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Towards indicative baseline and decarbonization pathways for embodied life cycle GHG emissions of buildings across Europe

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Towards indicative baseline and decarbonization pathways for embodied life cycle GHG emissions of buildings across Europe

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Abstract. Buildings' construction and operation are major contributors to global greenhouse gas (GHG) emissions, and the substantial reduction of GHG emissions across their full life cycle is required to enable meeting international climate targets. For effective climate change mitigation - as recent studies have shown - a special focus has to be put on lowering embodied GHG emissions, i.e., emissions related to construction production manufacturing and construction processes, maintenance and replacement as well as end-of-life processing. As the importance of reducing embodied GHG emissions rises, so does the need for understanding both the baseline and pathways for reduction across the full life cycle of buildings. In this paper, we offer insights into the data-driven analysis of embodied GHG emissions across the whole life cycle of buildings from recent studies. Our investigation builds on the data collection, processing and harmonisation of around 1.000 building LCA case studies. We offer an integrated perspective on GHG emissions across the life cycle of buildings, considering historical trends, current baselines and indicative reduction pathways for embodied GHG emissions in different countries across Europe. This serves to inform our current 'decade of action' and the transformation to a regenerative built environment by 2050.

Keywords: Buildings, Construction, Data analysis, Embodied carbon, GHG emissions, Benchmarks, Reduction pathway, Decarbonization, Roadmap

1. Introduction

While substantial progress has been made in lowering operational greenhouse gas (GHG) emissions from buildings over the past decades, there is an increasing need to look at the total impact of buildings across their full life cycle [1,2]. As previous research has shown, the contribution of so-called embodied GHG emissions to full life cycle emissions of buildings is increasing and a major challenge for effective climate mitigation [3–7]. “Embodied carbon”, as used in this paper, consists of all the GHG emissions associated with construction products including building materials (e.g. concrete), building components (e.g. windows) and technical systems (e.g. HVAC) and construction processes throughout the whole life cycle of a building. Embodied carbon emissions therefore include the following life cycle stages (acc. EN 15978): material extraction (A1), transport to manufacturer (A2), manufacturing (A3), transport to site (A4), construction (A5), use phase (B1), maintenance (B2), repair (B3), replacement of building components and systems (B4), planned refurbishment of building components (B5), deconstruction (C1), transport to end of life facilities (C2), processing (C3), and eventually, disposal (C4).

In order to enable a just and green transition of building construction and operation towards net-zero GHG emissions, policy makers and building design professionals, among other relevant stakeholders, require robust information on the current level of embodied carbon of buildings across Europe, as well as targets and guidance on how to reduce it going forward [8–10].

Against the backdrop of increasing efforts to understand and reduce whole life cycle carbon of buildings, this paper combines three perspectives to investigate the role of embodied carbon up until today and into the future, by examining: 1) the historic development of embodied carbon; 2) the current baseline for embodied carbon; and 3) an indicative pathway for embodied carbon reduction.

2. Materials and methods

2.1. Embodied carbon data case studies

In this paper we investigate full life cycle embodied carbon based on the analysis of a total of 1284 building LCA case studies, out of which 983 are effectively used for this analysis (cases from Europe, fulfilling quality requirements on transparency of the assessment and completeness of reporting). The cases were obtained from various data partners and literature sources, and have been compiled in two main datasets originating from a life cycle carbon meta-study conducted in context of the “IEA EBC Annex 72 - Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (Annex 72) [3], and the embodied carbon baseline analysis in “Towards Embodied Carbon Benchmarks for buildings in Europe” (EU-ECB) [11], respectively. Table 1 provides an overview of the case studies and data sources used in this study.

Table 1: Overview of case studies and data sources used in this study

Country	**No. of cases in datasets**	
Source(s)	"Annex 72” [Röck et al. 2020]	"EU-ECB" [Röck et al. 2022]
Austria	20	-
Belgium	4	105
Denmark	29	72
Finland	5	59
France	24	486
Germany	4	-
Ireland	4	-
Italy	43	-
Netherlands	-	47
Portugal	11	-
Spain	2	-
Sweden	19	-
Switzerland	23	-
United Kingdom	26	-
Total	**214 (430)**	**769 (854)**

2.2. Data processing and harmonization
The data utilized in this study is based on the existing LCA data on building cases from different countries. This requires consideration of differences in the data, 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 harmonization steps were implemented to prepare the data for a consistent analysis. We applied a procedure for harmonizing studies reference study periods, based on the protocol proposed in the IEA EBC Annex 72 meta-study [3].To improve comparability of the studies, we hence applied harmonization procedures, e.g., to harmonize the reference study period (RSP) of studies to a common timeframe of 50 years. No physical discounting is applied and no reduction of future emission intensity is considered. The values presented in this contribution are describing "committed embodied carbon" over a fictive 50-year life cycle, modelled using contemporary technology and related emission intensities. We further applied statistical approaches for inferring missing data to enhance the completeness and size of the dataset, e.g. based on the observed contribution of different life cycle stages or buildings parts, raising the value of the data for further use in research and practice. Further information on methods and materials, such as an overview of the attributes which we collected information on, via our data collection template, data structures, steps and scripts for processing as well as formulas applied for harmonization of embodied carbon emission values, is provided in the related project publication [11].

2.3. Three perspectives on embodied carbon
As introduced, this contribution presents three perspectives on embodied carbon, drawing on the data obtained from the different case studies, based on their year of construction.

(1) Historic development of embodied carbon is investigated based on the Annex 72 dataset, obtained through the systematic review and analysis of case studies described in published literature and reports. The construction years of the case studies range from as early as 1940 up until 2020. Plotting these cases' embodied carbon by their construction year made possible to analyse the historic embodied carbon trend.

(2) Current embodied carbon baseline, in different building types and across life cycle stages is investigated based on the data obtained for the baseline analysis within the EU-ECB project. The cases compiled in this dataset have a construction year between 2015-2019, and are hence considered examples of 'current' levels of embodied carbon.

(3) An indicative pathway for embodied carbon reduction is investigated based on the application of the "carbon law" approach. The *carbon law* approach stems from the 2017 article "A roadmap for rapid decarbonization", published in the renowned journal Science [12]. Therein, leading climate scientists provide a detailed modelling of the rapid decarbonization action required to enable meeting the Paris Agreement. Along with a detailed roadmap with reduction pathways for different sectors, the authors promote the application of a simple heuristic:

"To calibrate for short-term realpolitik, we propose framing the decarbonization challenge in terms of a global decadal roadmap based on a simple heuristic—a "carbon law"—of halving gross anthropogenic carbon-dioxide (CO_2) emissions every decade. Complemented by immediately instigated, scalable carbon removal and efforts to ramp down land-use CO_2 emissions, this can lead to net-zero emissions around mid-century, a path necessary to limit warming to well below 2°C." [12]

3. **Results**

3.1. Historic development of embodied carbon
Figure 1 presents the historical development of embodied carbon per m² gross floor area (GFA) over a 50 year building service period (y-axis) by year of building construction (x-axis), based on the Annex 72 meta-study dataset (see Table 1), showing trends for different energy performance levels (Existing Standard, New Standard, New Advanced) as defined in the original study [3]. The figure only shows cases from Europe, and limits the analysis to the years 2000 to 2020, excluding earlier cases for clarity.

Figure 1 reveals the recent trend of increased embodied carbon for new advanced buildings, as previously suggested in the original study [3], albeit with a more general geographical coverage, i.e. cases from different contexts combined. Confirming the authors previous conclusions, we find that there is an increase in embodied carbon, particularly for new advanced buildings with above-average requirements regarding energy efficiency during the use phase (green line), approaching a total carbon footprint of 500 kgCO2e/m² in recent years. This emphasizes the need for further understanding of embodied carbon level, for different types of buildings. The fact that a majority of embodied carbon is emitted upfront (i.e. for material production and construction, before even starting to use the building) [3] further highlights the need to better understand its temporal distribution across the building life cycle - See section 3.2.2 for details on emissions in different life cycle stages.

3.2. Current baseline for embodied carbon of different types of buildings

3.2.1. Life cycle embodied carbon per m². To improve understanding of current levels of embodied carbon, we analysed the whole life cycle embodied carbon baseline 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 2 presents the full life cycle embodied carbon (EC) baseline for residential and non-residential buildings, respectively, considering the total over a 50-year building service period. It shows EC values for residential buildings range from about 400 to 800 kg CO2e/m² with a mean value of around 600 kg CO2e/m². For non-residential buildings, we observe a larger spread of EC values, ranging from about 100 to 1200 kg CO2e/m², with mean values around 600 kg CO2e/m². A likely reason for the large variance in non-residential building results is the strong difference in building sub-types grouped together in this category.

Figure 3 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, we find the highest per-m² values for multi-family houses, with a mean value of around 700 kg CO_2e/m^2. The lowest per-m² values are observed for terraced (row) houses, with mean values of about 400 kg CO_2e/m^2. The other categories on the horizontal axis represent non-residential building types. For these we observe the highest per-m² values for 'hospital and health' and 'sport and entertainment' buildings,

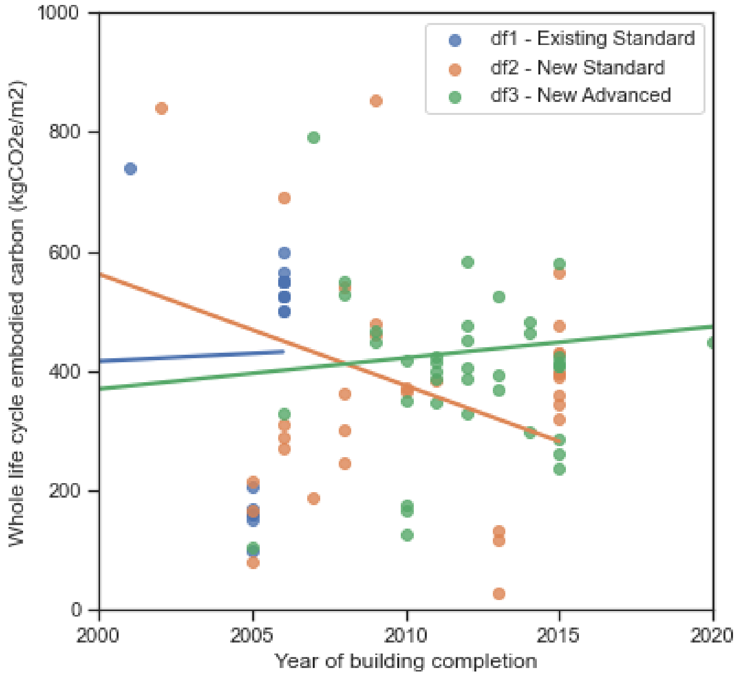

Figure 1. Historical development of embodied carbon per m² in IEA EBC Annex 72 dataset [3].

with mean EC values of about 800 kg CO_2e/m^2 for both. ‘Office’ buildings weigh in with a mean EC value of around 600 kg CO_2e/m^2, while displaying a large variation of EC values with multiple outliers. A large spread and high values are furthermore observed for ‘school and daycare’ buildings, with a mean value of around 750 kg CO_2e/m^2. Detailed analyses of EC baselines for different types and subtypes of building use in different countries as well as tables presenting the related descriptive statistics are provided in the related report [11].

3.2.2. Contribution of different life cycle stages. In order to provide further insights into the timing of embodied carbon emissions along the life cycle of buildings, the study investigated the contribution of different life cycle stages. The definition of the life cycle stages is based on EN 15978 / EN 15643. Embodied carbon emissions are hence disaggregated as occurring during: the production stage (A1-3); the construction process stage (A4-5); the use phase, for use, cleaning, maintenance, and replacement (B1-4); as well as the end of life stage, differentiated in

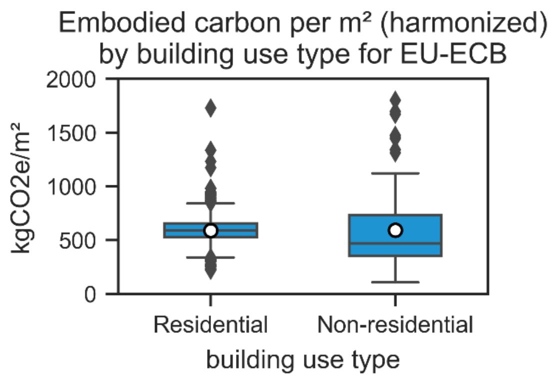

Figure 2. Life cycle embodied carbon per m² by building use type, based on EU-ECB baseline [11].

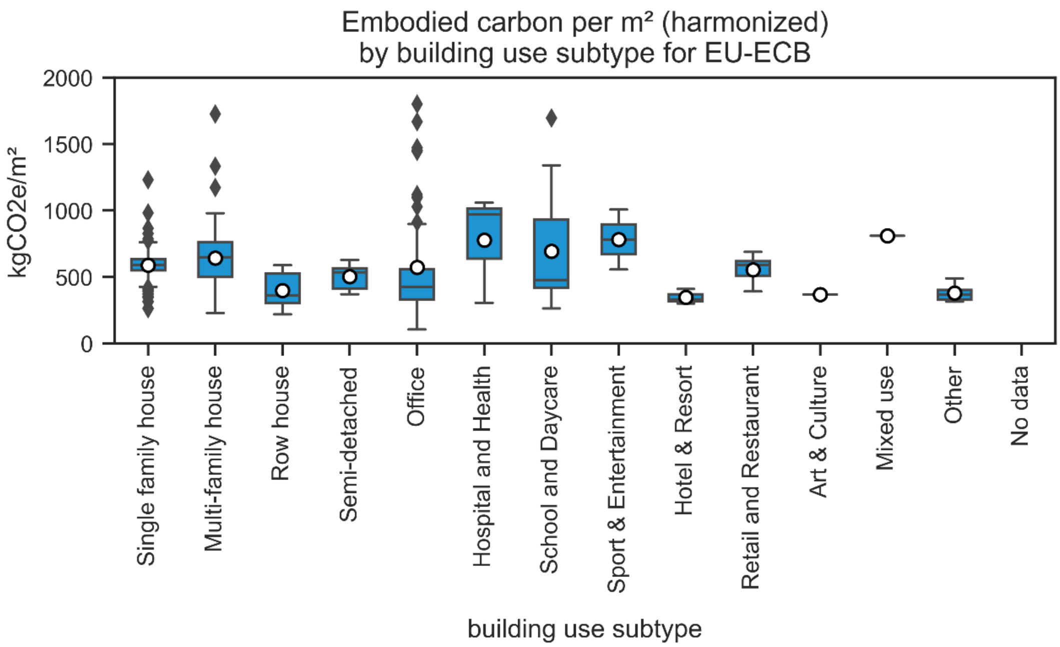

Figure 3. Life cycle embodied carbon per m² by building use subtype, based on EU-ECB baseline [11].

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 amount 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 D1), while requested to be documented in our data collection, were not considered in the visualisation, largely due to unsettled methodological discussions on its modelling and related large variation in results values and general availability.

Figure 4 presents these embodied carbon emissions for different life cycle stages. It shows that the largest contributions of embodied carbon emissions occur during the production stage (A1-3), with a mean value of about 300 kg CO_2e/m^2, and ranging from about 70 to 520 kg CO_2e/m^2. Second largest proportion of embodied carbon emissions occur during the use phase in relation to repair and replacement of building components and systems (B1-4), with a mean value of about 120 kg CO_2e/m^2, 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), use phase embodied carbon emissions (B1-4) show a large variation in values from 0 to about 350 kg CO_2e/m^2, which most likely depends on parameters such as the type of building use, the structural system and choices of materials, components and systems, the type and amount of BIPV as well as climate and weather conditions as reason for aging process. It is further relevant to note the variations in the scopes of studies regarding individual life cycle modules considered in the use stage, i.e., not all studies cover all modules of the use stage (B1-4), with mostly aspects such as cleaning or maintenance potentially missing. In extreme cases, the embodied carbon emissions occurring during the use stage (B1-4), reach the average level displayed during the production stage (A1-3). The other life cycle stages represent minor contributions to whole life cycle embodied carbon emissions. The construction process stage (A4-5) shows a mean value of around 40 kg CO_2e/m^2. For the end of life stage, deconstruction and transport (C1-2) shows a mean value less than 20 kg CO_2e/m^2, and waste processing and disposal (C3-4) indicates a mean value for emissions of around 60 kg CO_2e/m^2. The considerable amount of outliers observed for the latter (C3-4) might indicate the effect from different end-of-life scenarios as well as potential influence of methodological differences in modelling these processes. These differences will likely also have influence on the use phase (B1-4) embodied carbon values observed in this study.

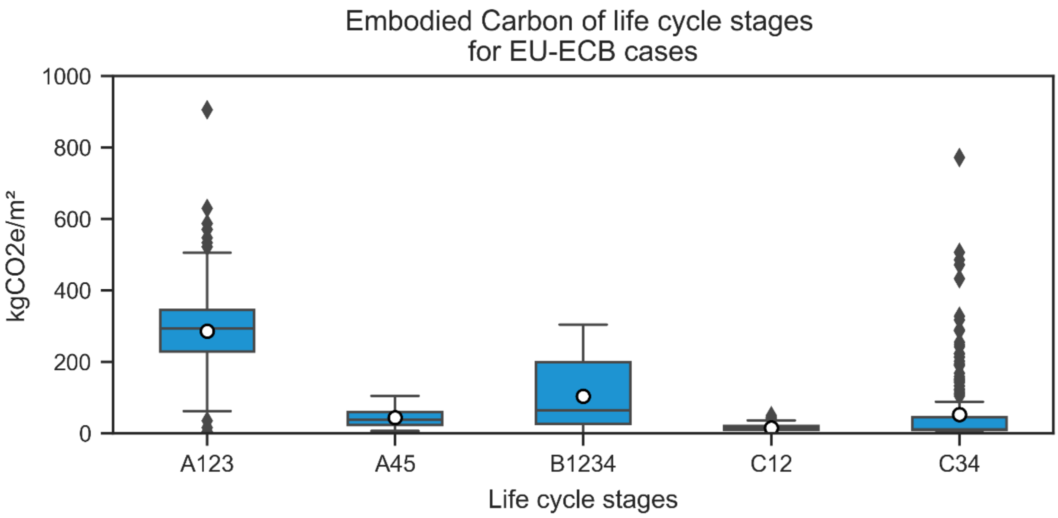

Figure 4. Embodied carbon per m² in different life cycle stages (A123, A45, B1234, C12, C34), based on EU-ECB baseline [11].

An overview of the average absolute and relative contribution of different life cycle stages is presented in Table 2. No benefits and loads beyond the system boundary (module D1) are shown, as mentioned earlier, which in any case should not be combined and not used to “offset” emissions from other life cycle stages.

Table 2. Mean contribution to full life cycle embodied carbon [kg CO_2e/m^2] from different life cycle stages, based on EU-ECB baseline [11].

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

3.3. Indicative reduction targets for embodied carbon

As a final step, we explore indicative decarbonization pathways for a reduction of embodied carbon emissions in the coming years and decades, based on the understanding of historical developments and current levels of embodied carbon,.

In Figure 5 we plot an indicative reduction pathway for embodied carbon emissions of buildings, starting from the current baseline of about 600 kgCO2e/m² (mean), as presented earlier, and applying the simple heuristic proposed in the “carbon law” approach for the timeframe of 2020 to 2050. The figure implements the suggested ‘halving [of GHG emissions] every decade’ and applies it to the whole life cycle embodied carbon emission values for residential and non-residential buildings, respectively. The analysis hence shows that indicative target values for full life cycle embodied carbon in 2030 would be half of what it is today, i.e. around 300 kgCO2e/m². As an intermediate step, a reduction target in line with the latest climate science for 2025 could be 450 kgCO2e/m². Going further, embodied carbon levels will have to be about halved each decade, leading to indicative target values for full life cycle carbon of 150 kgCO2e/m² in 2040, and 75 kgCO2e/m² in 2050, respectively.

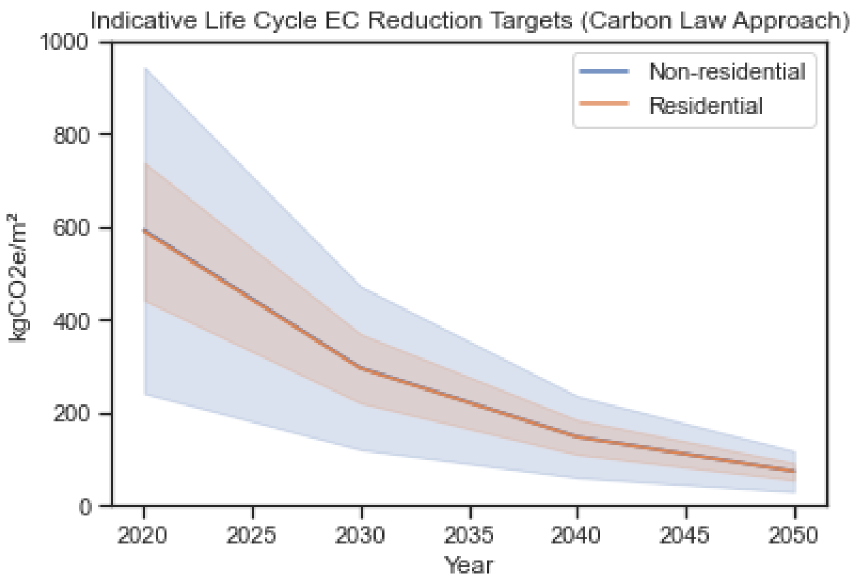

Figure 5. Indicative reduction targets for full life cycle embodied carbon emission [$kgCO_2e/m^2$] of residential and non-residential buildings, respectively, based on [11] and [12].

For a detailed understanding of what such a reduction pathway could mean, we calculate reduction targets for individual life cycle stages – presented in Figure 6 and Table 3 – based on the mean values obtained in the baseline analysis presented earlier. These values suggest indicative targets for the production stage (A123); construction process (A45); the use phase, including maintenance, repair and replacement (B1234); the deconstruction process (C12); and the end of life stage (C34), respectively, and lay out how the related levels of embodied carbon emissions should reduce by 2030, 2040 and 2050 with a carbon law approach.

While this application of the carbon law approach is a simple exercise to give an indication of the drastic reduction of embodied carbon emissions from buildings, it provides a hint on the required trajectory. The definition of more specific, relative reduction targets is required and underway, but implementation of ambitious carbon reduction strategies must not wait another decade for methodological discussion to move forward and allocation issues to be settled. The relative reduction target approach showcased here could, for example, enable to the application of reduction pathways from other sources and contexts, such as the pathways proposed in the latest IPCC AR6 report, based on latest carbon emission budget calculations, or decarbonization pathways of the European Union and its Member States, as outlined in the respective environmental policy documents. It might further support the alignment of different stakeholder perspectives, e.g. by using relative reduction targets from building and construction-related industry sectors.

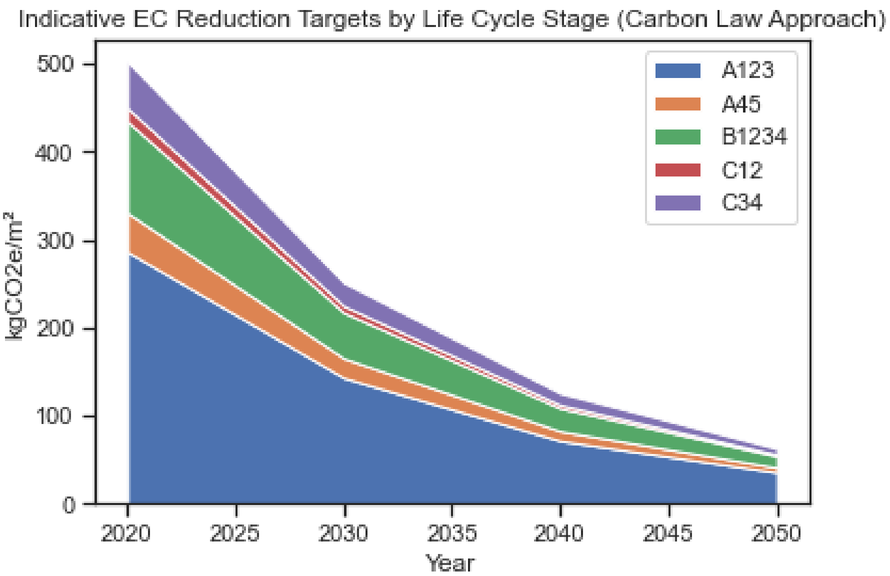

Figure 6. Indicative reduction targets for embodied carbon emission of both residential and non-residential buildings in different life cycle stages [$kgCO_2e/m^2$], based on [11] and [12].

Table 3. Indicative reduction targets for embodied carbon emissions [$kgCO_2e/m^2$] from different life cycle stages, based on mean values in EU-ECB data [11] and application of Carbon Law approach [12].

	A1-3	**A4-5**	**B1-4**	**C1-2**	**C3-4**
2020	286.26	44.20	103.76	15.38	52.41
2030	143.13	22.10	51.88	7.69	26.21
2040	71.56	11.05	25.94	3.84	13.10
2050	35.78	5.52	12.97	1.92	6.55

4. Discussion

4.1. Embodied carbon target values

There is ongoing discussion on how specifically to define ‘carbon budgets for buildings’ and how to do so in a manner that is consistent across countries, industry sectors and building-related activities [8]. We consider it important to engage with this struggle for a common understanding of emission allowances and reduction pathways for different areas of action like “buildings” and actors. At the same time, we want to highlight approaches that can be useful in guiding in the right direction regarding the (embodied) carbon emissions reduction needed in the coming decades, which can be applied today, using relative reduction targets and related pathways, such as the carbon law approach. While we present the application of the approach based on the average baseline results, a more specific application on country level could be considered for future research. Furthermore, the approach of applying relative reduction targets can be applied beyond the carbon law, e.g. drawing from national determined contributions (NDCs) and relative carbon reduction targets for different industry sectors potentially defined therein.

Robustness and feasibility of targets. The analysis of indicative reduction target presented in this study lays out the need for drastic reduction of life cycle embodied carbon in coming years and decades. The general trajectory and necessity of substantial reductions in emissions levels is in line with previous research on the topic [8,13] and, in particular, the ambition of achieving ‘absolute sustainability’ in the context of building construction and operation [14–18]. Similar emission reduction trajectories have recently been called for in a joint declaration of expert researchers on building life cycle assessment from IEA EBC Annex 72 in the so-called Graz Declaration and Monte Verità Declaration on a built environment within planetary boundaries [19].

4.2. Limitations and recommendations

Representativeness of the samples: The data samples analysed in this study are not representative of the building stock in a given country. The distribution of the number of cases from different countries (see Table 1) influences the results when analysing the datasets. For example, the high number of cases from France will have affected the current baseline results. The results obtained can hence only give a first indication of common levels of embodied carbon for different building types across Europe. A more detailed analysis per country is available for the EU-ECB dataset in the related publication [11].

Life cycle assessment methodology: As our study utilizes existing building LCA studies, several inherent methodological differences are influencing the emission results. For some of these aspects we took measures to harmonize the results – such as for reference study period and floor area definitions – or explicitly make differences visible by plotting results accordingly – e.g. for different building types, per area and per capita, or even for individual life cycle stages. Other methodological differences may still influence the results and deserve further investigation, such as the influence from differences in system boundaries (e.g., building parts and life cycle stages considered), background data, amongst others. The ongoing efforts to harmonize building LCA methodology as well as requirements for documenting assessment parameters and results are very welcome in this regard and should be points of attention for researchers and practitioners alike.

Research needs: Future research should aim to assess representative samples of buildings for different countries and regions, be based on consistent assessment methodologies, and enable comparability trough transparency in reporting, following minimum documentation requirements and comprehensive data formats. Furthermore, the assessment has to go beyond building level and investigate the development of building stocks at different scales to support policy and practice [20].

5. Conclusions and outlook

Embodied carbon emissions of buildings have increased in recent years and the upfront carbon spike of new building production is now dominating emissions in the life cycle of new buildings as well as the timeframe for effective mitigation of the climate crisis.

The indicative baseline for whole life cycle embodied carbon emissions ranges from around 400 to 800 kgCO2e/m² with a mean value of around 550 kgCO2e/m² for residential buildings, and from about 100 to 1200 kgCO2e/m² for non-residential buildings, with a mean value of 450 kgCO2e/m², respectively. The investigation of contribution from different life cycle stages shows that the largest fractions – almost 2/3 of embodied carbon emissions - occur upfront, i.e. during the production stage (A1-3) and construction process stage (A4-5), with on average about 340 kgCO2e/m² (63% of whole life cycle embodied carbon emissions).While emissions of the use stage (B) and end-of-life (C) activities may change for buildings constructed now, we want to emphasize the amount of “upfront" carbon, emitted during the production and construction process stages (A), which are taking place for production and construction of new buildings today, using contemporary technologies and causing related emissions today.

Our findings emphasize the importance of upfront carbon and the urgent need to reduce “the carbon spike” as soon as possible in order to avoid lock-in effects and committed emissions from new building construction and operation. Suitable, legally binding target values for whole life carbon of buildings should be sought across Europe and implemented no later than 2025. The indicative baseline presented in this paper and expanded on in the underlying research project reports, can serve as a starting point for further developing the required benchmarks for reducing whole life carbon of buildings across Europe.

The application of the carbon law approach enables the provision of indicative reduction targets for embodied carbon emission for both whole life cycle embodied carbon as well as different life cycle stages. Applying relative reduction targets could provide an approach for implementing existing target pathways, e.g. from the latest IPPC report or according to European Union policy. While the targets proposed for buildings in 2050 do not seem feasible today, there is evidence to at least support the first steps, and embark on an ambitious decarbonization pathway for reducing whole life cycle and embodied carbon of buildings until 2030 and beyond.

From the experiences with data collection and analysis in this project, we recommend to define extended documentation requirements for building LCA case studies beyond current industry practice, towards harmonized documentation of the methodology and scope of the assessments, as well as the provision of detailed, disaggregated information for results of individual building parts and life cycle stages. The use of different reference units to present baseline values (among others) can reveal different mitigation strategies – e.g. the effects of limiting dwelling unit size (average floor area per capita) on embodied emissions can be seen in per capita representations.

As research showed, the necessary carbon reductions will be achievable only with a combination of technological measures, such as increased energy and material efficiency or the application of circular economy principles, as well as the support and implementation of social innovations and lifestyle changes to enable demand-side emission reduction. An important next step for enabling the legal implementation of embodied and whole life carbon benchmarks and related measures in practice, is the development of a clear and science-based roadmap for their reduction, including specific milestones and target values. The development of a roadmap for the reduction of Whole Life Carbon of buildings, including the support study recently commissioned by the European Commission, are important steps in that regard.

Acknowledgement
The analyses presented in this paper are based on the two sources of data and the related publications: Namely, the 2020 meta-analysis of IEA EBC Annex 72 experts on “Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation” [3] and the 2022 study “Towards embodied carbon benchmarks for buildings in Europe” (EU-ECB). The EU-ECB reports on the data collection [21], the baseline analysis [11], as well as the summary report [22] served as particular sources for figures and text presented in this contribution. The underlying building LCA data collected in the EU-ECB study has been published as “Embodied Carbon of European Buildings Database” and is available open access via [23].

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