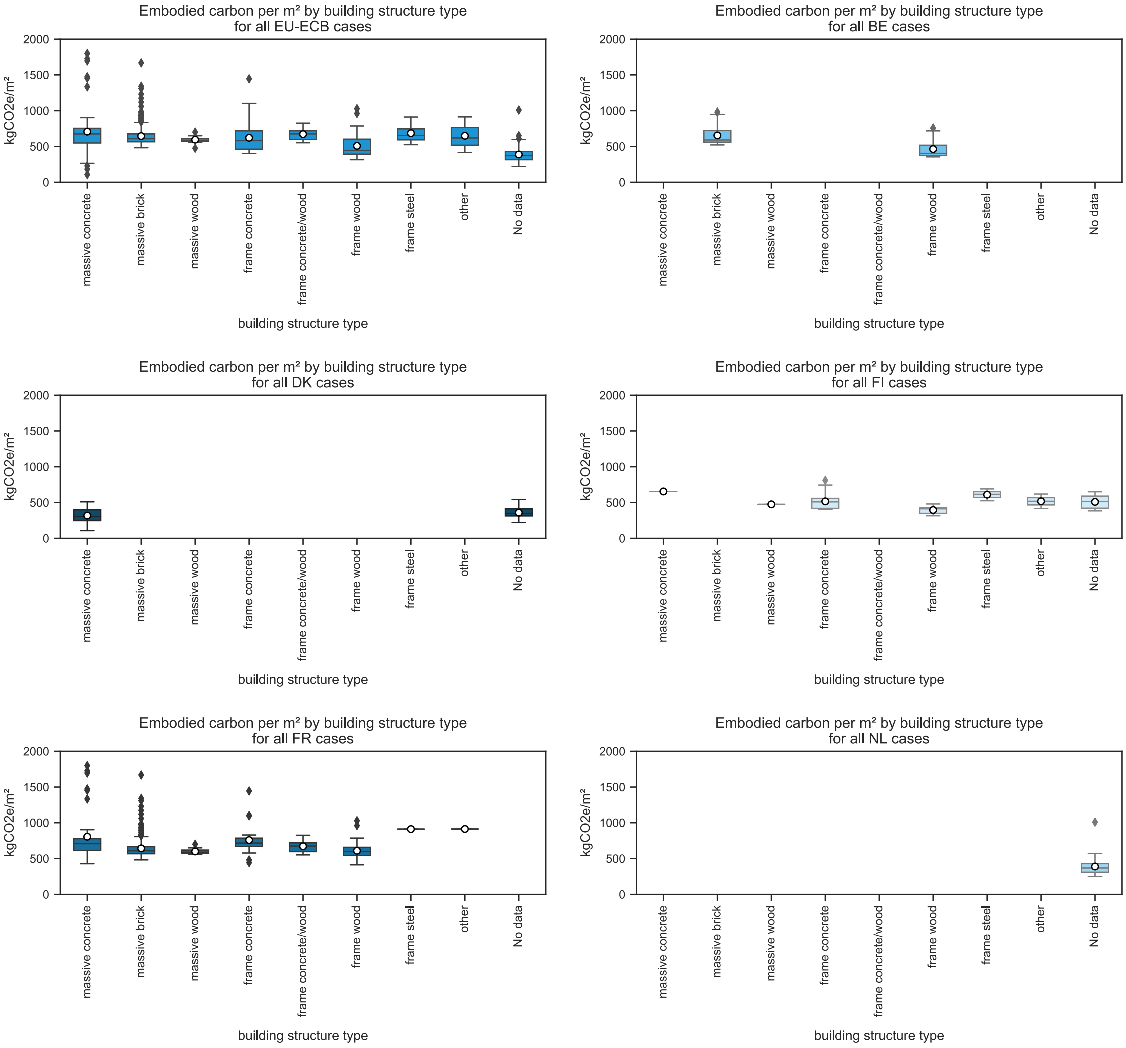


Figure 6: Overview of embodied carbon [kg/m²/a] by building use subtype for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to limitations for data from the respective countries.

Baseline for different types of structure


Embodied carbon per m² by building structure type for all EU-ECB cases

Embodied carbon per m² by building structure type for all BE cases

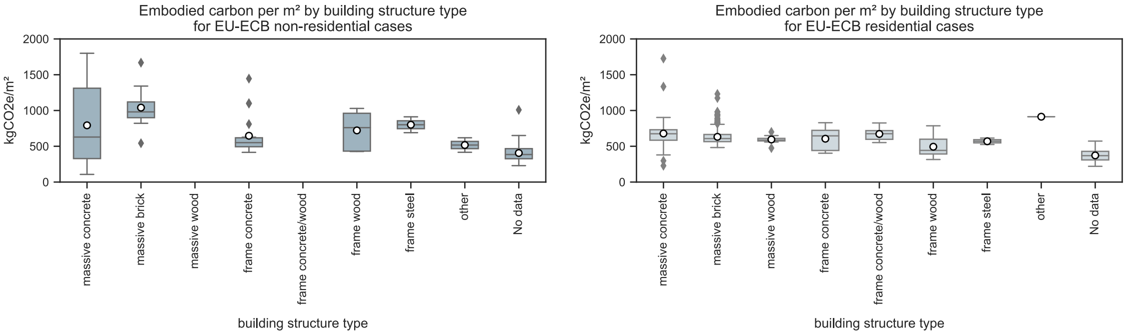
Embodied carbon per m² by building structure type for all DK cases

Embodied carbon per m² by building structure type for all FI cases

Embodied carbon per m² by building structure type for all FR cases

Embodied carbon per m² by building structure type for all NL cases

Figure 7: Overview of embodied carbon [kg/m²/a] by building structure type for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to limitations for data from the respective countries.


Embodied carbon per m² by building structure type for EU-ECB non-residential cases

Embodied carbon per m² by building structure type for EU-ECB residential cases

Figure 8: Embodied carbon by building structure type and building use type.

Table 1: Number of cases (count) of different types of structure for the five main countries (EU-ECB).

Metric \ Type of structure		BE	DK	FI	FR	NL	EU-ECB
count	All structures	105	72	59	461	47	744
	frame concrete	-	-	26	20	-	46
	frame concrete/wood	-	-	-	6	-	6
	frame steel	-	-	3	1	-	4
	frame wood	35	-	12	29	-	76
	massive brick	70	-	-	337	-	407
	massive concrete	-	11	1	44	-	56
	massive wood	-	-	1	23	-	24
	No data	-	61	14	-	47	122
	other	-	-	2	1	-	3

Contribution from different life cycle stages

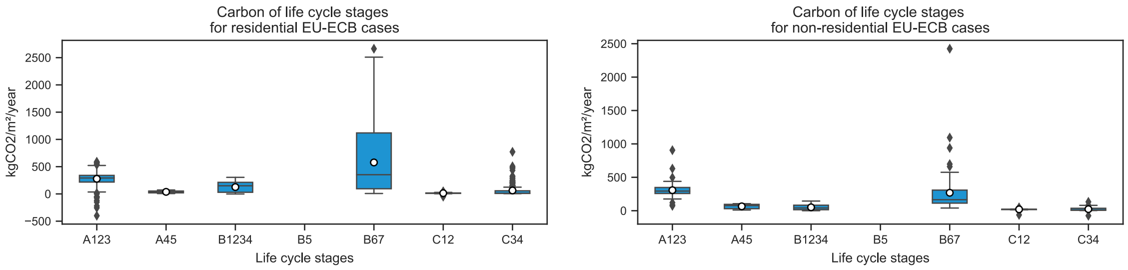


Figure 9: Embodied carbon from different life cycle stages for residential (left) and non-residential (right) buildings.

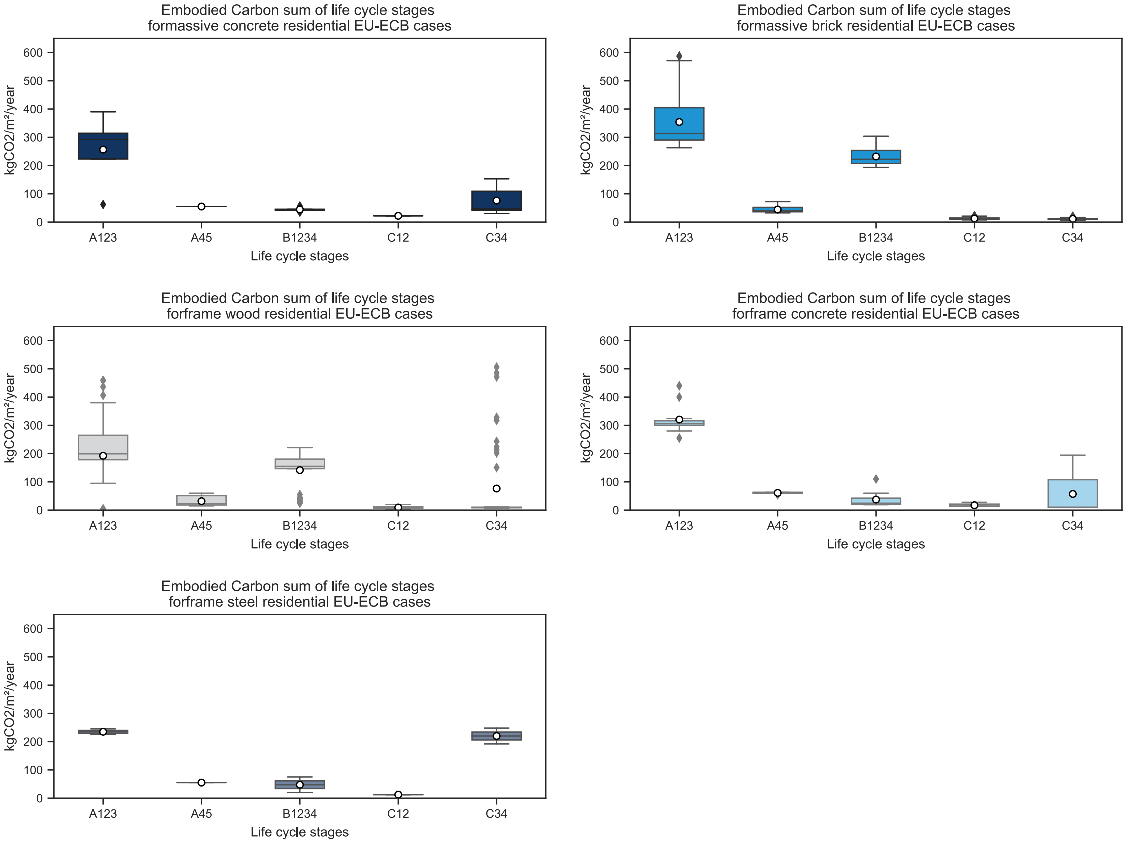


Figure 10: Embodied carbon from different life cycle stages for different type of structure, residential buildings.

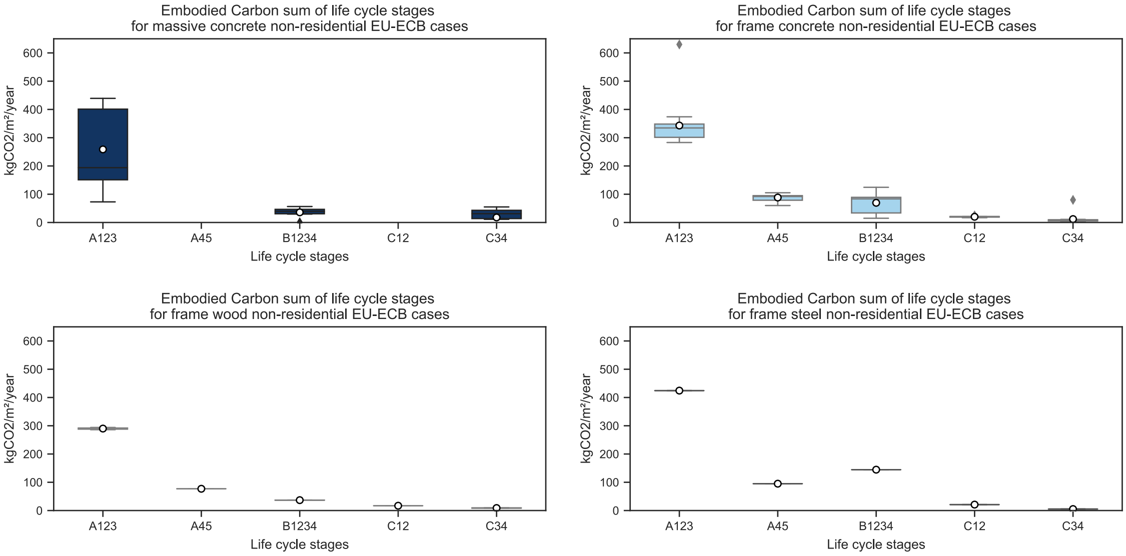
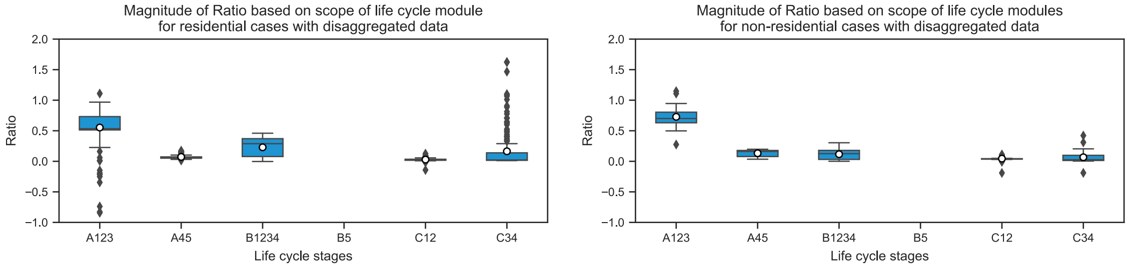


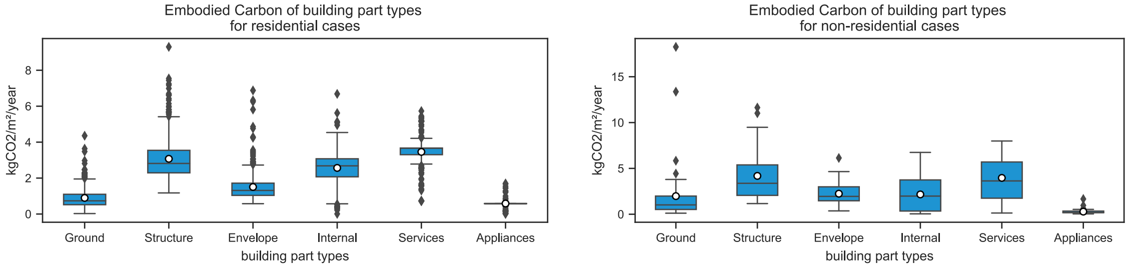
Figure 11: Embodied carbon from different life cycle stages for different type of structure, non-residential buildings.


Magnitude of Ratio based on scope of life cycle module for residential cases with disaggregated data

Magnitude of Ratio based on scope of life cycle modules for non-residential cases with disaggregated data

Figure 12: Magnitude of contribution ratio from different life cycle stages for residential and non-residential, respectively. Based on the EU-ECB dataset.

Contribution from different building part groups


Embodied Carbon of building part types for residential cases

Embodied Carbon of building part types for non-residential cases

Figure 13: Embodied carbon emissions from different building parts for residential (top) and non-residential (bottom) cases, respectively. Based on the EU-ECB dataset.

Variation for different countries

Table 2: Descriptive statistics for the life cycle embodied carbon of different building use types across the five main countries and for the EU-ECB average.

Metric \ Building use type		BE	DK	FI	FR	NL	EU-ECB
std	**Non-residential**	NaN	91.24	93.93	316.54	167.12	351.20
	Residential	157.95	80.50	105.92	116.95	92.65	148.33
	All types	157.95	85.21	106.02	175.05	124.84	191.80
min	**Non-residential**	NaN	106.88	414.99	542.83	250.81	106.88
	Residential	354.76	220.00	315.00	413.00	250.36	220.00
	All types	354.76	106.88	315.00	413.00	250.36	106.88
percentile25	**Non-residential**	NaN	305.88	443.88	NaN	330.01	352.25
	Residential	521.54	300.58	402.18	NaN	309.04	528.46
	All types	521.54	303.53	417.54	NaN	309.24	505.00
median	**Non-residential**	NaN	335.25	524.50	983.86	358.04	469.00
	Residential	571.46	352.25	418.85	609.55	373.73	590.08
	All types	571.46	347.25	477.00	614.57	368.93	583.83
percentile75	**Non-residential**	NaN	402.50	591.49	NaN	398.00	733.46
	Residential	677.58	411.13	491.25	NaN	445.84	654.76
	All types	677.58	410.38	572.00	NaN	429.73	655.89
max	**Non-residential**	NaN	509.90	810.00	1799.72	1008.74	1799.72
	Residential	979.96	542.50	744.25	1726.66	572.48	1726.66
	All types	979.96	542.50	810.00	1799.72	1008.74	1799.72

Variation for different scopes

Table 3: Number of cases (count) for different building use types and scopes of life cycle stages and buildings parts.

	Non-residential		Residential	
Parts \ LCS	**PCMDW**	**PMW**	**PCMDW**	**PMW**
GLEISA	45	1	458	NaN
LEISA	1	NaN	18	NaN
GLESA	NaN	NaN	5	NaN
GLEIS	30	32	115	36
GLES	NaN	1	NaN	NaN
GLEI	NaN	NaN	NaN	2

Embodied carbon across whole life cycle (original RSP)

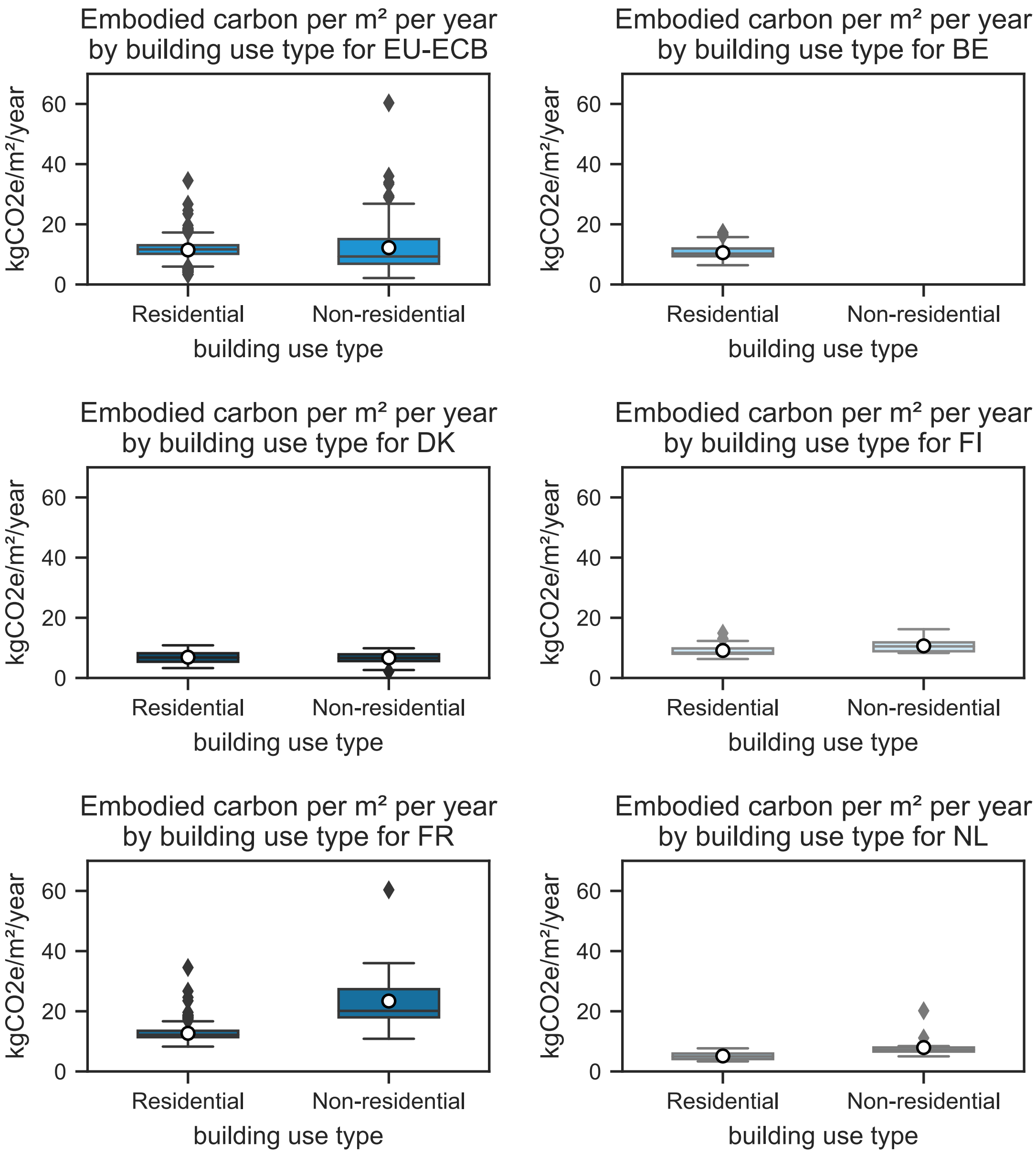


Figure 14: Overview of original (non-harmonized) whole life cycle embodied carbon per m² and year [kg/m²/a] for the combined EU-ECB dataset as well as for the main five countries.

Embodied carbon per capita (original, non-harmonized)

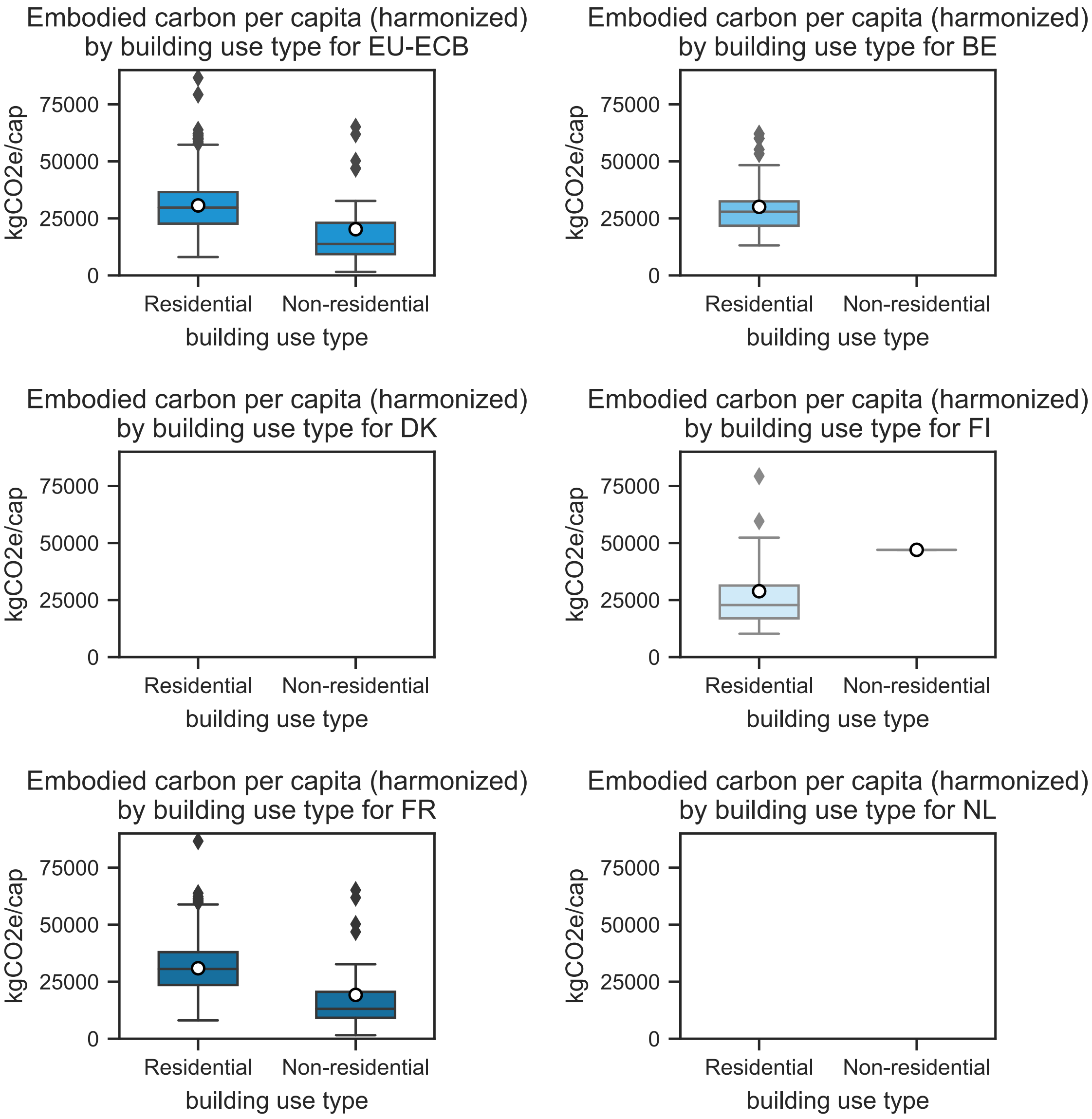


Figure 15: Overview of original (non-harmonized) whole life cycle embodied carbon per capita and year [kg/capita/a] for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to data gaps (number of users) for data from the respective countries.