Towards embodied carbon benchmarks for buildings in Europe

#1 Facing the data challenge

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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 in the following consider 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 life cycle of a building[1]. While past efforts have mostly focused on increasing energy efficiency in building operation, 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 urgent state of climate change requires rapid action without any further delay.

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. Through a series of four reports[2], 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. In particular, the focus is on upfront embodied emissions which represent the largest share of embodied carbon and can be shaped at the design stage.

For this purpose, data on the GHG emissions from building construction is essential for calculating the current baseline levels of embodied carbon. Additionally, the current data landscape will shape the options available to us for monitoring future buildings against specific benchmarks, once these have been established. Therefore, this report describes the experience gained in collecting building-level embodied carbon data from life cycle assessments (LCAs).

Results – What did we find?

The objective of this part of the project was to compile LCA data from European countries, for which 50 cases or more could be found. Each case represents a building where LCA data was available which could be used to provide information on the current level of embodied carbon in buildings. This would allow relatively robust conclusions to be made regarding the baseline level.

However, the data collection process conducted across Europe resulted in only five countries being identified for which sufficient data could be used. These were Belgium, Denmark, Finland, France and the Netherlands. Figure 1 summarises and illustrates the situation across Europe.

The data collection process highlighted a series of data challenges which resulted in the low number of cases which could be used. These challenges are summarised in Table 1.

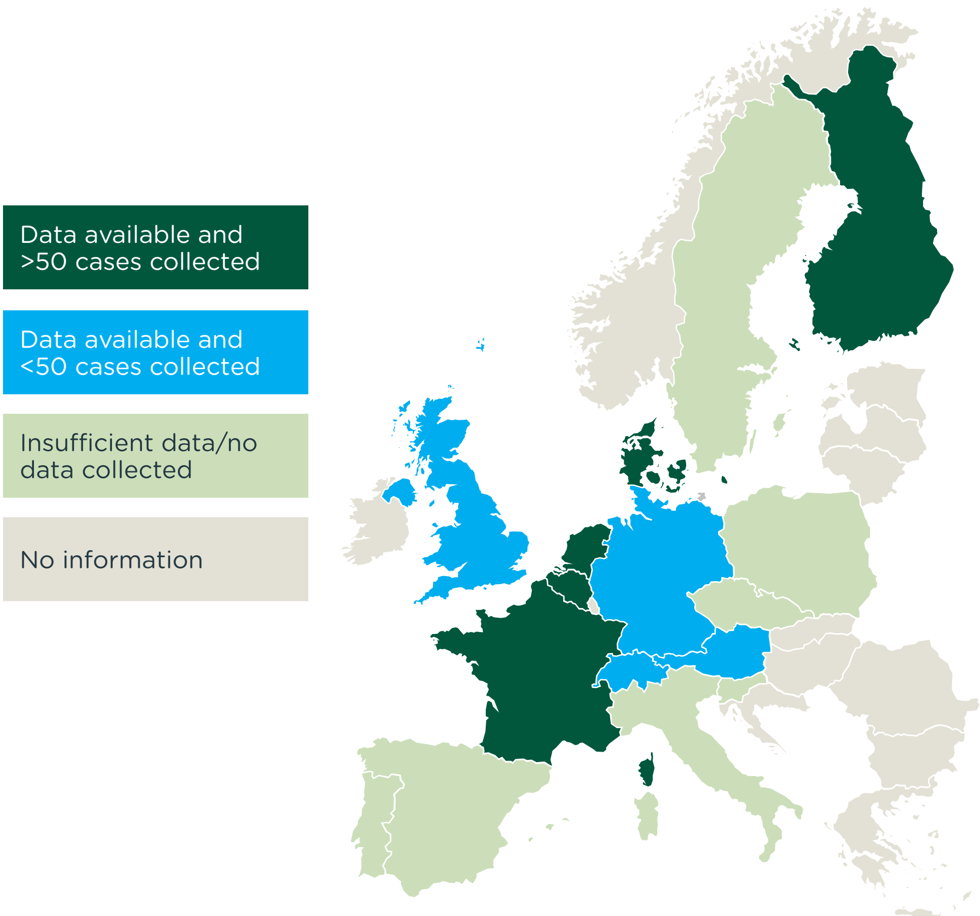
[1] Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, maintenance, repair, replacement, refurbishment, deconstruction, transport to end-of-life facilities, processing, disposal.

[2] Reports: #1: Facing the data challenge; #2: Setting the baseline; #3: Defining a carbon budget; #4: Bridging the gap

Table 1: Key challenges encountered in the LCA data collection

Challenge	Definition	Effect on building LCA data
Availability	Existence of data at the national level	In many European countries, the practice of conducting LCAs does not exist, or the results are not fed into a central repository.
Accessibility	Possibility to access existing data	LCA data may be collected into a central repository but is not shared by the owner because of data protection or intellectual property concerns.
Quality	Data meets accuracy, completeness, timeliness, validity, and uniqueness criteria	Entries in national databases vary in completeness, have unclear time origins or include duplications.
Comparability	Data scope and collection method are comparable with each other	The scope of life cycle stages, building parts or environmental impacts, or the data collection and results calculation methods differ. This is a particular challenge when comparing data across countries.
Representativeness	The data represents the building stock, in terms of new construction, well	Even if all the above factors are met, data can come from selected buildings with high environmental performance, for instance where obtaining sustainability certification is envisaged. This delivers a skewed and incomplete picture of the embodied carbon in new buildings. Sufficient data points are needed for each different building type to be able to draw representative conclusions. The larger the sample, the better it is in this respect.

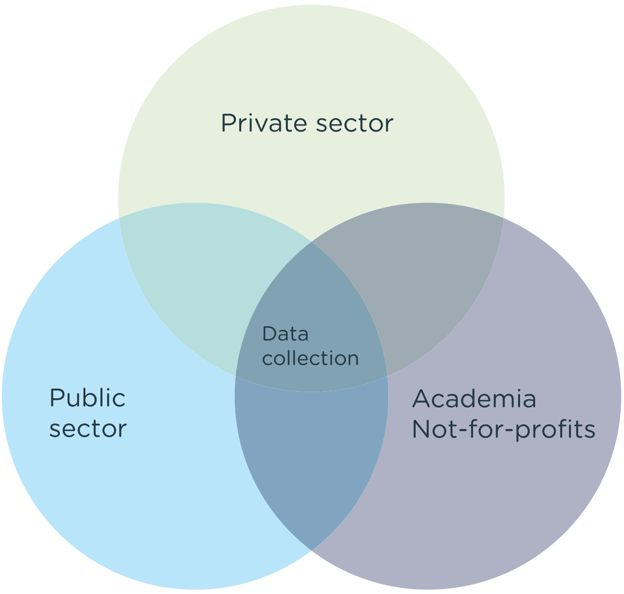
Figure 1: Overview of data availability in Europe



Conclusions – What does this mean?

In conclusion, we found that the LCA data required for a benchmarking system to reduce embodied carbon in new buildings needs to be more extensive. Furthermore, the challenges identified in this report need to be addressed and overcome quickly in order to avoid any delay to action being taken.

The experience from those countries for which data could be collected shows that overcoming the challenges is the result of incentives to conduct LCAs and to make the results available being included in national legislation and other policy initiatives. Additionally, the effectiveness of data collection can be increased through triple-helix cooperation between the public and private sectors, as well as academia and not-for-profit partners.



Call to action – What should we do?

Based on the findings of this work, we arrive at the following recommendations:

National LCA methods and data collection systems are urgently needed to avoid any further delay in this fundamental step towards measuring and reducing embodied carbon as part of whole life carbon emissions.

To this end, legal or sectoral requirements that mandate the production of LCAs in accordance with standardised calculation and documentation methodologies are highly relevant at national level, as well as harmonisation at EU level through tools such as the Level(s) framework. Standardisation based on coordination between stakeholders in the building design and construction value chain should, for example, include: scope of life cycle modules, scope of building elements, reference study period, environmental data on building materials, etc.

Data collection and compilation efforts are needed from all those involved in designing and assessing buildings. For this purpose, collaboration and complementary activities between public institutions, building designers, investors, certification organisations and researchers are needed. This step requires a common language and standardised method for LCAs, as described in the first point above.

As this process may take some time, the challenge of gaps in data could also be mitigated through the following approaches. These should be considered complementary.

- **Data on recent and current building projects could be generated at a centralised level by applying a single LCA method in order to provide information on these specific cases, as it is likely that this data can still be obtained.** This exercise would benefit from input from the different actors involved, including the building industry, certification bodies, researchers and public bodies. This cooperation could be greatly facilitated through the use of standardised calculation methods and software tools to form a central database. A similar approach has provided a large database in France.
- **Existing data, that has been created in a scattered form using varying methodologies by different stakeholders, has the potential to be gathered together and harmonised to form a centralised database**. Harmonisation methods, adapted to the specific differences between the LCA methodologies, could be agreed upon by a coalition of actors to support this undertaking. Examples of such action are the international activities in Annex 72 to the IEA-EBC Programme, as well as the UK initiatives LETI and BRE.
- **Where empirical data faces the challenges described in this report, relying on results from modelled building archetypes could provide an insight into the life-cycle impacts.** Building archetypes offer the advantage of providing representative and comparable values. However, limits remain in translating building stock models into LCA data, which is challenging, particularly for the diverse landscape of non-residential buildings. Also, monitoring future buildings, in comparison with benchmarks, is not possible. Nonetheless, efforts to translate this data can help in the transition towards standardised empirical LCA data. This approach has been used successfully in projects such as the Tabula/Episcope project.

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.

Altogether, the total amount of embodied and operation emissions is referred to as whole-life carbon emissions. Reducing this total sum of emissions in a building is of the highest priority, to which this work aims to contribute.

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 require 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 considerations 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.

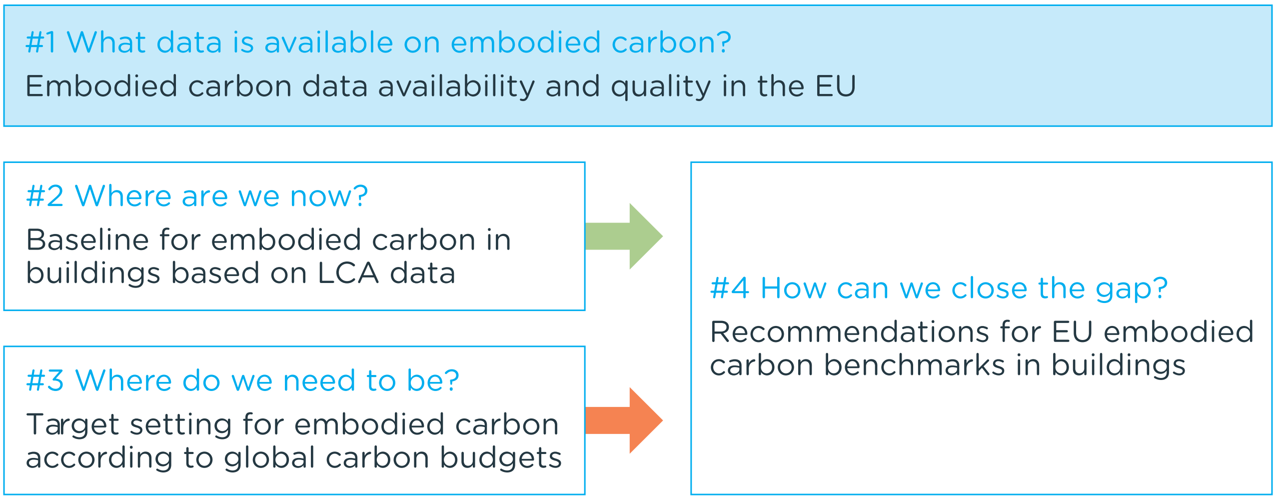
[3] Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, use phase, maintenance, repair, replacement, refurbishment, deconstruction, transport to end of life facilities, processing, disposal.

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?

The report herein is the first report in this series.

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



The purpose of the report herein is to summarise the insights gained on embodied carbon data from life cycle assessments (LCA). A search for such data was carried out across EU countries (and the United Kingdom) to form a basis for the baseline setting process and for drawing up a benchmarking framework.

The report presents the current situation as encountered in the EU countries and the UK, points to the key issues in LCA data and provides solutions for overcoming these challenges. The findings in the report are supplemented with country sheets for the five countries for which sufficient data was available: Belgium, Denmark, Finland, France and the Netherlands.

2. What is the situation on building LCA data in Europe?

2.1 The ambition

Developing robust recommendations for a benchmarking system for embodied carbon in buildings requires an evidence base in order to be able to understand the status quo and to set the baseline for reduction efforts.

For calculating the baseline of embodied carbon in new construction in the EU, this study aimed at gathering **national datasets consisting of at least 50 cases** of high-quality building LCA data per country from EU Member States and the United Kingdom. This target was set to create a sample for analysis that was as broad as possible, while taking into account the currently limited collection of building LCA data.

However, considering the overall number of construction projects, this target number was deemed sufficient for making feasible statements on the embodied carbon levels in new buildings.

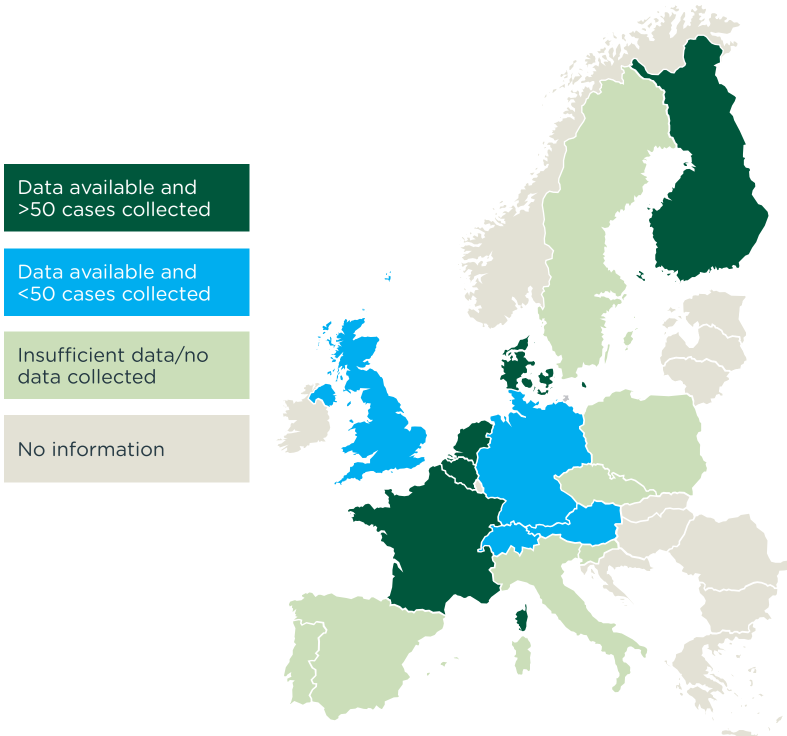
2.2 The reality

The research into the national methods and cases of available LCA data for all EU Member States revealed that obtaining a larger amount of data is impossible in the majority of countries. **The results show that the majority of EU Member States have low to no LCA data available for calculating bottom-up embodied carbon benchmarks**, with only five Member States identified as having 50 or more LCA cases available. The details for these five countries are compiled in the country sheets in Appendix 1, while an overview of the embodied carbon data landscape in all EU Member States is provided in Appendix 2.

Figure 3 summarises and illustrates the data available in European countries, as assessed during the data collection process for this project. It illustrates that, **within the countries included in the study, samples of sufficient size and quality could only be collected in Belgium, Denmark, Finland, France and the Netherlands**. In four additional countries, some data could be identified, but it did not pass the threshold of 50 cases.

This highlights a significant variation in the building LCA data available, which limited a broader coverage of countries to assess current embodied carbon levels. This impacted the calculation of the baseline and the carbon budgets, as well as the determination of benchmarks required to guide the reduction of said emissions. The variation in the data landscape and the need for this evidence base highlights the urgency for expanding and improving data collection, and suggests that lessons could be learnt from the Member States included in this study at the forefront of data collection. The following sections provide additional analysis and discussion of what drives data development and data accessibility in these countries.

Figure 3: Overview of data availability in Europe



3. What are the issues with LCA data?

This section summarises the key issues encountered in the data collection and analysis process. As suggested by the map of data availability in Figure 3, embodied carbon LCA data can be challenging to come by, as in most EU Member States there is no precedent or requirement to develop LCAs which include embodied carbon in buildings. However, other factors may also pose data challenges when using LCA data to develop embodied carbon benchmarks. This includes the following points (as summarised in Table 2 above) which will be discussed below, based on the experience gained from the data collection at national level.

Table 2: Key challenges encountered in LCA data collection

Challenge	Description
Availability	Existence of data at national level
Accessibility	Possibility to access existing data
Quality	Data meets accuracy, completeness, timeliness, validity and uniqueness criteria
Comparability	Data scope and collection methods are comparable with each other
Representativeness	Data represents the building stock, in terms of new construction, well

3.1 Data availability

As already outlined, finding existing LCA data for buildings has proved challenging in most countries. In many of the countries in which the expected sample size could not be reached, LCAs are not commonly performed in practice or are not collected. The reasons for this can be a lack of awareness, guidance on methodology, or incentives for LCAs for building projects. Two examples highlight the challenges of data availability from countries in which data could not be collected.

Firstly, in **Poland**, where there is no regulation on whole life carbon, the Polish Green Buildings Council expressed difficulties in accessing data on embodied carbon as the results of LCAs are not systematically gathered into a central repository. In this case, the development of LCA data was driven by investment companies and developers expressing an interest in conducting LCAs on construction projects to achieve voluntary sustainability certifications. Thus, the data was found to remain with the private sector (building owners, consultancy companies conducting the LCAs, the LCA tool owner, or certification bodies); and was not readily accessible by research institutions or the green building council. This case was found to be representative of the majority of EU Member States where the lack of a central LCA repository and private sector data holding were found to create barriers to developing nation-wide embodied carbon benchmarks. This case, therefore, is emblematic of the data availability and accessibility challenges.

In the **Czech Republic**, an active academic research project (CVUT) was identified on the topic of building LCA, its implementation in the design process, and the definition of carbon targets for buildings. However, the limited number of available building LCA case studies prevented the inclusion of these LCA cases in this study's analysis. This suggests that future support for local actors to build on this experience in order to increase the number of LCA cases could enable a suitable database to be established in the future. Consequently, this is representative of the lack of data availability.

3.2 Data accessibility

If data is collected through LCAs at the building level, this **data may still not be usable in a general assessment of embodied carbon in the country due to challenges in accessing the data**. In the countries for which data has been successfully collected for this study, the data partners were able and willing to share their data. In other countries, this was not possible. In such cases, the consideration of an EU level baseline for embodied carbon is not possible in the current situation.

For instance, in **Germany**, we found a different landscape. Here, due, on the one hand, to the requirement for federal buildings to conduct a BNB assessment including an LCA, and, on the other hand, a popular uptake of the DGNB buildings certifications, LCA data was found to be available and held by the DGNB. However, barriers were encountered in accessing it due to data protection and intellectual property considerations. This became such a challenge that the data could not actually be accessed for this study. By the end of this project, and as a useful and timely contribution to the overall discussion around embodied carbon benchmarks, the DGNB published their own report on benchmarks for embodied carbon in buildings in Germany [2]. The findings of this report proved to be consistent with the findings present in report #2 “Setting the baseline” of this study.

3.3 Data quality

To be able to use the data as an evidence base for a robust assessment of current embodied carbon levels, **quality criteria have to be met**. This relates to the accuracy of building data, the completeness of reported data for each of the cases in the datasets, the timeliness of reporting to reflect the current level of embodied carbon, and duplications in the dataset. Variations in these criteria impacted the results and reduced confidence in the findings and related recommendations.

For instance, the embodied carbon data collection in France provides a contrast as, in this case, the data was both easily accessible and plentiful. This can be attributed to the existence of a central data repository held by a public body, and the key role of the Ministry of Ecological Transition in ensuring data is collected as per the E+C- experiment, and forthcoming RE2020. However, as the data was being processed, challenges were encountered regarding the completeness of the entries, where incomplete cases had to be removed. Consequently, what started as 1,197 LCA cases had to be reduced to 486 due to quality considerations.

3.4 Data comparability

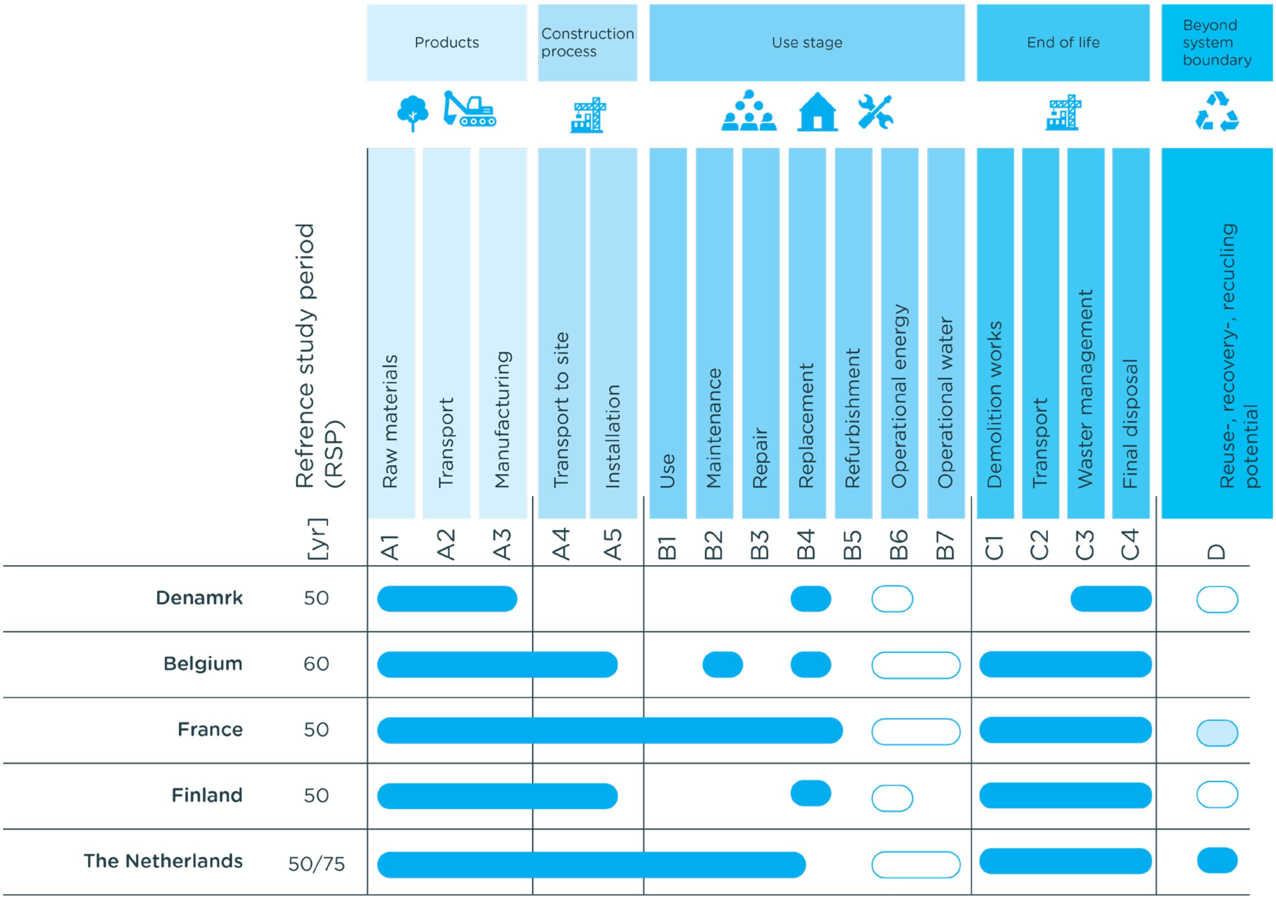
The consistency of the data quality is linked to the comparability of data based on the collection method. This challenge is particularly relevant when comparing and aggregating data from different countries in an EU-level baseline, or proposing actions such as a benchmarking system at EU-level. For these applications, the different approaches used further reduce the robustness of the evidence base.

Two main parameters can differ and impact the comparability:

- Scope of life cycle stages
- Assessment methods

Firstly, as Figure 4 shows, the inclusion of **life cycle modules in the scope** of the collected data differs between all of the five national LCA methods compared in detail in this project. The comparison illustrates that **France**’s LCA scope is the most encompassing, with **Denmark**’s being the least encompassing. Differences in the inclusion or exclusion of certain life cycle modules led to different baseline and LCA results. It is, therefore, important to consider, in the context of developing a harmonised baseline, which baselines can be used to set targets and benchmarks on embodied carbon, as the baseline for one country may be higher than another; not due to a higher embodied carbon footprint, but due to the inclusion of a broader scope.

Figure 4: Life cycle modules included in the scope of the collected data



Secondly, other elements in the assessment method can also vary and cause challenges in comparing the data. For example, the reference study period differs to some extent between the analysed cases (see Figure 4), which was also found to be the case for the scope of building parts included, and the background data used for modelling the building LCA. For instance, in France, the division of building parts was sometimes carried out using proxies, which could create biases as a result of their sources and the purposes they serve.

3.5 Data representativeness

Even if all of the aforementioned challenges are overcome, the data collected **may not be representative of the new buildings or building stock in total, and may therefore provide an incomplete and skewed picture of the embodied carbon situation**. For instance, this was discovered in the cases provided from Denmark and Finland, but also more generally for other EU Member States. The key challenge is that the majority of LCA studies are carried out for buildings which are already high-performance or new builds, and are less commonly carried out for average low-budget construction projects. This suggests that greater attention should be given to ensure the availability and accessibility of LCA cases for different building typologies to be able to ensure that the eventual national benchmark is representative of the general building stock. For this purpose, a large sample is highly beneficial, while smaller samples need to be particularly well-structured in order to be able to provide a full picture.

Conversely, there exist examples of alternatives. In **Belgium**, for example, KU Leuven could provide the required building case studies. There is a dedicated method for building LCA, called the MMG (Environmental Profile of Building Elements) method, and an open-access, online tool developed by the three regions in Belgium (Flanders, Walloon Region and the Brussels region) called TOTEM. KU Leuven had previously modelled the LCAs of various buildings as part of their research, these included studies of representative buildings, developed on the basis of the Belgian TABULA archetypes. KU Leuven could update their assessments and provide high quality case studies and detailed LCA results data.

4. What can be done about it?

The data challenges described in the previous chapter create a difficulty in establishing a robust benchmarking system for embodied carbon. On the one hand, this is caused by the challenges in establishing the baseline while, on the other hand, a comparison of future buildings against reference values also relies on a clearly defined methodology.

The data collection process and experience gained by the project team point to promising solutions in overcoming these barriers.

4.1 Incentives for LCA data collection in legislation and government initiatives

EU and national legislation or other forms of government initiatives can support LCA data collection by creating incentives, reducing barriers and promoting standard methods.

An assessment of regulatory measures covering embodied carbon across EU Member States found that very few Member States have developed legislation that includes requirements or standards for LCA methodology or embodied carbon in buildings (see annex 1). Thus far, Denmark, Finland, France and the Netherlands are the only Member States with existing or forthcoming regulatory measures covering embodied carbon.

However, to achieve an overview of embodied carbon legislation in the EU, the project team reached out to EU Member State infrastructure, development, and construction departments. The results indicate that additional Member States are in the process of planning legislation to set standards for both the level of embodied carbon emissions in buildings, and LCA methodology. For example, this is taking place in Sweden, where a second version of the Klimatdeklaration (a regulation to be enforced in 2022 making it obligatory to conduct LCAs on new builds [3]) is being planned for 2027, which will include limit values for LCA results.

In Switzerland, it was also noted that an LCA-based regulation is being planned, and a public official from Lithuania responded that plans are underway to prepare a methodology for modelling whole buildings life cycle emissions, including embodied carbon. Furthermore, in Ireland, a public official remarked that the international certification schemes for non-residential buildings LEED and BREEAM are driving interest amongst professionals wanting to calculate embodied carbon emissions, and that an increased interest from the investment community in embodied carbon has also been experienced. The official added that with these developments, alongside the Level(s) and the introduction of legislation in Finland, the Netherlands and France, they believed a plan for legislation would be forthcoming: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:

> "There are currently no definitive plans in Ireland for regulations but there are a number of positive indicators that this is likely to happen over the next five years. Holland and France have already introduced regulations, with Finland introducing regulations in 2025 and other countries likely to follow.
>
> Changes to the EU Construction Products Directive will likely see a requirement for use of ecological footprinting of products through either EPD or Product Environmental Footprint (PEF) The EU commission has introduced the Level(s) framework"

Three key **types of regulatory measures on embodied carbon** and LCA methodology were identified. These are:

- A requirement to calculate LCAs on public buildings, as exemplified by Germany.
- A requirement to calculate LCAs on all buildings, as exemplified by France (progressively from 2022 onwards), the Netherlands and Denmark (from 2023 onwards for all buildings).
- A graduated standard for the level of embodied carbon allowed in buildings with the benchmark changing over time, as exemplified in Denmark and in France (both for whole life carbon, i.e. embodied and operational emissions).

The assessment suggests that requirements for LCA calculations on buildings leads to a greater number of LCA cases available per country and, as exemplified by the study, a greater number of available LCA cases allows for more accurate target-setting and benchmarking for policy making.

4.2 Effective data collection through triple-helix cooperation

In addition to government initiatives to promote and support data collection, greater effort is needed on implementing said collection. Here, the experiences from the five countries highlight that, where data is available, **triple helix cooperation between public, private, and research/not-for-profit partners** plays a significant role.

In **Denmark**, for example, the Danish Housing and Planning Authority could commission a study to calculate a baseline and an embodied carbon benchmark from the Build institute of Aalborg University, who were then able to use data collected by the Danish Green Building Council. This exemplifies the necessity for partnerships between the agencies driving action on whole life carbon in the building sector. In addition, it displays the key role of national governments in having a financial investment and internal motivation to develop embodied carbon benchmarks (in this case, for the purpose of regulatory development).

Similarly, in **Finland**, the 50 cases required were available due to a government-led initiative in 2016, where the Finnish Ministry of Environment began testing and planning for LCA-based regulation. In order to carry out such scoping and planning, technical assistance and data was provided by two Finnish consultancy firms: Granlund and OneClickLCA. The result was legislation that includes mandatory requirements for LCAs on new constructions including limit values on WLC.

In the **Netherlands**, data development was found to be driven by a mandatory requirement for LCAs to be conducted on new buildings in order to obtain a building permit. In addition, since 2018, the LCAs must also meet a limit value which includes a maximum impact from the global warming potential, in addition to other environmental impact categories (expressed in €/m2). The calculation tool and national database are maintained by the Stichting Bouwkwalitei foundation. However, for the purpose of the project, several data partners were also included in order to obtain the data required, with each having access to different building level calculations from private projects. The NIBE coordinated this process: collecting data at the level of the construction work and anonymising it. This case similarly suggests that it is the regulatory requirement which is driving the uptake of data development.

In **Belgium**, there is no requirement to produce LCAs or include embodied carbon in the certification schemes. In this case, data is available as three regional authorities, in collaboration with a research institution, developed an open-access LCA tool called TOTEM. As application of the tool makes the building eligible for BREEAM certification and achieving said certification is becoming more important to investors, use of the tool has become widespread. This has led to a database of MMGs (Environmental Profile of Building Elements) being created, from which, in this case, KU Leuven could develop building archetypes and model a baseline of embodied carbon for Belgium, based on the generic building archetypes provided by the Tabula archetype definitions.

In France, data availability can be attributed to the cooperation between the CSTB and the Ministry of Ecological Transition which, firstly through the E+C- labeling scheme, and very soon through the RE2020, have created strong incentives for LCAs to be conducted on new buildings. This encouragement has led to a sizable, open-access building LCA database, although with variable quality. A similar database will be set up for the RE2020 cases.

An additional case to note is that of the **UK**, where popular uptake of BREEAM and LEED has led to over 11,800 new buildings being certified, and 285 buildings already in use being certified [4].The wide use of BREEAM and LEED may explain why many of the bigger consultancy firms in the UK are familiar with conducting LCAs. Another example is London, where regional legislation lays down requirements for new residential buildings with more than 150 housing units or with a floor area exceeding specific limits, depending on the location in the London area. For these construction projects, an LCA must be conducted in order to gain a building permit. This has further increased the number of LCA cases in the UK. This was, in large part, attributed to the LETI public/private partnership. Additionally, advances in product-level environmental data in the BRE IMPACT database mean that data barriers to LCAs have been reduced.

In all cases, **governmental initiatives** and support, alongside **partnership approaches**, are highlighted as being key in driving data development. This suggests that methods to incentivise governmental buy-in to develop studies, or legislation to tackle embodied carbon, or standardising LCA methods may facilitate the calculation of future embodied carbon baselines, targets and benchmarks across the EU. Finally, the findings suggest that popular uptake of certifications and the new Level(s) framework, alongside increased investor interest in certified buildings (e.g. buildings with BREEAM certification), may further incentivise LCA harmonisation and thus data development on embodied carbon.

5. Conclusions and recommendations

5.1 Conclusions

This report has provided an overview of embodied carbon data availability from LCAs across EU Member States.

The process, and resulting dataset, show that LCA data on embodied carbon in the EU is sparse, and that there are data collection and analysis challenges to overcome in terms of accessibility, quality, comparability and representativeness. In Europe, it was only possible to obtain samples of more than 50 cases of buildings from Denmark, Finland, the Netherlands, Belgium and France.

The report herein highlights two relevant solutions for overcoming the current challenges, based on the experiences observed in the five frontrunner countries:

- Firstly, legislation in EU Member States that addresses embodied carbon and sets standards or requirements for LCAs is beneficial in creating the framework needed for harmonised data collection (e.g. the Level(s) framework), and it increases investor interest in certified buildings (e.g. BREEAM).
- Secondly, triple helix cooperation in the form of partnerships between governmental agencies, research and/or not-for-profit institutions, and private enterprise acts as a key component in the development of databases, legislation and benchmarks on embodied carbon in buildings. Governmental support in the commissioning of LCA-based studies to identify embodied carbon baselines, benchmarks or targets was found to be of particular importance.

5.2 Recommendations

Based on these findings, we arrive at the following recommendations:

National LCA methods and data collection systems are urgently needed to avoid any further delay in this fundamental step towards measuring and reducing embodied carbon as part of whole life carbon emissions.

To this end, legal or sectoral requirements that mandate the production of LCAs in accordance with standardised calculation and documentation methodologies are highly relevant at national level, as well as harmonisation at EU level through tools such as the Level(s) framework. Standardisation based on coordination between stakeholders in the building design and construction value chain should, for example, include: scope of life cycle modules, scope of building elements, reference study period, environmental data on building materials, etc.

Data collection and compilation efforts are needed from all those involved in designing & assessing buildings. For this purpose, collaboration and complementary activities between public institutions, building designers, investors, certification organisations and researchers are needed. This step requires a common language and standardised methods for LCAs as described in the first point above.

As this process may take some time, the challenge of gaps in data could also be mitigated through the following approaches. These should be considered complementary.

- **Data on recent and current building projects could be generated at a centralised level by applying a single LCA method in order to provide information on these specific cases as it is likely that this data can still be obtained**. This exercise would benefit from input from the different actors involved, including the building industry, certification bodies, researchers and public bodies. This cooperation could be greatly facilitated through the use of standardised calculation methods and software tools to form a central database. A similar approach has provided a large database in France.
- **Existing data, that has been created in a scattered form using varying methodologies by different stakeholders, has the potential to be gathered together and harmonised to form a centralised database**. Harmonisation methods, adapted to the specific differences between the LCA methodologies, could be agreed upon by a coalition of actors to support this undertaking. Examples of such action are the international activities in Annex 72 to the IEA-EBC Programme, as well as the UK initiatives LETI and BRE.

- **Where empirical data faces the challenges described in this report, relying on results from modelled building archetypes could provide an insight into the life-cycle impacts**. Building archetypes offer the advantage of providing representative and comparable values. However, limits remain in translating building stock models into LCA data, which is challenging, particularly for the diverse landscape of non-residential buildings. Also, monitoring future buildings, in comparison with benchmarks, is not possible. Nonetheless, efforts to translate this data can help in the transition towards standardised empirical LCA data. This approach has been used successfully in projects such as the Tabula/Episcope project.

Appendix 1- COUNTRY SHEETS ON EMBODIED CARBON LCA DATA

BELGIUM

Overall data situation in the country, and the relation to the data collected for this project.

To date, Belgian building practitioners use the TOTEM tool[1] for the life cycle assessment of buildings. The TOTEM tool is an open-access online tool developed by the three regions in Belgium (Flanders, Walloon Region and Brussels region) and that uses the MMG (Environmental Profile of Building Elements) method. The tool has been available since February 2018 and is frequently updated to include new features, enlarge the database, include new methodological developments, etc. Although the use of the TOTEM tool in practice is not mandatory, it is being used by many practitioners and is often referred to in design contests.

Since March 2020 TOTEM is available for BREEAM certification[2]. It concerns the standards "BREEAM International New Construction 2013 and 2016" and "BREEAM International Refurbishment and Fit Out 2015 calculators", in the material criterion "MAT 01". TOTEM allows buildings to obtain a rating of "5+ EXEMPLARY", which is the maximum number of credits for this criterion.

GRO is a sustainability meter that the Facilities Company of the Flemish government uses for all construction projects, regardless of scale and function, in order to realize its ambition in the field of sustainability and circular construction. The GRO refers to TOTEM for the assessment of the environmental impact of materials and hence TOTEM is also used by building practitioners using the GRO.

KU Leuven was, and still is, involved in the development of the MMG method and the TOTEM tool and has provided this project with 105 cases. The MMG method has been used for the data in this project.

Status on LCA methodology

The MMG methodology embedded in the TOTEM tool is common and widely accepted in the Belgian construction sector. All life cycle modules are included, except for module D. The MMG method version as used in this project, follows the EN 15804:A1 and a set of additional environmental impact categories (in line with ILCD[3]). The environmental impacts are reported both in characterized values and as a single score, expressed in EURO (external environmental cost).

The method has fixed transport scenarios, cleaning scenarios and waste scenarios for the construction materials. The service life of the building is fixed to 60 years.

Status on LCA-based regulation

There is no LCA-based regulation yet for construction in Belgium. It is expected that this will be the case in the near future, although no exact timing is given by the authorities yet.

Identified key actors on the topic

- KU Leuven: The Design and Engineering of Construction and Architecture unit at KU Leuven has taken part in developing the MMG method.
- VITO: has taken part in developing the MMG method.
- BBRI: has taken part in developing the MMG method.
- Public Authorities of Wallonia: Supported the development of the TOTEM tool for the life cycle assessment of buildings.
- OVAM, the Public Waste Agency Flanders: Supported the development of the TOTEM tool for the life cycle assessment of buildings.
- Brussels' Environment Office: Supported the development of the TOTEM tool for the life cycle assessment of buildings.

Data collected for this project

Number of cases and data source

Number of cases: 105

Source: Cases from KU Leuven (Karen Allacker, Martin Röck) based on the modelling of the Belgium TABULA[4] cases in the MMG LCA Tool with adaptation to contemporary energy performance requirements.

The cases were initially conducted as part of the work of the research group in the context of master thesis and PhD research. Cases are based on the modelling of the Belgium TABULA cases in the MMG LCA Tool with adaptation to contemporary energy performance requirements for the purpose of the Laudes/Ramboll project.

Scope of data

Modules: A1, A2, A3, A4, A5, B2, B4, B6, B7, C1, C2, C3, C4

Reference study period: 60 years

Square meter definition: Gross floor area (Belgian definition)

Tool: MMG-Building-LCA-Tool developed by KU Leuven (identical methodology as the TOTEM tool)

Background data: Ecoinvent 2.2 database

Other comments on scope: Module D not included

[1] https://www.totem-building.be/

[2] BREEAM is an environmental assessment method and rating system for buildings, with 200,000 buildings with certified BREEAM assessment ratings and over a million registered for assessment since it was first launched in 1990.

[3] https://publications.jrc.ec.europa.eu/repository/handle/JRC58190

[4] The TABULA/EPISCOPE projects developed Building Typologies for Energy Performance Assessment of National Building Stocks for various European countries - https://episcope.eu/welcome/

DENMARK

Overall data situation in the country, and the relation to the data collected for this project.

Until today the main incentive to conduct a building LCA in Denmark has been in relation to DGNB certifications of buildings. The DGNB certification is operated by Green Building Council Denmark, who has developed a Danish version of the DGNB system, that originates from Germany. The method description of Danish LCA criteria and reference values used differs slightly from the German version.

In 2020 The Danish Green Building Institute reported that 90 DGNB projects had been conducted over the past 8 years [4]. It is not mandatory to conduct an LCA as a part of a DGNB project, but as it counts so much in the final DGNB score, in practice, all projects get one done.

BUILD at Aalborg University conducted an analysis of the climate impacts of 60 building cases suggesting benchmark of whole life carbon in Denmark [5] . About 40 of the 60 building cases where DGBN certified buildings that all had been through conformity check in relation to the certification process. BUILD and Ramboll have provided this project with 60 and 12 cases, respectively.

Status on LCA methodology

The most LCAs in Denmark has been generated as a part of DGNB-projects. The Danish version of DGNB has been developed by the Danish Green Building Council with involvement from the industry and expertise form BUILD. The scope of the LCA includes the following life cycle modules: A1, A2, A3, B4, B6, C3, C4 and D. BUILD has been developing a Danish LCA tool called LCAbyg, which is most often used in DGNB projects today. The same scope is expected to be used in the forthcoming whole life carbon requirements in the building regulation from 2023.

In addition to DGNB and the forthcoming requirements in the building regulation, a Voluntary Sustainability Class for buildings was introduced by the authorities in May 2020 with a two-year test phase from mid-2020 to mid-2022. LCA is one of nine criteria in the Voluntary Sustainability Class. It builds upon the DGNB-scope, but with two further modules included: A4 and A5. The Voluntary Sustainability Class contains detailed guidelines for methodology and key assumptions, e.g. that must be performed in accordance with EN15978, EN15804 and relevant product category rules (PCRs).

Module A4 and A5 are also included as voluntary modules in the new DGNB-DK 2020 manual from 2021.

When reporting for the Voluntary Sustainability Class, it is recommended to use LCAbyg, but this is not mandatory. There is a strong acceptance in the industry of the LCA scope and method described in DGNB and the overlapping method described in the rather new Voluntary Sustainability Class.

Status on LCA-based regulation

A Voluntary Sustainability Class for buildings was introduced by the authorities in May 2020, and which now is in a testing phase with a two-year test phase from mid-2020 to mid-2022. LCA is one of nine criteria. The LCA criteria includes expansion of the scope compared to previous practice (including A4 and A5), but test phase of the Voluntary Sustainability Class includes no limit values.

In March 2021, the Danish government with cross-parliamentary support issued a new national strategy on sustainable construction including requirements on whole life carbon in new constructions in the building regulation enters into force in 2023. The forthcoming changes in the building regulation require that whole life carbon is assessed in all new constructions, and that buildings larger than 1000 m2 shall fulfill a mandatory limit value of 12 kg CO2/m2/year and that they have the possibility to fulfill a more ambitious voluntary CO2 class with a limit value of 8 kg CO2/m2/year. The strategy also includes phasing and tightening CO2 requirements in the period 2023 to 2029. From 2025 buildings smaller than 1000 m2 will also have to comply with limits on whole life carbon. The regulation will be reviewed every second year to set new, stricter requirements. The sketched pathway for tightening the regulation ends with limits in 2029 at 7,5 kg/CO2-eq/year for all buildings and 5 kg/CO2-eq/year for the voluntary CO2 class.

Identified key actors on the topic

- The Danish Housing and Planning Authority: Administrates and develops building regulation.
- The Danish Green Building Council (DK-DBC): Advocates for action on embodied carbon and provides certifications to buildings based on certain standards.
- BUILD, Department of the built environment, Aalborg University: Influential department on building research and on developing suggestions for future building regulation. BUILD is responsible for verifying the LCAs conducted as a part of the Voluntary Sustainability Class.

Data collected for this project

Number of cases and data source

Number of cases: 72 (60 from Build and 12 from Ramboll)

Source: The Ramboll cases have initial been conducted as a part of DGNB-DK projects. The 60 cases from build have been conducted or updated as a part of a report by BUILD for The Danish Housing and Planning Authority (BUILD, 2021). 37 of the 60 cases are also DGNB projects.

Scope of data

Modules: A1, A2, A3, B4, B6, C3, C4 and D

Reference study period: 50 years

Square meter definition: Gross floor area (Danish definition)

Tool: LCAbyg (developed by Build AAU)

Background data: LCAbyg includes the Ökobau database as generic data and possibility to use EPD’s when appropriate. BUILD cases are mostly calculated with generic data based on Ökobau 2020. The updated version of the 60 building cases from 2021 also includes use of average sector EPD’s for Danish concrete and wood (BUILD, 2021).

Other comments on scope: Module D is calculated separately

FINLAND

Overall data situation in the country, and the relation to the data collected for this project.

At present, there is no systematic collection of buildings-level LCA data in Finland. However, in the future, the government aims to develop requirements for collecting, analyzing, and aggregating generic reference data based on normative climate declarations of buildings.

Regarding product-level LCA data, there is an EPD operator (RTS) in Finland. This is, however, not run by authorities. The government has developed a generic database (www.CO2data.fi) for typical construction products and processes.

The data used for this project was created as a part of the test phase of upcoming regulation, the Climate Declaration for Buildings. Two different consultants (Granlund and OneClickLCA) were assigned by the Finnish Ministry of The Environment to deliver cases for this project.

Status on LCA methodology

The Ministry of The Environment published the 2nd version of the whole life carbon assessment of buildings in June 2021. It is based on European standards and Level(s), as well as feedback from the first public consultation round from the summer of 2020. The method is a draft developed for the upcoming LCA regulation and will be updated after the ongoing public hearing round in autumn 2021. Reporting following this method includes the following life cycle stages: A1-A5, B4, B6, C1-C4 and D.

Status on LCA-based regulation

In Finland the initial planning and testing of LCA-based regulation began in 2016 by the Finnish Ministry of The Environment, who developed a roadmap for reducing the carbon footprint of buildings. An upcoming regulation is currently being developed under the name of 'The Climate Declaration' and includes mandatory LCA-studies on all new construction as well as limit values to whole life carbon. The regulation will be implemented at latest in 2025.

Identified key actors on the topic

- The Ministry of The Environment: Responsible for developing the upcoming regulation and the related methods and reporting standards behind it.
- SYKE (Finnish Center of the Environment): In charge of CO2data.fi, the national generic database for building products and processes.
- Green Building Council Finland: In charge of Embodied Carbon Commitments (voluntary commitments for companies to decrease the embodied carbon of their products).
- OneClickLCA: An influential consultancy company and LCA tool provider with large amounts of data from Finish LCA studies (as well as data from other countries).

Data collected for this project

Number of cases and data source	**Number of cases:** 59 **Source:** 40 cases from Bionova and 19 cases from Granlund Oy.
Scope of data	**Modules:** A1, A2, A3, A4, A5, B4, (B5), B6, C1, C2, C3, C4, D **Reference study period:** 50 years **Square meter definition:** Heated floor area (Finnish definition) **Tool:** One Click LCA **Background data:** Various sources **Other comments on scope:** Cases from Granlund Oy do not include module B5 in the scope of the LCA while cases from OnceClickLCA do include module B5. Module D is calculated separately for all cases.

FRANCE

Overall data situation in the country, and the relation to the data collected for this project.

The collected LCA data from France comes from the Scientific and Technical Centre for Buildings (CSTB) database, which has been generated as a part of the voluntary reporting on whole life carbon encouraged in an experiment launched by the French Ministries in charge of construction and environment in 2016, in parallel of the second period of the RT2012 regulation. The database, called E+C- Observatory, is open source and contains 1197 cases. The LCA cases all follow the guidelines presented in the E+C- framework which has been used as an experimental precursor to the coming embodied carbon regulation for new buildings RE2020 (E as environmental) which enters into force from January 2022 (with several steps). CSTB has made an assessment of the quality of the LCAs in the database and found that they are of varying quality. For this project, CSTB has pointed us to 712 cases of good high quality. For the analysis in the Embodied Carbon Benchmarks project, these have been further filtered down to 486 cases, removing cases with missing data.

Status on LCA methodology

The LCA methodology defined in E+C-, which is based on the methods described in the European Standard EN15978 (2012), with minor variation, is common and widely accepted in the French construction sector and will help the transition to the mandatory RE2020 regulation in 2022. Nevertheless, the RE2020 LCA methodology differs from the E+C- one and from EN15978 on several points, and the GWP results obtained with RE2020 are not directly comparable to the one obtained with E+C- because a "dynamic" LCA method was introduced in RE2020 for GWP indicator.

Status on LCA-based regulation

In 2022 a substantial revision, called RE2020, enters into force. This replace the RT2012 regulation. It is applicable for new residential buildings from January 2022 and for new offices and schools from July 2022. So far conducting an LCA was optional, encouraged by voluntary certifications, but the new regulation introduces mandatory LCA-studies on these 3 building types. The next revision of the RE2020 regulation is expected to include LCA-requirements for all building types. The regulation also includes other sustainability measures, such as requirements to report on transportation of building materials, energy- and water use on the building site, as well as waste from the construction site. The regulation has been developed by the Ministry for Ecological Transition with technical support from CSTB and the involvement of many stakeholders.

For residential buildings (single homes and apartment buildings), regulatory thresholds were defined for operational energy-related carbon and embodied carbon, first for 2022 and becoming gradually stricter (smaller) until 2031. For embodied carbon, the 2031 value will be the 2022 one minus 1/3.

For other types of buildings, carbon thresholds are not defined yet, but they will probably follow a similar approach.

Identified key actors on the topic

- Scientific and Technical Centre for Building (CSTB): A public industrial and commercial company that supports the Ministry for Ecological Transition in collecting LCA data through certifications and classifications for buildings.
- HQE^{TM}: Certification that rewards buildings sustainable design, construction, operation and responsible management as well as urban planning projects. Accredited operators are Certivéa and Cerqual Qualitel Certification.
- Alliance HQE-GBC: French Green Building Council.
- Ministry for Ecological Transition: The governmental department responsible for the development and enforcement of the RE2020.

Data collected for this project

Number of cases and data source	**Number of cases:** 487 **Source:** Cases from the French database "E+C- Observatory". The cases have been selected with assistance from CSTB.
Scope of data	**Modules:** All life cycle modules **Reference study period:** 50 years **Square meter definition:** GFA (French definition, "surface de plancher") **Tool:** 9 tools were allowed in the E+C- experiment, among them the LCA tool ELODIE developed by CSTB. **Background data:** INIES database (including specific EPDs complemented by generic datasets) **Other comments on scope:** for materials, 1/3 of Module D is included if beneficial

NETHERLANDS

Overall data situation in the country, and the relation to the data collected for this project.

In the Netherlands, LCA data on product level is generated by industry, and after mandatory review, it can be uploaded to a National database known as the "Nationale Milieudatabase". From the national database, the data is provided to an approved software for calculations on the level of construction work (both building and infrastructural works). A team dedicated to the National Environmental Database maintains the system and the database and provides access (under license) to the data. The database contains both LCA on specific products (EPD's) and generic data.

The data for this project is collected on the level of construction works. The data was provided by several data partners that have access to building level calculations from their customers, or from the projects they have worked on. The data is made anonymous so it cannot be traced back to the specific building. NIBE has conducted the data collection and has a proprietary list of the individual buildings and data owners that have provided the data.

Status on LCA methodology

Conducting an LCA is mandatory for obtaining a building permit in The Netherlands. The requirements for the LCA are described in "Bepalingsmethode Milieuprestatie Bouwwerken" (method for calculating the environmental performance from buildings). All life cycle modules are included in the obligatory method. The "Bepalingsmethode Milieuprestatie Bouwwerken" follows the EN 15804:A2 and provides additional information regarding scenarios and default environmental profiles for transport and energy.

The method has fixed waste percentages for building materials. These are respectively 3% for prefab elements (e.g. concrete elements), 5% for in-situ applied materials (e.g. bricks) and 15% for 'assisting materials' (e.g. paint).

Status on LCA-based regulation

In the Netherlands it is required to conduct an LCA in order to get a building permit. This was introduced in 2012. The results from the LCA must live up to a limit value (since 2018), that sets a maximum of impact from GWP as well as other environmental impact categories. The limit is expressed in €/m2 and is calculated by a weighting of all impact categories (shadow prices). This implicates that one cannot derive the resulting GWP/m2, if one only has the results in €/m2.

The limit value is tightened periodically and is announced to decrease from 1,0 (introduction value)€/m2 in 2018 to 0,5 €/m2 in 2030. The Dutch software for performing calculations on Building level also provides the underlying environmental effects (like GWP). Consequently, the user can also obtain environmental effect data, per LCA module for the complete building.

Identified key actors on the topic

- Stichting Bouwkwaliteit (The Building Quality Foundation): In charge of developing the national LCA methodology. The members are both governmental representatives and industry players.
- NIBE: An influential, private consultancy firm specialized in services related to sustainable construction.
- Dutch Green Building Council: Advocates for action on embodied carbon and provides certifications to buildings based on certain standards.

Data collected for this project

Number of cases and data source	**Number of cases:** 50 **Source:** NIBE.
Scope of data	**Modules:** A1, A2, A3, A4, A5, B1, B2, B3, B4, C1, C2, C3, C4, D **Reference study period:** 50 or 75 years **Square meter definition:** Gross floor area (Dutch definition) **Tool:** SimaPro **Background data:** Ecoinvent 3.6 **Other comments on scope:** Module D is subtracted (credit)

Appendix 2 - EMBODIED CARBON LANDSCAPE IN THE EU

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
Austria	No, but there is a nationally accepted methodology	No **Relevant regulations:** IBO ÖKOPASS	IBO – Österreichisches Institut für Baubiologie und -ökologie	While there is no formal government-set methodology, IBO – Österreichisches Institut für Baubiologie und -ökologie has published what constitutes the nearest to a national embodied impact evaluation methodology. The name of this methodology is Ökoindex 3 (Ökologischer Kennwert der thermischen Gebäudehülle). This methodology is a weighted score of global warming potential (carbon footprint), primary energy depletion, and acidification, expressed as an A to E rating. The scale of performance has been fixed by IBO. The calculation data applied for these analyses are provided by Baubook, which is a limited company owned by a regional energy association and IBO. Austria has a governmental environmental rating system called klimaaktiv, which applies the Ökoindex 3 as the methodology for the building materials environmental impact assessment. Materials assessment is a mandatory part of the certification. Performing well in this certification can make residential buildings eligible for an additional environment-related subsidy. This certification has been applied to over 500 buildings.
Belgium	No, but there is a nationally accepted methodology	No **Relevant regulations:** Circular Flanders: Green Deal Circular Building, Open Call Innovative Circular Economy Projects Brussels: 'Guide de gestion des déchets de construction, Programme Régional en Economie Circulaire (PREC) Wallonia: TOTEM: instrument to evaluate the environmental impact of buildings	See section above	See section above
Bulgaria	No	No	Data not obtained	Regulation soon to include operational energy "The upcoming legislation transposing the EPBD at national level will ensure that energy performance requirements are part of the building codes. It is also required by the EPBD to relate energy performance requirements to primary energy consumption, in order to have a more accurate picture of the energy quality and related CO2. No requirements for compulsory use of renewable energy in new buildings. However, in the Energy Efficiency Law it is mentioned that the renewable energy use should be considered as a possible option during the design phase of the buildings"

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
Croatia	Data not obtained	Data not obtained	Data not obtained	
Cyprus	Data not obtained	Data not obtained	Data not obtained	
Czech Republic	No	No	Technical and Testing Institute of Civil Engineering Prague, sp (TZÚS Praha, sp) Research Institute of Civil Engineering – Certifikační společnost, sro (VÚPS)	**embodied carbon is optionalà SBToolCZ is Czech method for complex quality assessment of building performance in which the characteristics of the building and its surroundings are evaluated with respect to the sustainable development. Building's impacts on the environment, social-cultural aspects, functional and technical quality, economic and management issues and location of a building are included in the assessment. The method contains a set of criteria which is evaluated based on the basic characteristics of the building and its surrounding; and based on this evaluation the building obtain one of the three certificates (bronze, silver or gold)
Denmark	Yes	Yes **Relevant regulations:** The National Strategy for Sustainable Construction	Danish Ministry of Environment and Food; Ministry of Industry, Business and Financial Affairs; Danish Energy Agency Build Institute, Aalborg University Danish Green Building Council	See section above
Estonia	No	No **Relevant regulations:** Estonia's 2030 National Energy and Climate Plan (NECP 2030)	Ministry of Economic Affairs and Communications TalTech expert level knowledge working on the development of national methodology and creating LCA materials database (for CO2eq emissions).	Currently there is an ongoing study by TalTech, which should establish suitable method and scope, is carried out. The results of the study will be finalized by the end of the year 2021. The proposed method is carefully aligned with the European Standards EN 15804+A2:2019 and EN 15978, the European Level(s) framework, and with international best practice. Scope: A1-A5, B4, B6, D. Scope of functional systems: Ground, Wall, Slab, Roof. Impact of use stage operational energy (B6) is considered via EPC (EPBD) requirements. As Estonia has very high grid electricity emissions factor, it is important and can be considered as part of LCA assessment. An official from Estonia notes that the number of experienced individuals and enterprises capable of performing LCA assessments is low, and that less than 10 individuals/enterprises could be identified with such skillsets. It is estimated that less than 5 cases are available.
Finland	Yes	Yes	See section above	See section above

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
France	Yes	Yes	See section above	See section above
Germany	No, but a nationally accepted method exists	No **Relevant frameworks**: Bewertungssystem Nachhaltiges Bauen or BNB Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council, DGNB) BNB Assessment System for Sustainable Building.	DGNB BNB The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety	In Germany there is no national LCA-based regulation. However, an official method for assessing the sustainability of a building, BNB (Bewertungssystem für Nachhaltiges Bauen), has been developed and introduced in 2009. Conducting an LCA is a part of this assessment, and the results from the LCA will be a part of the final score. The score determines whether the building obtains a bronze, silver or gold level. Since 2011 it has been obligatory for all federal buildings to conduct an BNB assessment, and as a part of this, an LCA. Federal buildings must obtain a silver level in order to get a building permit. Although there are no requirements at national level for the execution of building LCAs, there are some states that set regional requirements where they have also chosen to follow the BNB system, and also require a minimum of silver level. Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) is the most popular sustainability certification scheme in Germany. The results from an LCA counts in the overall score, and DGNB is therefore a driver in normalizing the use of LCAs in the German construction sector.
Greece	No	No **Relevant regulation:** National circular economy strategy	Not assessed	
Ireland	No, but a nationally approved method exists	No **Relevant regulation:** EN15978		EN15978 sets out how the full life cycle carbon and other environmental impacts should be calculated setting out the modules relevant to each part of the building lifecycle. There are currently no definitive plans in Ireland for regulations but there are a number of positive indicators that this is likely to happen over the next five years. Ireland's national certification scheme for homes – Home Performance Index awards credits for embodied carbon calculation and LCA. The international certification schemes for non-residential buildings LEED and BREEAM also award credits for the calculation of Life Cycle Assessment and embodied carbon. This is driving interest amongst professionals in calculation. However, there is also an increasing interest from the investment community in embodied carbon and this is likely to grow over the coming years.

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
Italy	No	No **Relevant legislation:** Towards a Model of Circular Economy for Italy - Overview and Strategic Framework	Casaclima Nature, Casaclima Nature, GBC Home Ministry of Environment	No systematic collection of data on embodied carbon from of the Italian systems evaluate embodied carbon. There are is regulatory measures on embodied carbon. No national, common agreed LCA method or tools has been identified.
Lativa	Data not obtained	Data not obtained	No data obtained	
Lithuania	No	No	Environmental Protection Agency in Lithuania which is subordinate to the Ministry of Environment of the Republic of Lithuania is one of the main institutions involved in Lithuania’s greenhouse gas (GHG) emissions inventory preparation.	There are plans to prepare the methodology for modelling whole building life cycle and to model all stages of life cycle it is important to have this information about construction products. The preparation should begin in 2023. One of the plans of the Ministry for the future is to prepare the methodology for modelling building life cycle to evaluate the impact of structures, buildings, construction products/materials on the environment, climate change, health, the opportunities of waste recycling, second use, circular economy principles in all stages of building life cycle (planning, design, construction, use, demolition). To evaluate these things like formation of waste, greenhouse gas emission in the whole cycle of the building in the early stages of planning and design would be very helpful and useful for all participating in the fields of waste and construction sectors. The preparation of the methodology is planned to start in 2023.
Luxembourg	No data obtained	No data obtained	No data obtained	
Malta	No data obtained	No data obtained	No data obtained	
Netherlands	No, but a nationally approved method exists	No **Relevant regulation:** A Circular Economy in the Netherlands by 2050 + Dutch Building Code (Bouwbesluit 2012), Article 5.9.	See section above	See section above

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
Poland	No	No	Polish Green Building Council Institute of Innovation and Responsible Development Polish Circular Hotspot	There is no regulation of whole life carbon in Poland. Large investment companies and developers are showing interest in conducting LCAs on construction projects as a part of voluntary sustainability certifications. The Polish Green Building Council expressed difficulties on getting data on the topic of embodied carbon, since the results of the LCAs are not systematically gathered in a central repository. As in many other countries, the data stays with the building owners, the consultancy companies conducting the LCAs, the providers of the LCA tools or the certification bodies.
Portugal	No	No regulation includes embodied carbon. **Relevant regulation:** Action plan for circular economy in Portugal: 2017-2020 Green Growth Commitment	Certification: LiderA	LiderA: acronym for Leading for the Environment for sustainable construction, is the designation of a Portuguese voluntary system that aims to carry out.
Romania	No	No regulation includes embodied carbon. **Relevant regulations:** Romania's strategy for the transition to a circular economy (ROCES) 2020-2030	Romania Green Building Council and the Green Homes Certification Owners Association Office	In Romania, the energy performance certificate has been compulsory for new buildings since 2007. Romania has building code requirements only for new buildings and no whole building energy performance-based requirements for new buildings and renovations. Romania has prescriptive/ element-based criteria for thermal insulation and an overall heat transfer coefficient G-value. From 2011 energy certificates are mandatory whenever a flat or house is sold or rented, thus creating an awareness raising wave that could be used to push for a stronger refurbishment and a new nearly zero-energy construction programme.
Slovakia	No data obtained	No data obtained	No data obtained	
Slovenia	No	No **Relevant regulations:** Roadmap towards the circular economy in Slovenia	Ministry of the Environment and Spatial Planning ZAG	The majority of LCA in Slovenia is still done on product level (for EPDs). It is estimated there are less than 5 cases.

Country	Standardized LCA method/ scope (Y/N)	Embodied carbon regulation (Y/N)	Embodied carbon front runners (govt/ academia/ industry/ certification bodies)	Details / comments
Spain	No	No **Relevant regulations** *Climate Change law* (recently approved in 2021), "encourages the use of materials with the smallest possible carbon footprint" *VERDE certification* (GBC España), a volunteer Spanish sustainability rating system that used a qualitative LCA based approach in the assessment process.	• GBC (España) (https://gbce.es/blog/proyecto/buildinglife/) • ITEC(Catalunia) BEDEC database (https://metabase.itec.es/vide/es/bedec) • Instituto Torroja (Madrid) (https://www.opendap.es/) • Asociación Ecómetro (Madrid) (http://ecometro.org/evaluar-un-proyecto/) • University of Sevilla (TEP 130 and TEP 986) (Andalusia) • Other Spanish universities such as University of Granada (TEP 968), University of Zaragoza, UPM, UPC, UNESCO Chair in Life Cycle and Climate Change	Some academic studies have been made on embodied carbon in the Spanish building stock, but with variation in scope and method, since there is no agreed national standard on how to conduct an LCA (Soust-Verdaguer, 2021). It might be possible to collect enough data from these studies to do a baseline, but it would take a lot of effort to make the data comparable due to the different methodological approaches. There are no regulatory measures on embodied carbon in Spain, nor any official methods or tools. More than 50 Spanish LCA case studies indexed publications are detected in Scopus in the last 5 years, however, different methods and tools are used for the LCA implementation.
Sweden	Yes	Yes **Relevant regulation:** The Climate Declaration Act for new buildings	Boverket The National Board of Housing, Building and Planning	In 2022 regulation targeting sustainable construction called *Klimatdeklaration* (the climate declaration) will come into force in Sweden. As a part of this, it will become obligatory to conduct building LCAs on new build (Boverket, 2020). A second version of the regulation is to be implemented in 2027, where limit values for the results from the LCA will be introduced.
Switzerland	No	No	• LCA studies related to the SIA • PORR (construction company)	There is upcoming LCA-based regulation (BPIE, 2021). The construction company PORR provided a cross-country dataset of 22 cases for AT, DE, CH for the study.

Appendix 3 - REFERENCES

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[3] Boverket, Klimatdeklaration vid uppförande av byggnad - Boverket, (2020). https://www.boverket.se/sv/byggande/uppdrag/klimatdeklaration/ (accessed February 23, 2022).

[4] T. Institute, Klimavenligt byggeri og LCA, (2021) 1–28. https://www.trafikstyrelsen.dk/da/-/media/TBST-DA/Byggeri/Lister/Publikationer/Klimavenligt-byggeri-og-LCA-2021.pdf.

[5] R.K. Zimmermann, C.M.E. Andersen, K. Kanafani, H. Birgisdottir, Whole Life Carbon Assessment of 60 buildings Possibilities to develop benchmark values for LCA of buildings (BUILD Report 2021:12), 2021.

Towards embodied carbon benchmarks for buildings in Europe

#2 Setting the baseline: A bottom-up approach

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Laudes Foundation

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
Date	March 2022
Authors	Martin Röck, Andreas Sørensen
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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.

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.

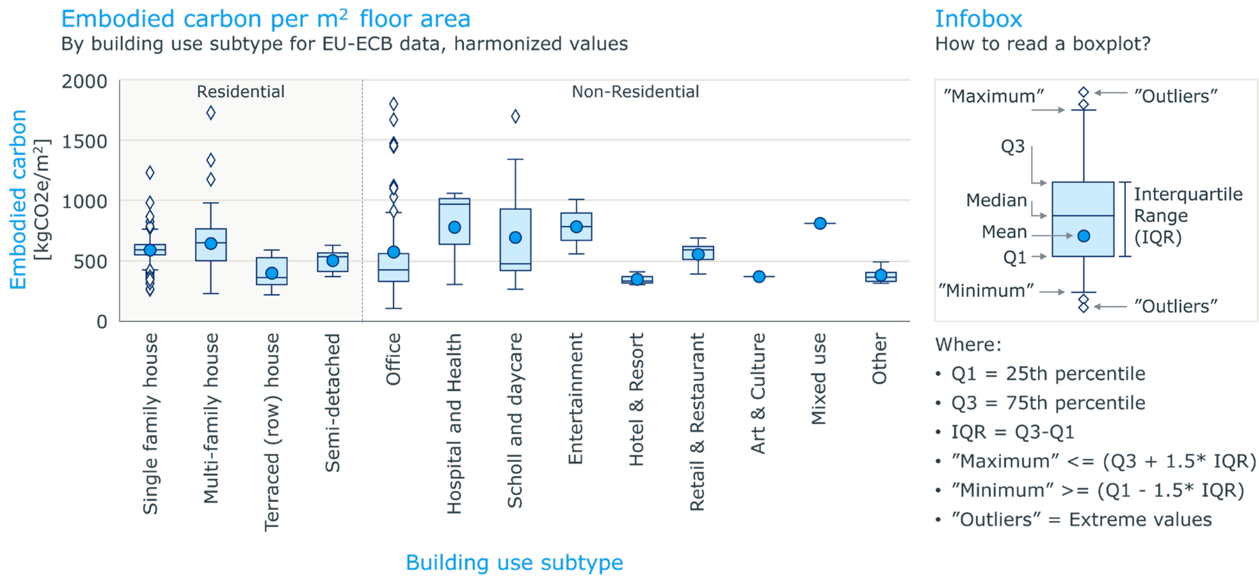
Results – What did we find?

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/m² with a mean value of around 600 kg CO2e/m². For non-residential buildings, the study observes a wider spread of embodied carbon values, ranging from around 100 to 1,200 kg CO2e/m², with mean values, again, of around 600 kg CO2e/m².

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 m² for different building use subtypes [kg CO2/m²]



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.

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.

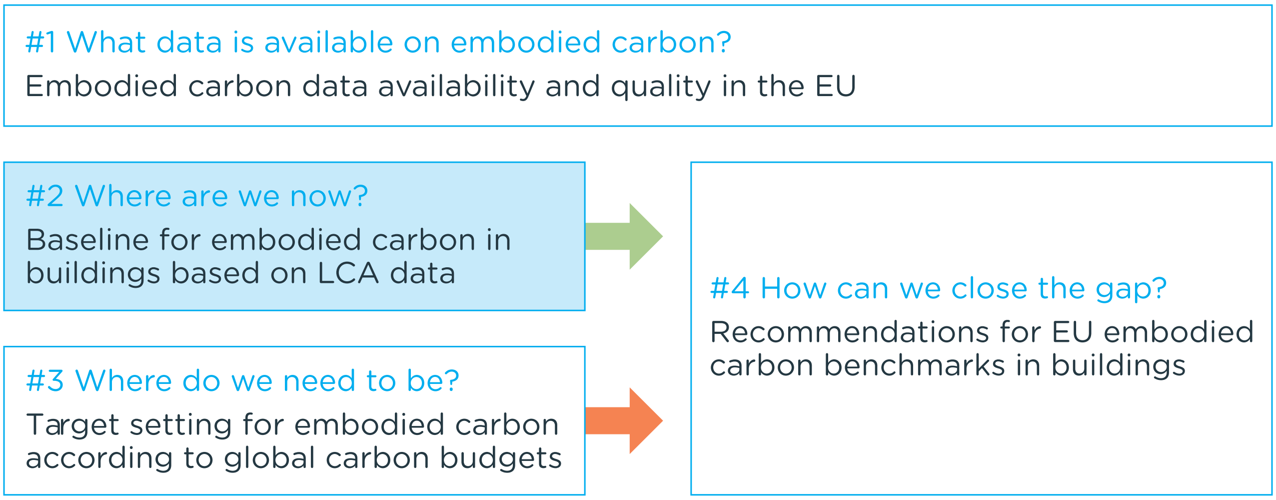
This project focused on the European Union (EU). This is due to its position as a pioneer in GHG emission reduction policies with instruments such as the Energy Performance of Buildings Directive, the Taxonomy for Sustainable Activities and the EU Climate Transition Benchmark Regulation. Additionally, 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?

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).

a) Global trends in embodied and operational, life cycle GHG emissions

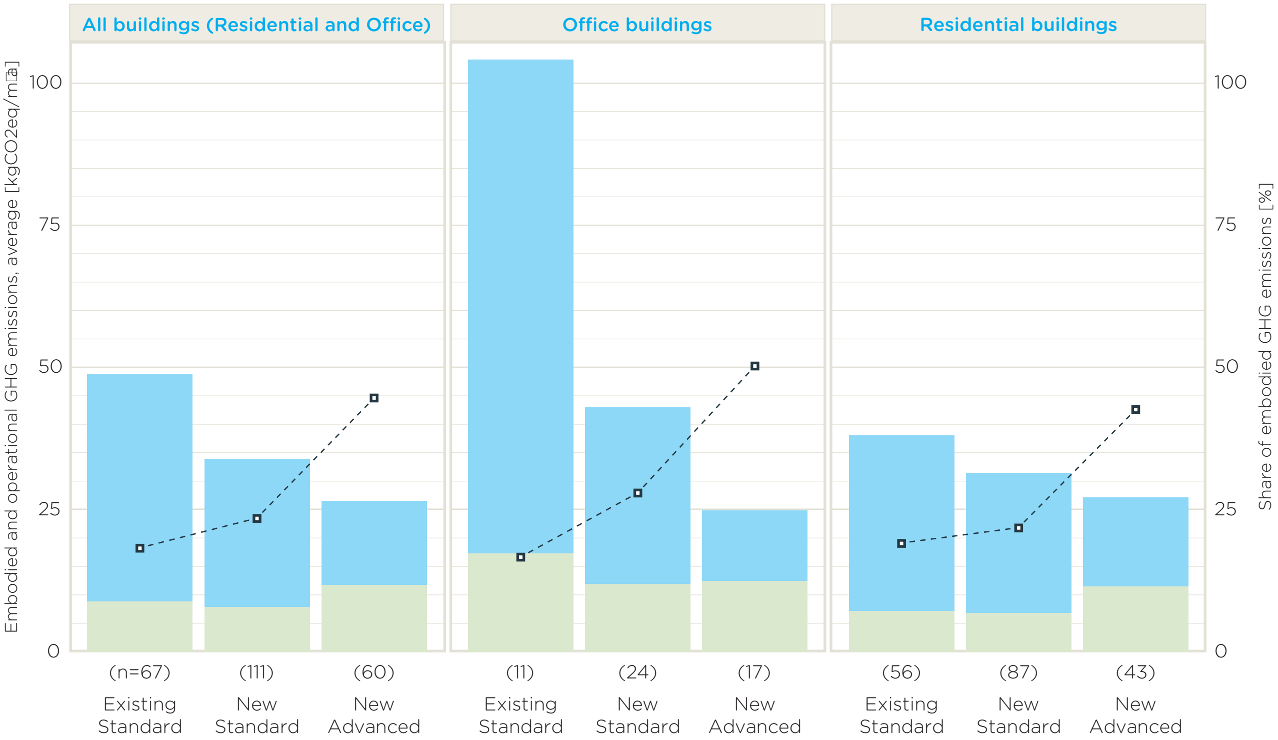


Figure 3 presents the results of the meta-study regarding the whole life cycle of GHG emissions for buildings in different energy performance classes (Existing standard; New standard; New advanced). The stacked bar charts show results for both embodied (red) and operational (blue) emissions, respectively. 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?

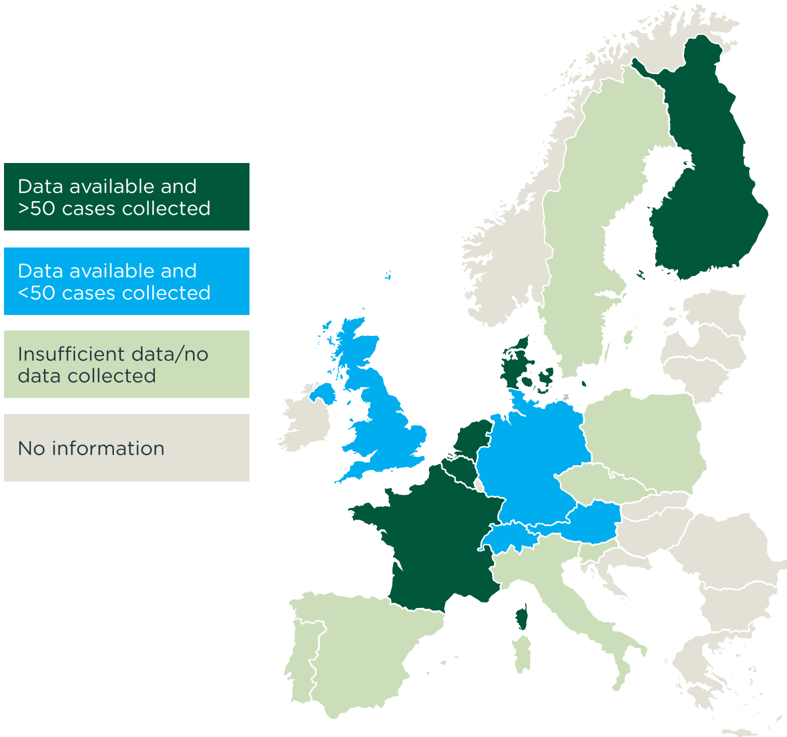
Disclaimer: In this report, the widely used term 'embodied carbon' is applied. The term is considered synonymous with 'embodied GHG emissions'. The data and values presented in the following consider both CO2 and non-CO2 GHG emissions.

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.

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

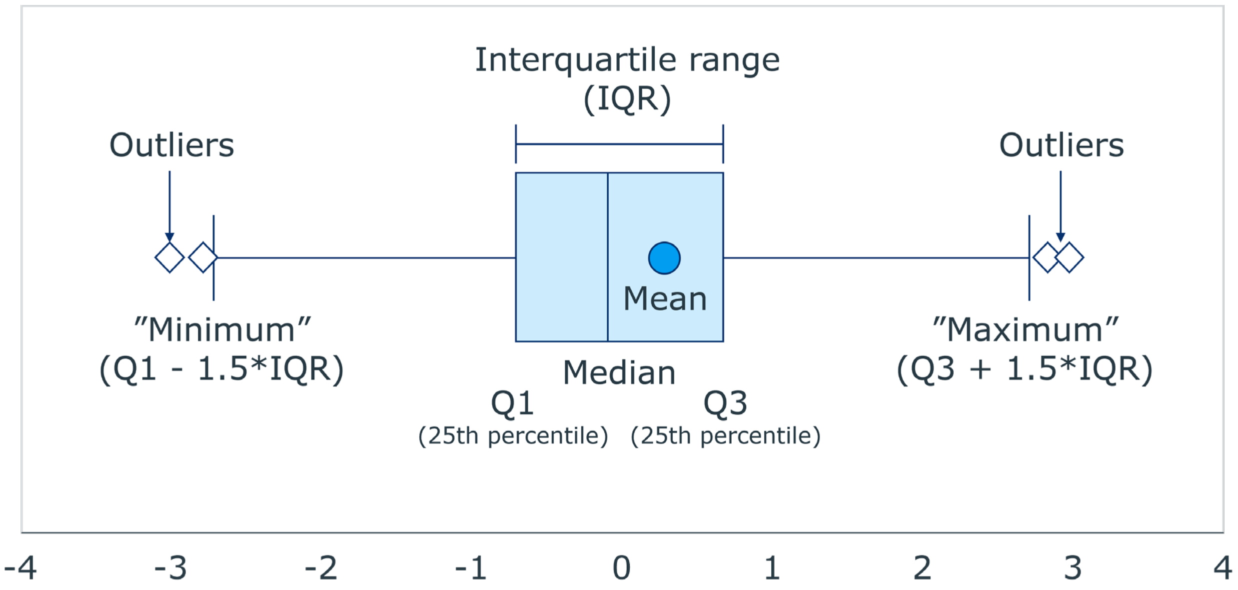
3. What are the current levels of embodied carbon?

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)



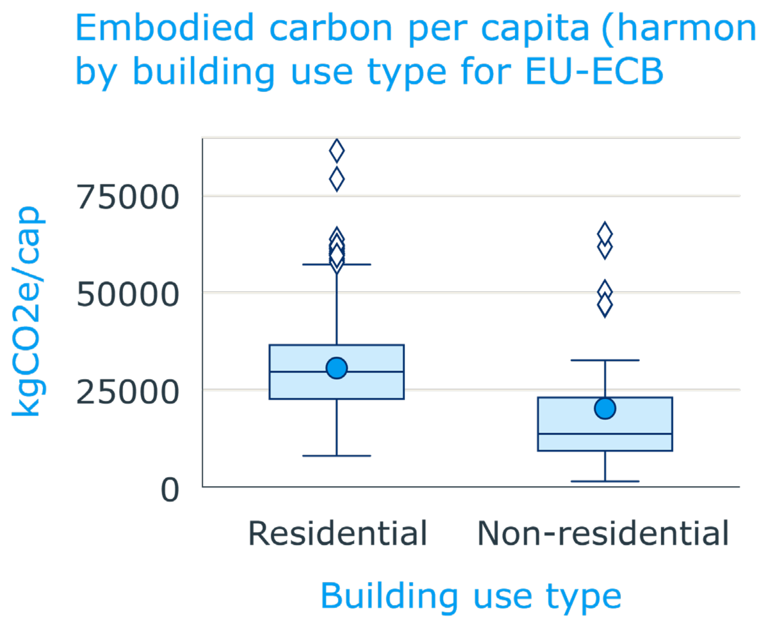
The figures presented in Figure 5 above are mostly boxplots which follow established conventions. The line in the box represents the median value, i.e. the middle value of cases in the dataset. A single white-filled circle represents the mean value, i.e. the statistical average of values in the dataset. 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 m²

Figure 6: Harmonised life cycle embodied carbon per m² 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/m² with a mean value of around 600 kg CO2e/m². For non-residential buildings, a wider spread of EC values can be observed, ranging from around 100 to 1200 kg CO2e/m², with mean values of around 600 kg CO2e/m²**. 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

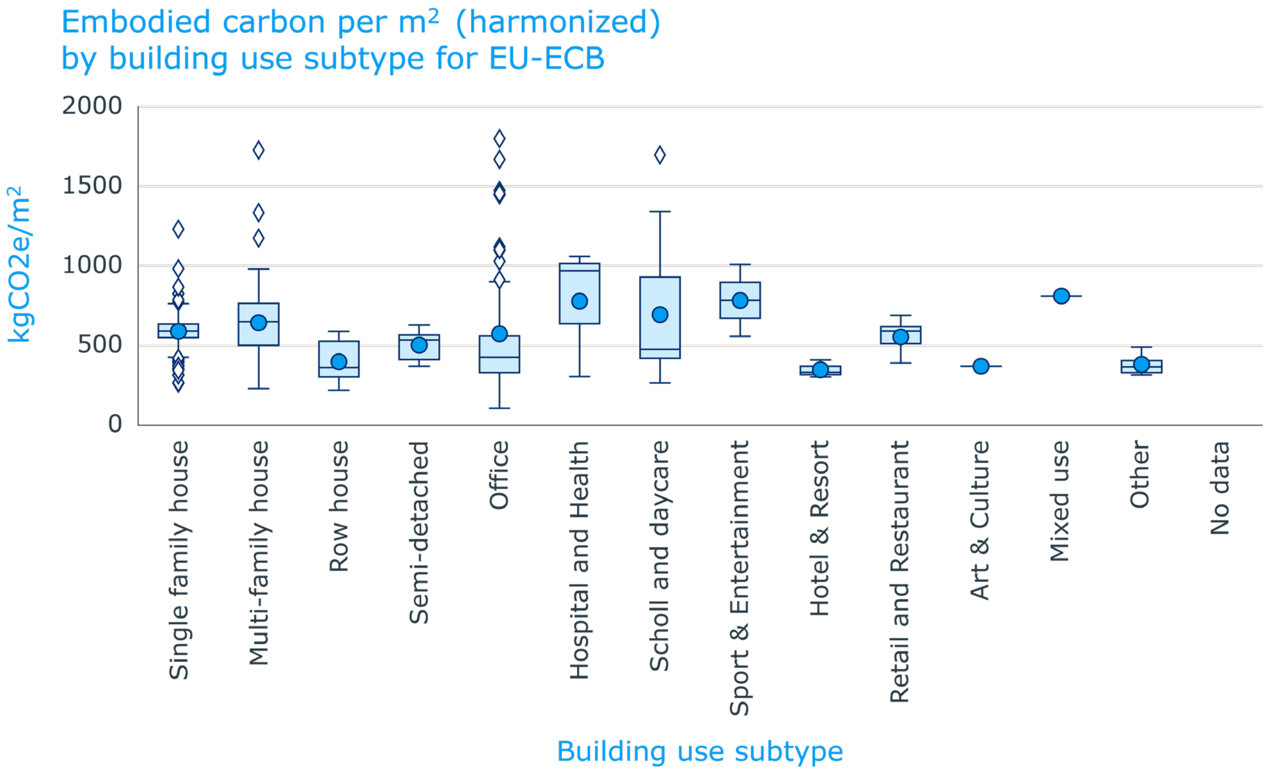


Figure 7 presents the life cycle embodied carbon baseline for different subtypes of building use. The first four categories presented on the horizontal axis represent residential building types. Out of these, the highest per-m^2 values are found for multi-family houses, with a mean value of around 700 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

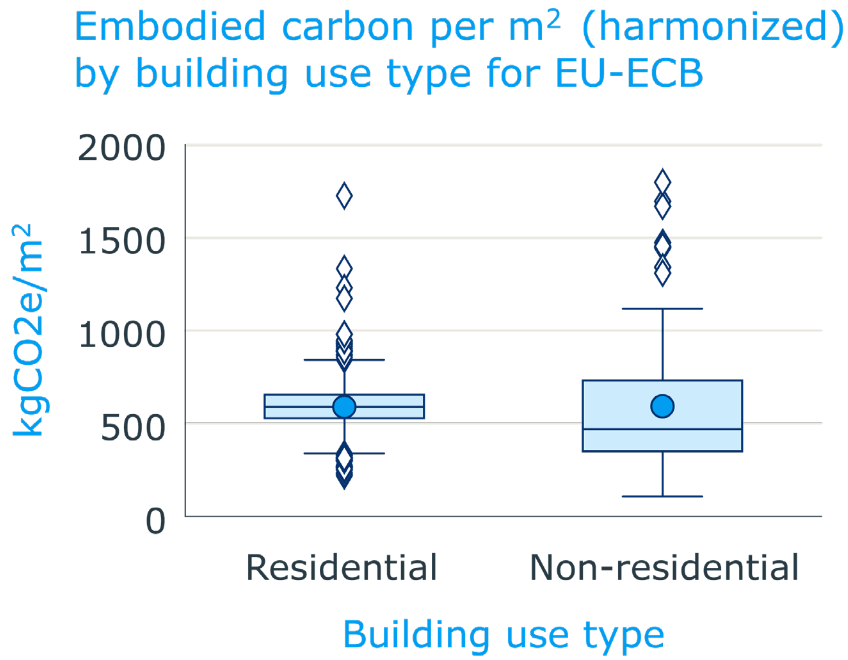


Figure 8 presents the embodied carbon baseline per capita for the different building types. For residential buildings it shows a mean value of around 32 t CO2e/cap, with values ranging from 5 to almost 60 t CO2e/cap. For non-residential buildings, values range from around 2 to 35 t CO2e/cap, with a mean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

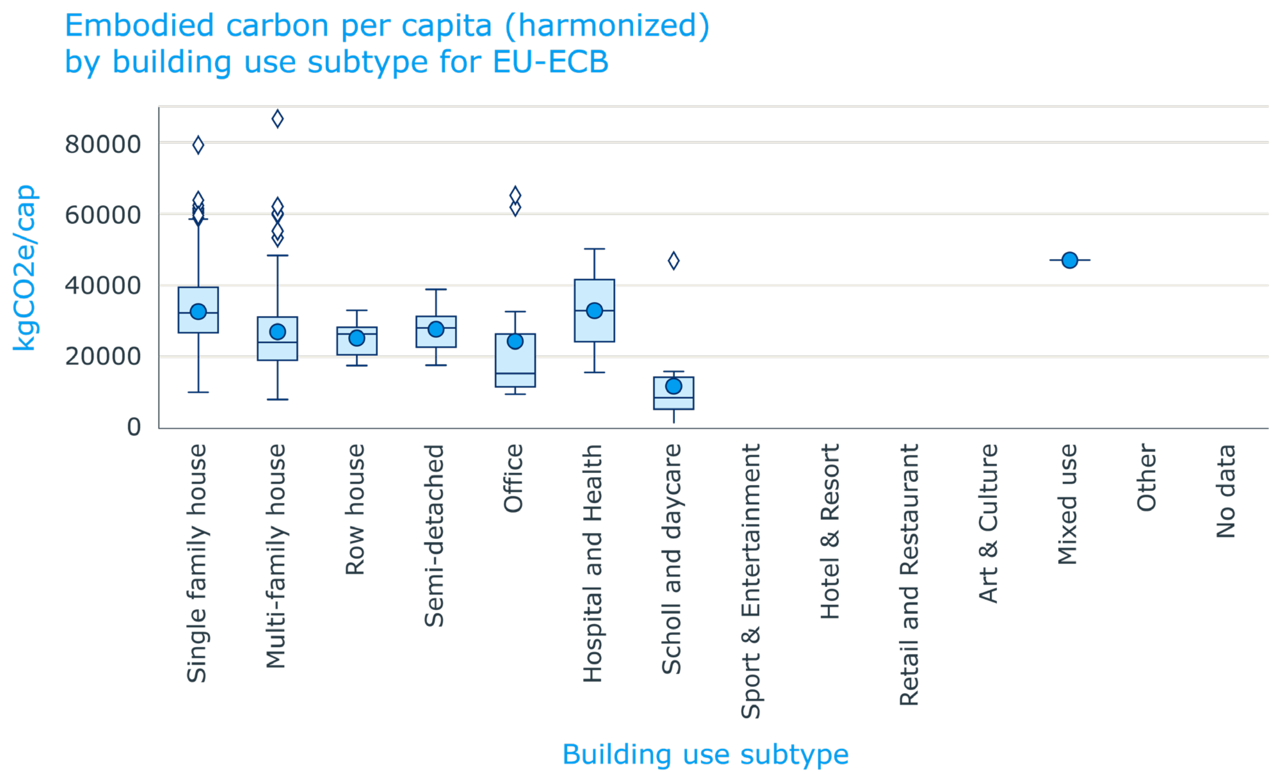
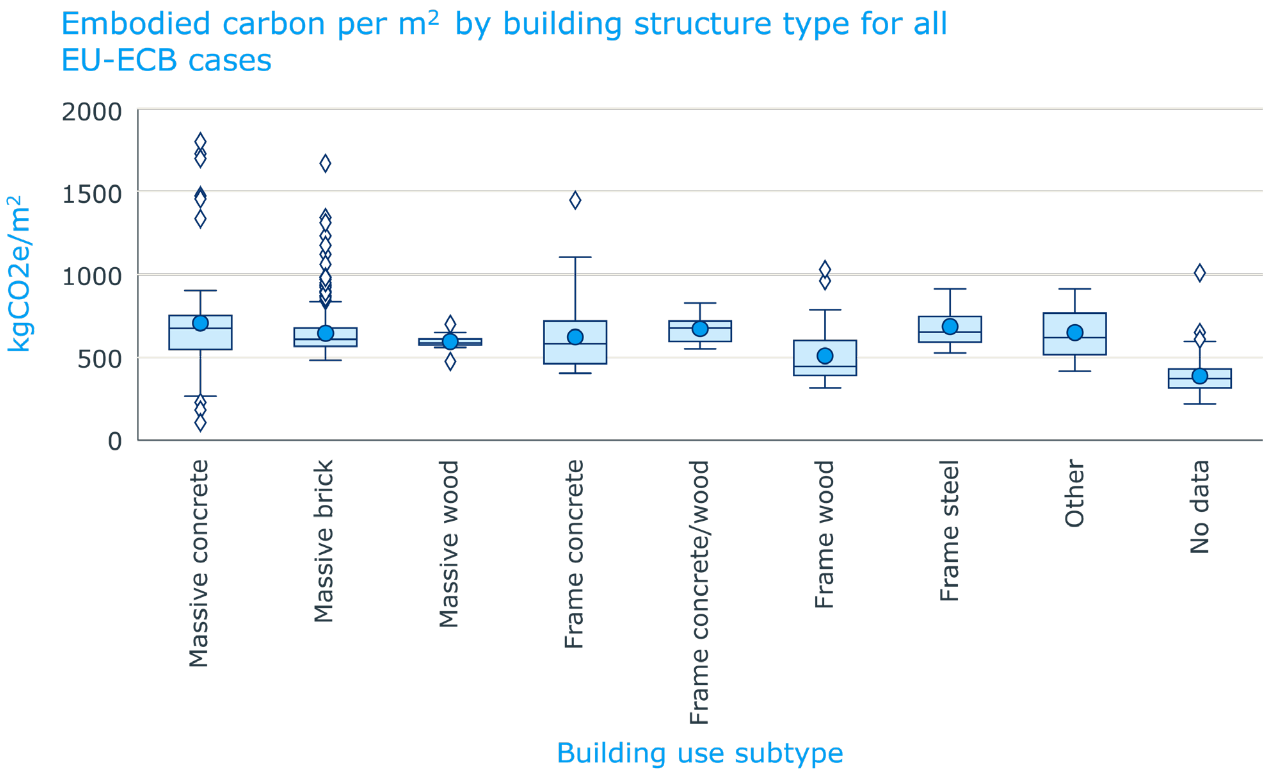


Figure 9 shows the analysis of EC baselines per capita for different building use subtypes. It reveals several substantial differences to the per-m² analysis. **On a per capita basis, the EC baseline for residential buildings is lowest for multi-family houses and terraced/row houses**, with a mean value 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-m² 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 m²) 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 m² 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 m² 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/m² - as well as the widest spread, ranging from approximately 250 to 900 kg CO2e/m²**, with outliers approaching 1850 kg CO2e/m². Massive brick cases display a mean of around 700 kg CO2e/m², with various outliers ranging up to 1700 kg CO2e/m². **Values for massive wooden buildings show only minor variations, with a mean of around 600 kg CO2e/m²**. 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/m², with the mean being around 650 kg CO2e/m². **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.

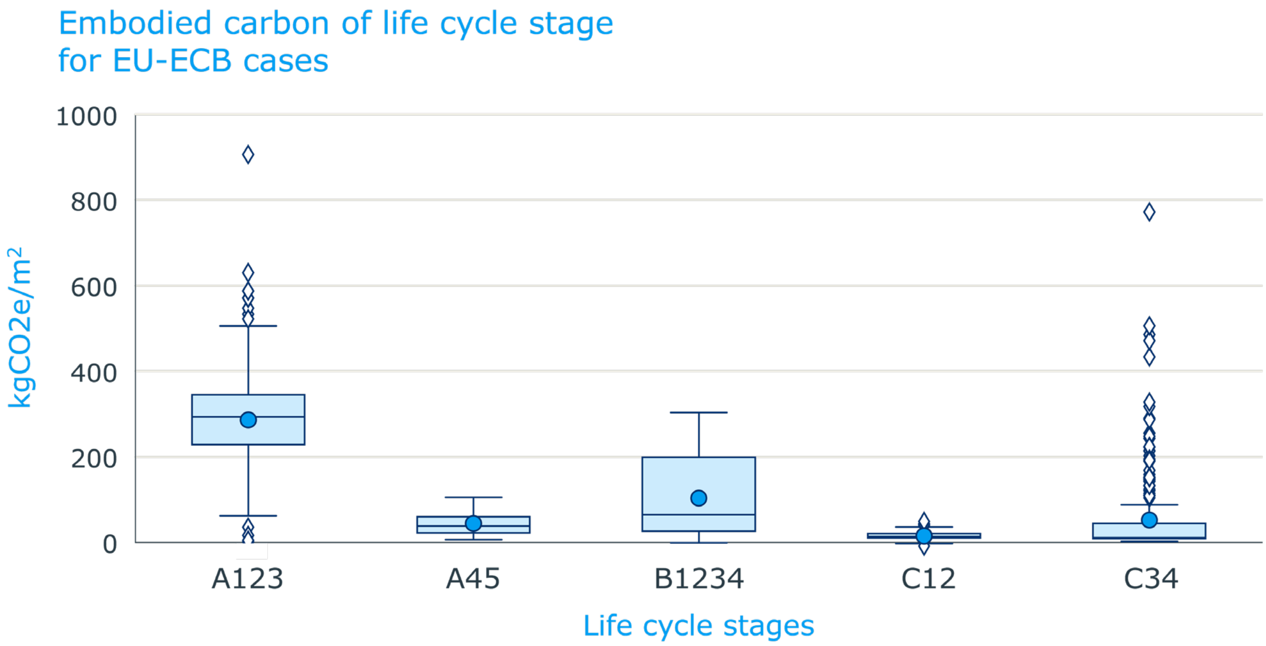
Table 3: Life cycle embodied carbon (mean) for buildings with different types of structure [kg CO2e/m²]

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

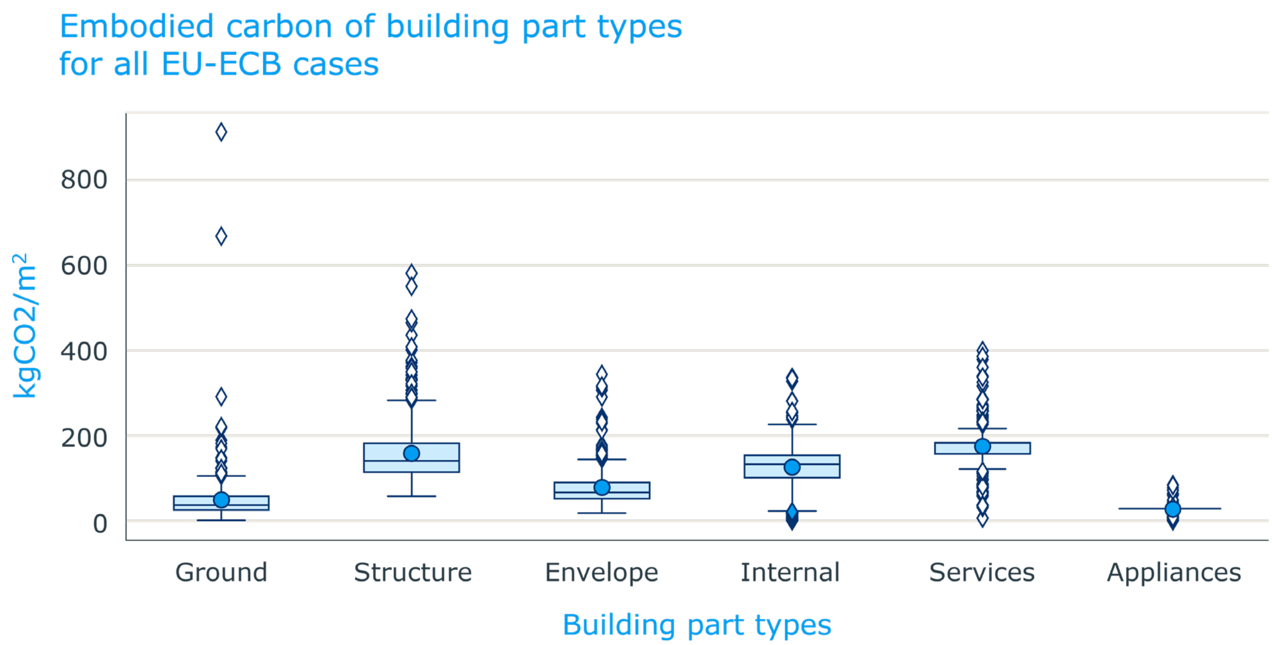
Table 4: Mean contribution to full life cycle embodied carbon [kg CO2e/m²] from different life cycle stages

	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%

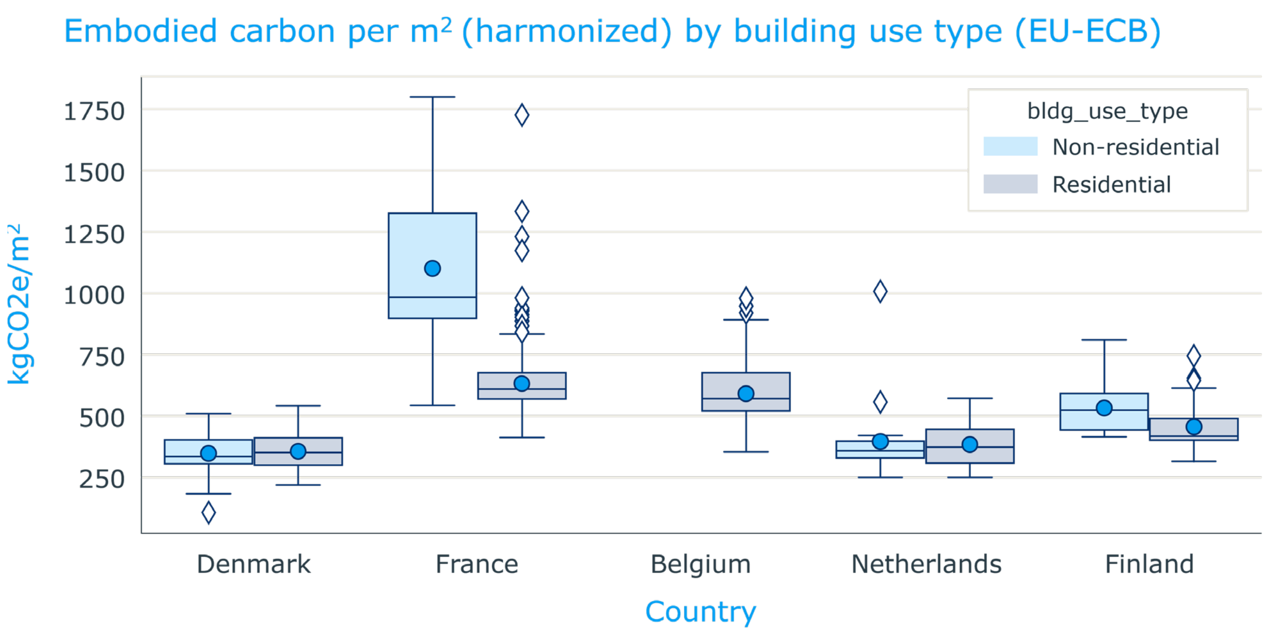
Figure 12 shows the embodied carbon per m² from the different building part groups (Ground, Load-bearing structure, Envelope, Internal, Services and Appliances). It shows that a major contribution to the life cycle embodied carbon emissions, on average, stems from the technical services (e.g., heating, 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 m² 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/m², ranging from 550 to more than 1800 kg CO2e/m². 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/m², respectively. The data on non-residential buildings from Finland suggests a slightly higher mean value close to 550 kg CO2e/m², ranging from 450 to 850 kg CO2e/m². 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/m², respectively, and values ranging from around 200 to 650 kg CO2e/m² 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/m² and a range of 400 to 850 kg CO2e/m². The variation of average values between the different countries is therefore around 250 kg CO2e/m². Residential buildings in Finland show mean values of just above 450 kg CO2e/m², ranging from around 400 to 650 kg CO2e/m². 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/m²], 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/m²) or for the different types of structural systems and materials (~250 kg CO2e/m²), 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 m², 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/m²]

	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 m²

	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.

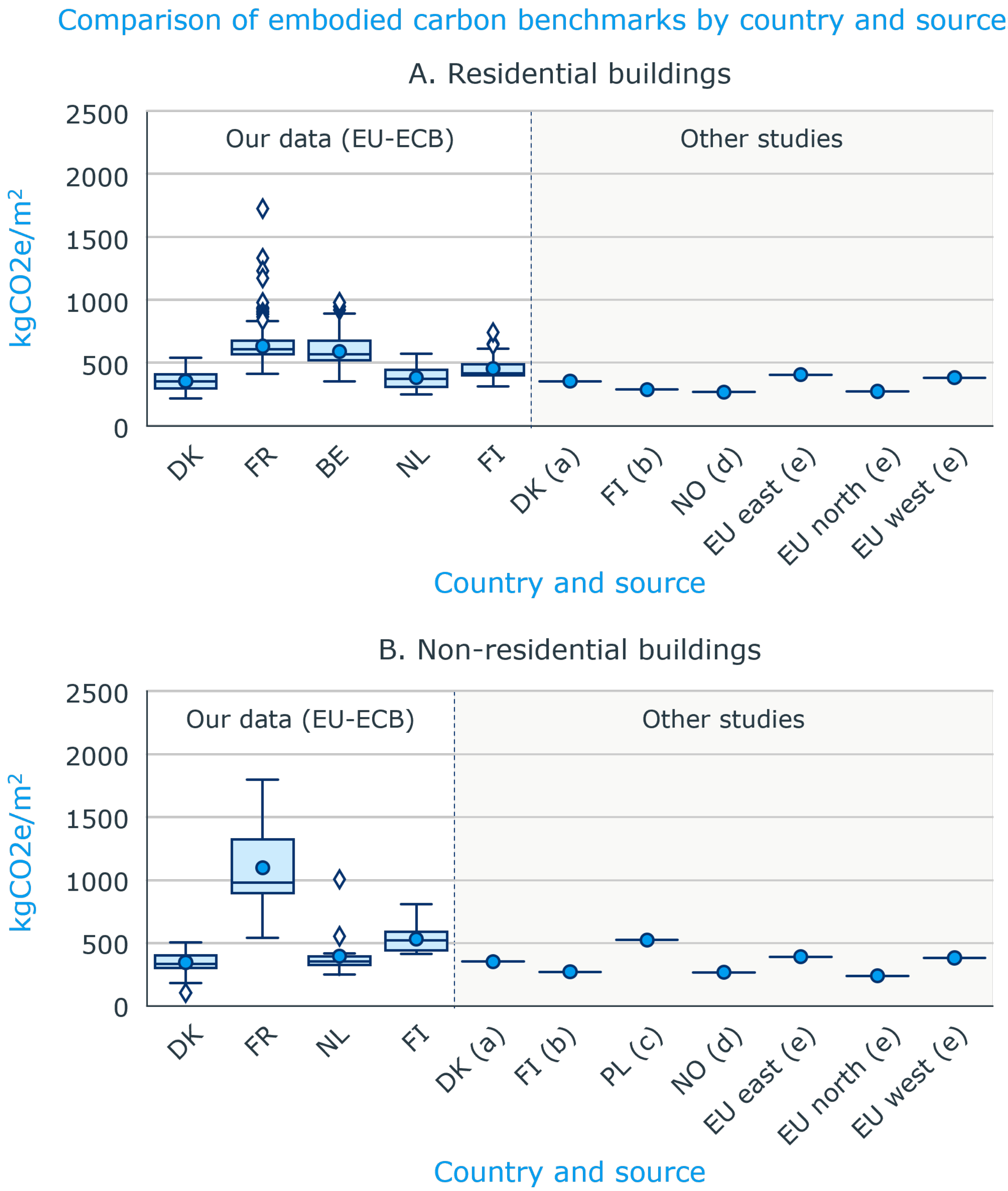


Figure 14 plots the results of our analysis of the life cycle embodied carbon values, as found based on the EU-ECB data, in comparison to benchmarks and reference values found in other studies for different countries. This analysis aims to compare the results for different countries with values from 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/m² with a mean value of around 550 kg CO2e/m² for residential buildings, and from around 100 to 1200 kg CO2e/m² for non-residential buildings, with a mean value of 450 kg CO2e/m².

- **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-m² metric. Such is the case for multi-family houses, which show higher per-m² 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/m²) or for the different types of structural systems and materials (~250 kg CO2e/m²), 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/m² 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/m² (56% of whole life cycle embodied carbon emissions), ranging from around 70 to 520 kg CO2e/m². The second largest proportion of embodied GHG emissions occurs during the use phase (B1-4), with mean values of around 120 kg CO2e/m² (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/m² (ranging from 170 to 230 kg CO2e/m²) and 170 kg CO2e/m² (ranging from 100 to 320 kg CO2e/m²), 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/m² (ranging from 30 to 250 kg CO2e/m²).

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.

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 CO_2e/m^2 and CO_2e/capita, in parallel.

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

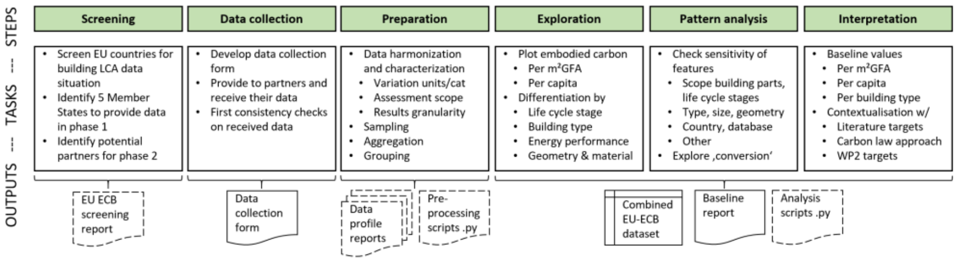

Figure 1: Methodology overview of steps, tasks and related outputs.

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

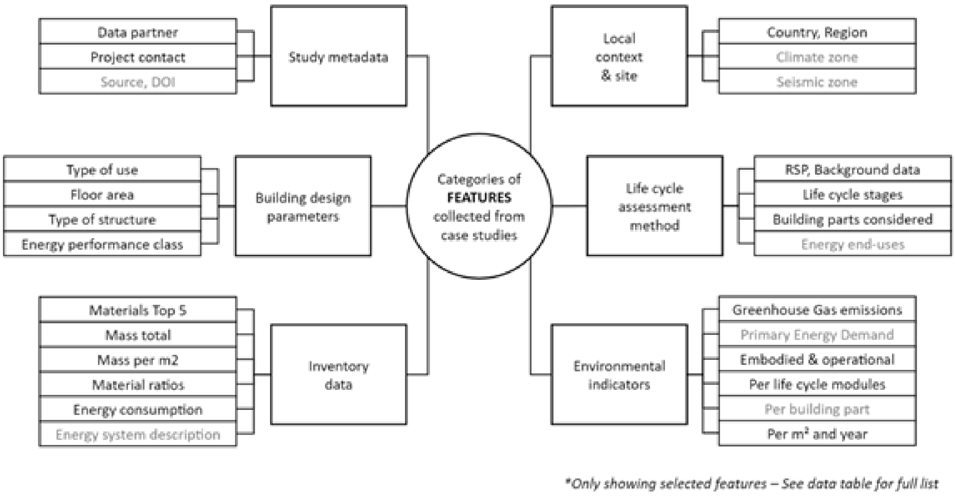

Figure 2: Overview of categories and features parameters collected from case studies.

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.

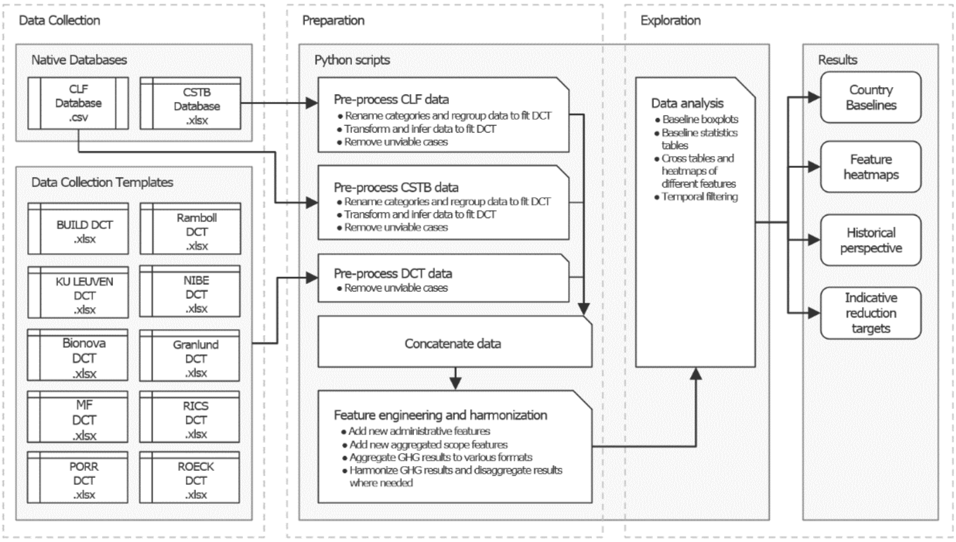

Figure 3: Flowchart of the data collection, preparation and analysis workflow for the different data sources.

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.

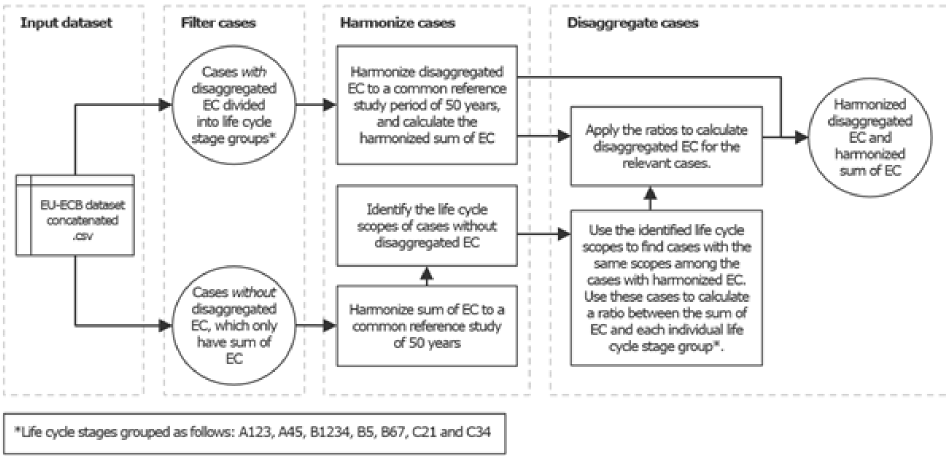

Figure 4: Conceptual presentation of the harmonization and disaggregation process.

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/m²]*
- *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/m²]*
- *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/m²]*
- *GHG_B5_m2_harm = Cumulative embodied GHG emissions of retrofit (Life cycle stages B5) (only for few cases) [kg CO_2e/m²]*
- *GHG_B5_m2_harm = Cumulative operational GHG emissions of building in use (Life cycle stages B6-7) [kg CO_2e/m²]*
- *GHG_C12_m2_harm = Cumulative embodied GHG emissions of deconstruction process stage (Life cycle stages C1-2), based on harmonized RSP [kg CO_2e/m²]*
- *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/m²]*

- *_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)

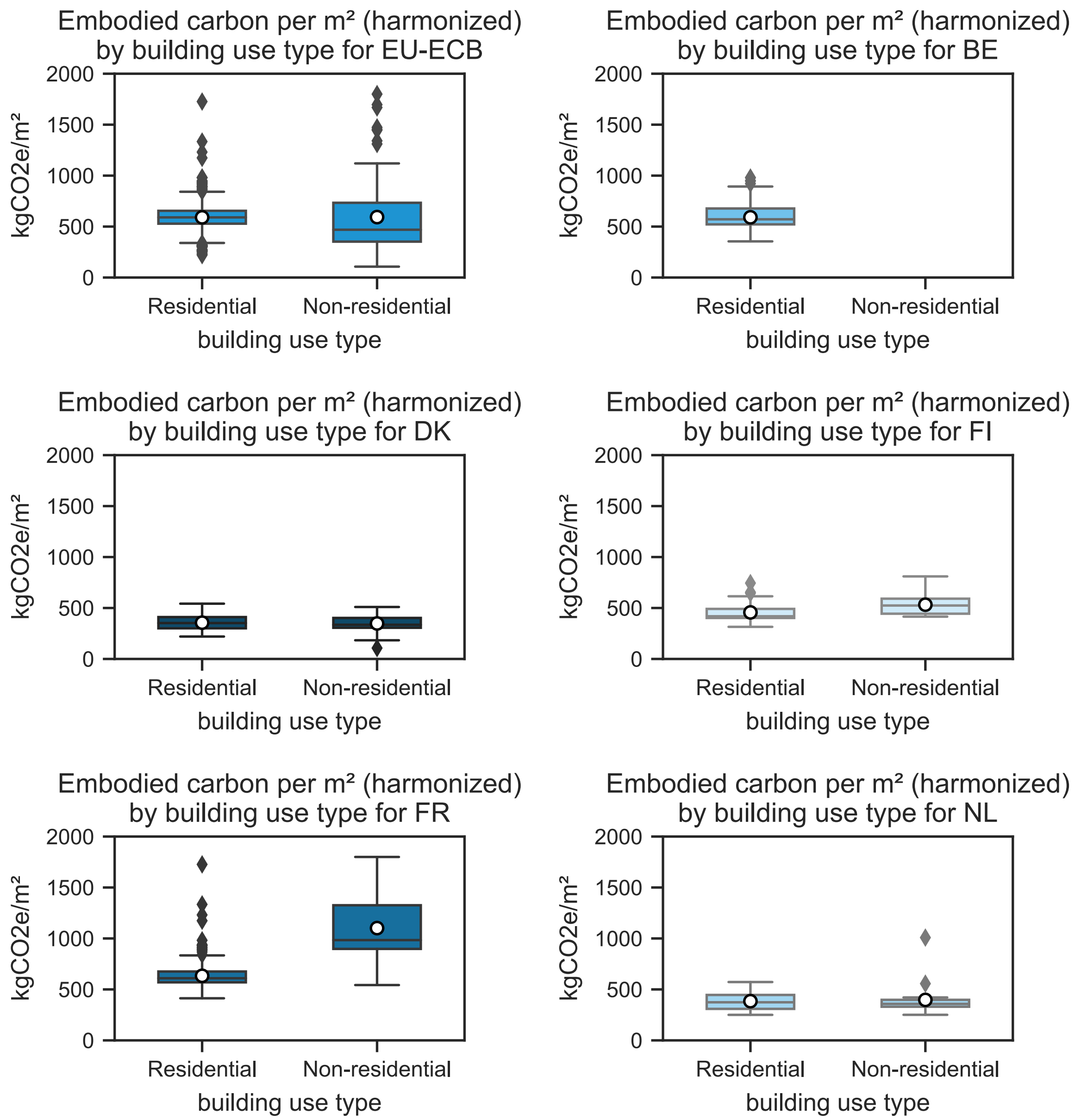

Figure 5: Overview of harmonized, whole life cycle embodied carbon per m² and year [kg/m²/a] for the combined EU-ECB dataset as well as for the main five countries.

Baseline for different building use subtypes

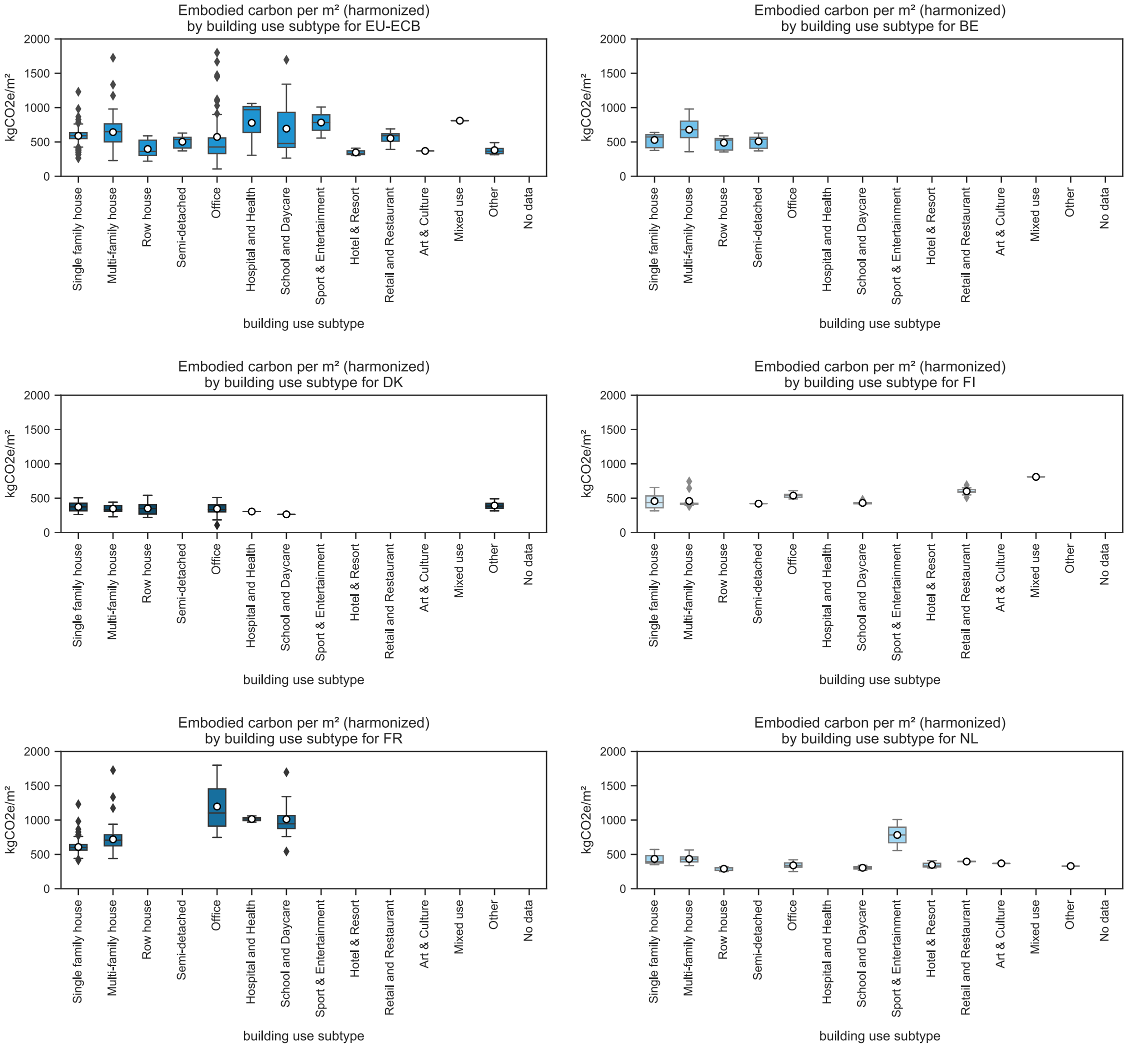

Figure 6: Overview of embodied carbon [kg/m²/a] by building use subtype for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to limitations for data from the respective countries.

Baseline for different types of structure

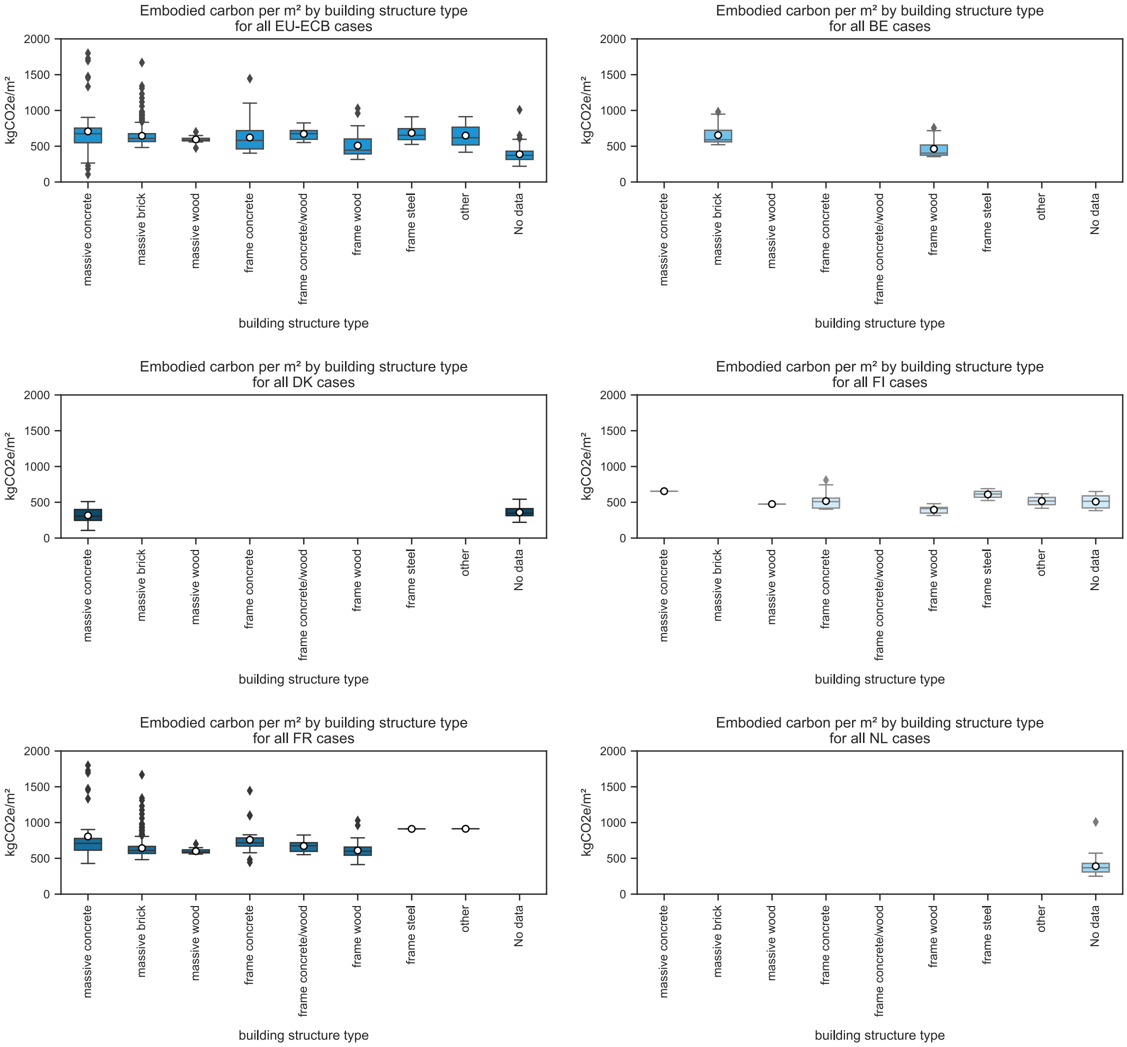

Figure 7: Overview of embodied carbon [kg/m²/a] by building structure type for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to limitations for data from the respective countries.

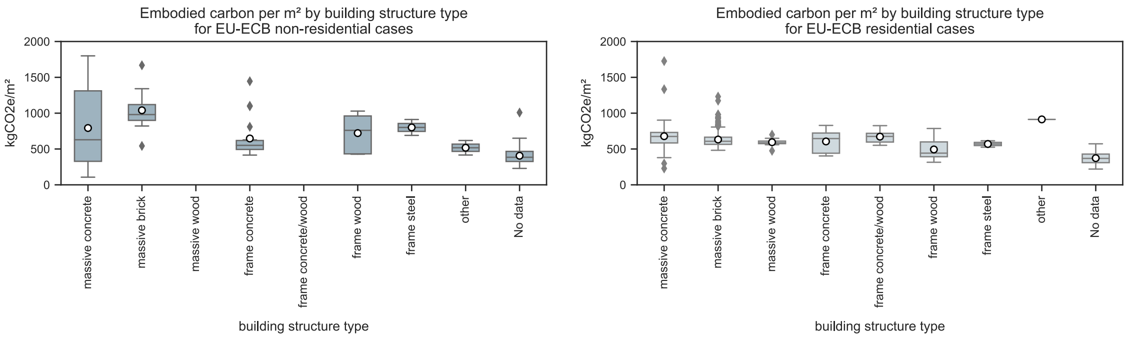

Figure 8: Embodied carbon by building structure type and building use type.

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

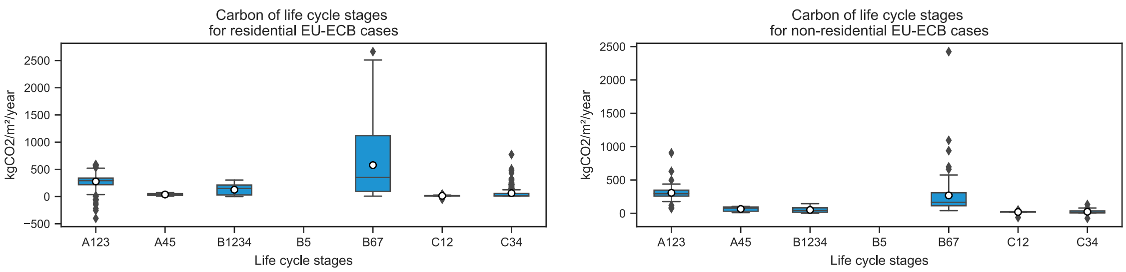

Figure 9: Embodied carbon from different life cycle stages for residential (left) and non-residential (right) buildings.

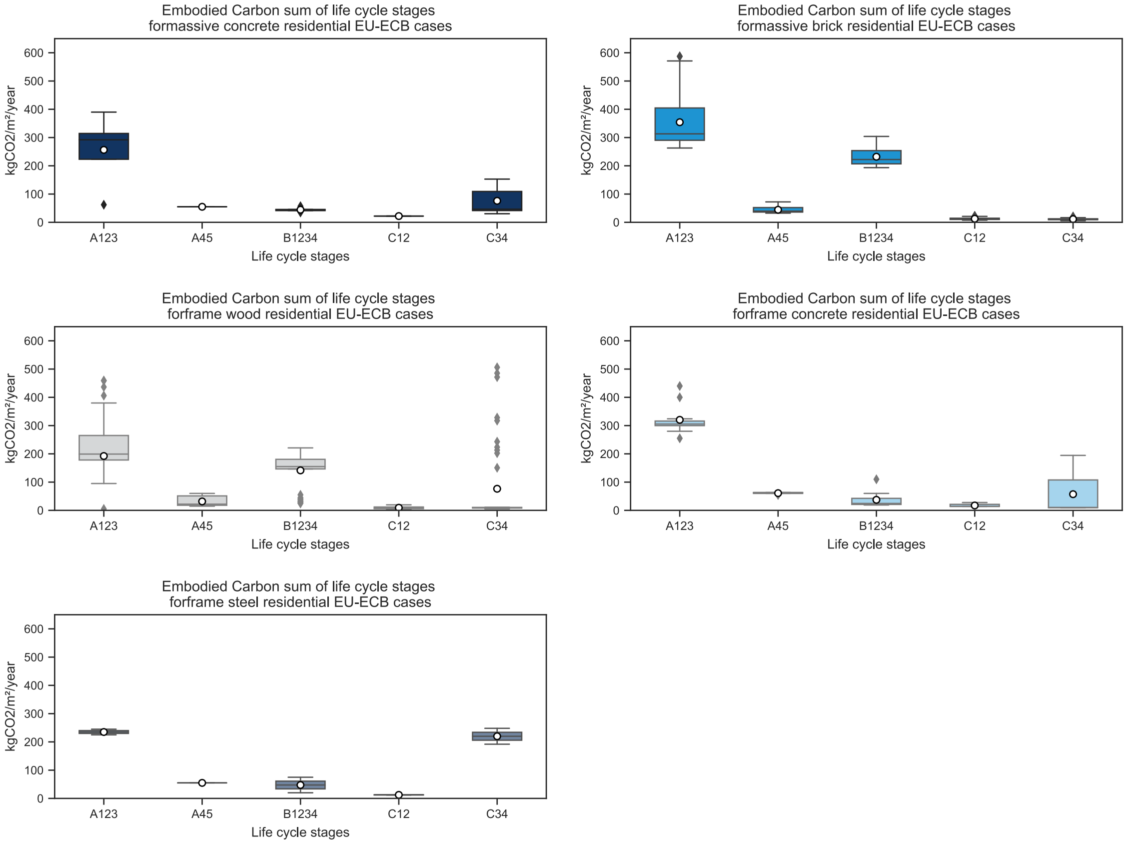

Figure 10: Embodied carbon from different life cycle stages for different type of structure, residential buildings.

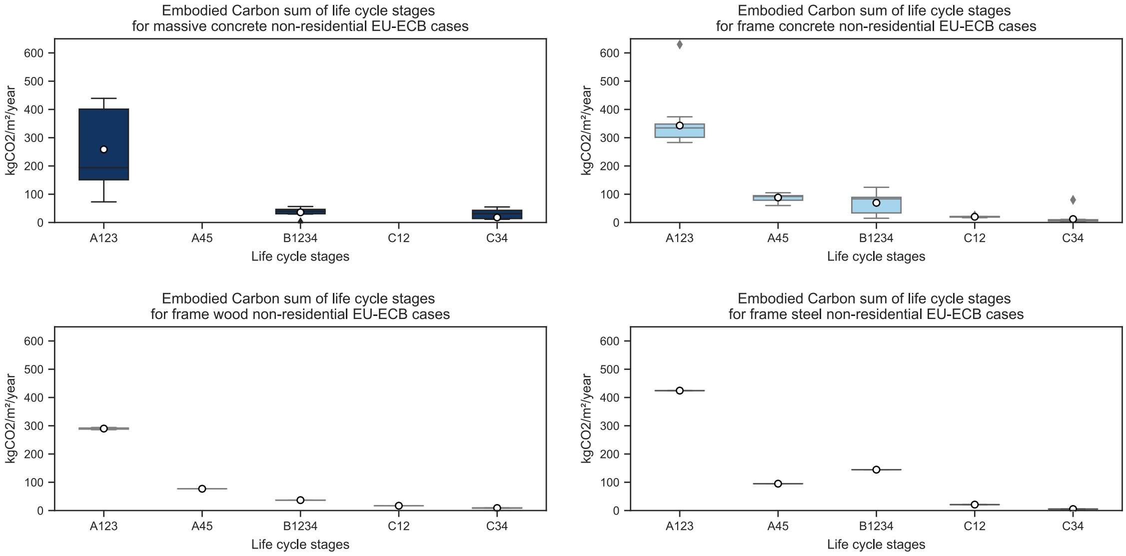

Figure 11: Embodied carbon from different life cycle stages for different type of structure, non-residential buildings.

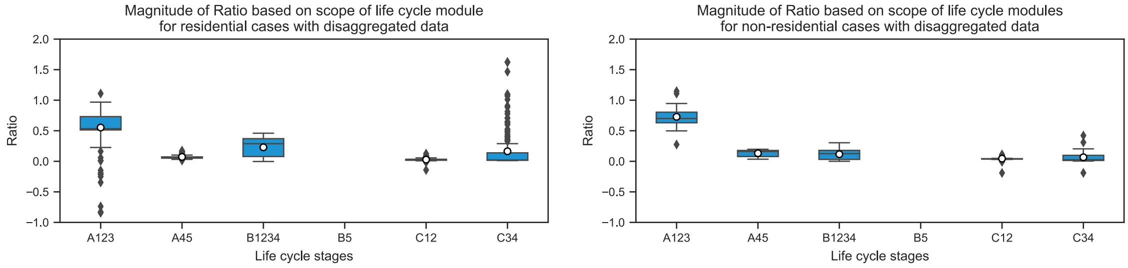

Figure 12: Magnitude of contribution ratio from different life cycle stages for residential and non-residential, respectively. Based on the EU-ECB dataset.

Contribution from different building part groups

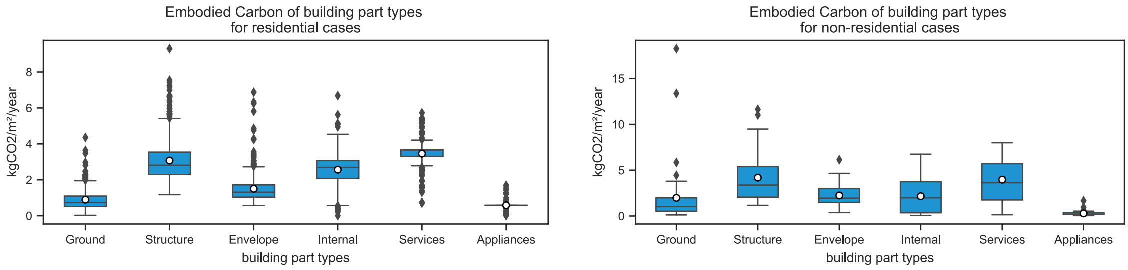

Figure 13: Embodied carbon emissions from different building parts for residential (top) and non-residential (bottom) cases, respectively. Based on the EU-ECB dataset.

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)

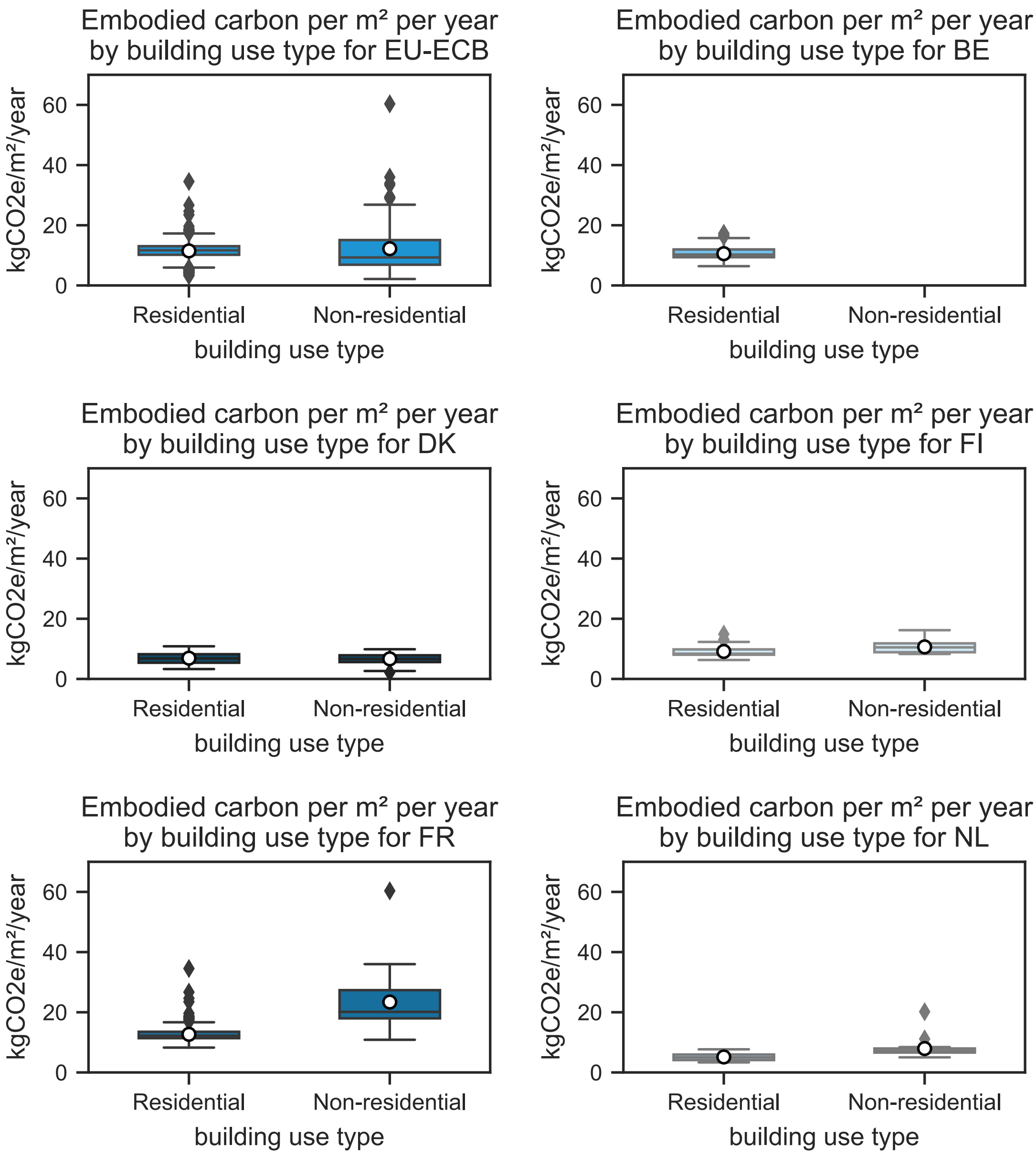

Figure 14: Overview of original (non-harmonized) whole life cycle embodied carbon per m² and year [kg/m²/a] for the combined EU-ECB dataset as well as for the main five countries.

Embodied carbon per capita (original, non-harmonized)

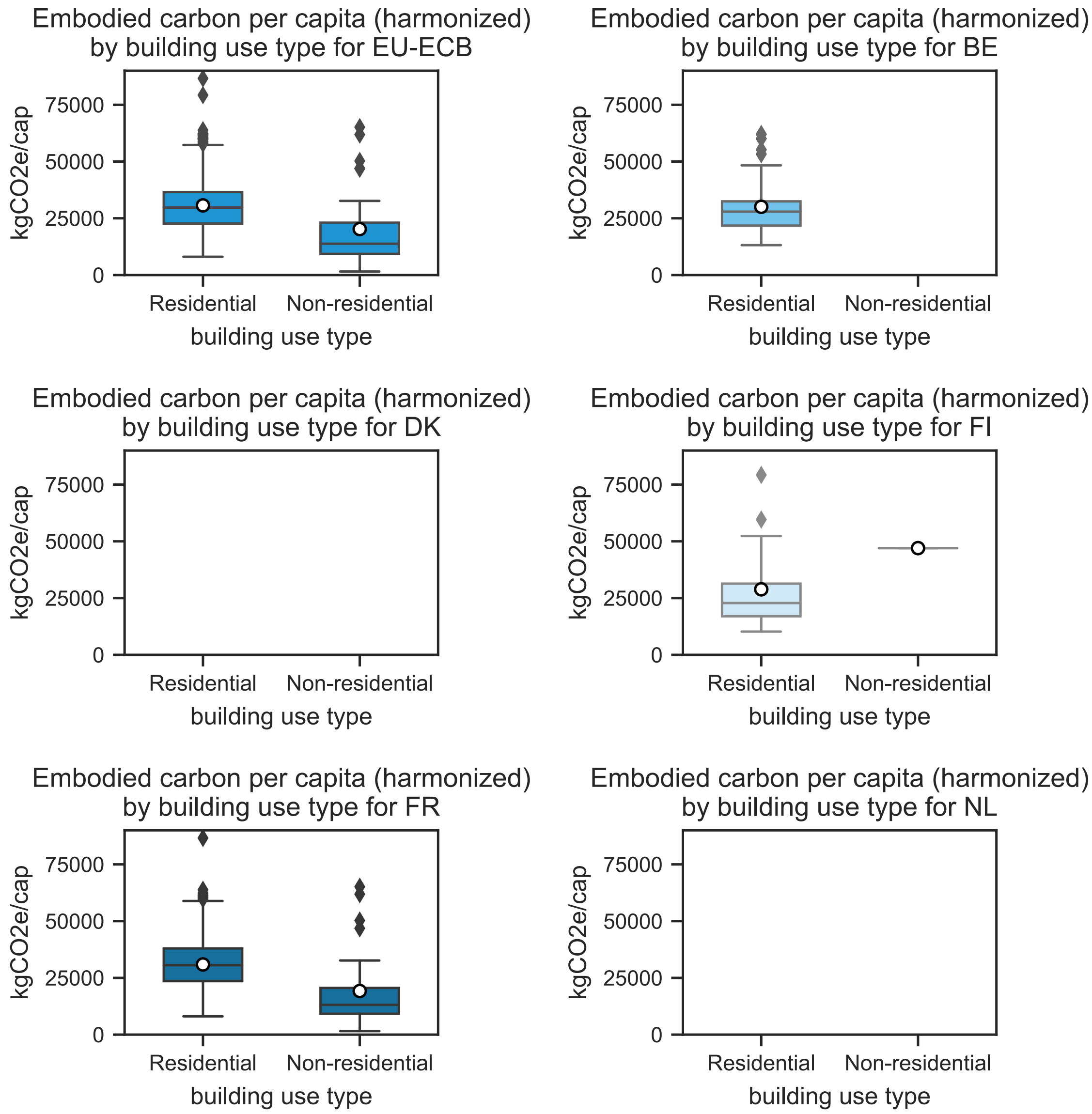

Figure 15: Overview of original (non-harmonized) whole life cycle embodied carbon per capita and year [kg/capita/a] for the combined EU-ECB dataset as well as for the main five countries. Note the empty plots due to data gaps (number of users) for data from the respective countries.

Towards embodied carbon benchmarks for buildings in Europe

#3 Defining budget-based targets: A top-down approach

Bright ideas.
Sustainable change.

BUILD DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Laudes Foundation

Towards embodied carbon benchmarks for buildings in Europe
#3 Defining budget-based targets: A top-down approach

Project name	Towards EU embodied carbon benchmarks for buildings
Date	March 2022
Authors	Lise Hvid Horup, Jacob Steinmann, Xavier Le Den
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Disclaimer

In this report, the widely used terms 'embodied carbon' and 'carbon budgets' are applied. Herein it is considered synonymous with 'embodied GHG emissions' and 'GHG budgets'. These terms therefore refer to both CO2 and non-CO2 GHG emissions. The data regarding global emission budgets presented in this report do, however, differentiate between carbon- only and GHG emissions and thus refer to either GHG emissions (CO2-eq) or CO2 emissions.

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Cite as

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Executive summary

Rationale – Why is this important?

"Embodied carbon" consists of all the greenhouse gas (GHG) emissions associated with materials and construction processes throughout the whole life cycle of a building[1]. 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 related to construction material production and processing.

The project "Towards Embodied Carbon Benchmarks for buildings in Europe" was established by Ramboll and BUILD AAU - Aalborg University with the support of the Laudes Foundation. Through four reports[2], the objective is to enhance our understanding of embodied carbon in buildings and set the framework conditions for reducing it. To do so, the project explores the concept of embodied carbon baselines, targets and benchmarks for buildings in Europe.

To drive embodied carbon emissions reduction as part of a reduction of whole-life emissions, targets for embodied carbon are needed. Targets define the number of emissions that can be emitted in line with scientific and political decarbonisation requirements to hold global warming to well below 2oC, and preferably limit it to 1.5oC, compared to pre-industrial levels, to avoid the worst impacts of the climate crisis. This report therefore outlines how a carbon budget of the remaining emissions quantity, in line with global warming limits and targets linked to this budget, can be set for embodied carbon as a reference point for policymakers and industry.

Methodology – What did we do?

This report brings together a review of existing methodologies for setting targets based on carbon budgets and a discussion of the characteristics of embodied carbon in buildings. It starts by presenting the elements needed to set a budget-based target as applied in common target-setting approaches. Building on scientific literature, it then presents the challenges that lie in applying these elements to embodied carbon.

Based on all these considerations, the report proposes a way forward for defining a carbon budget and setting targets along the budget trajectory for Paris-aligned embodied carbon levels for upfront emissions from new buildings per square metre (m2). A key challenge of this is downscaling the global carbon budget to specific numbers for embodied carbon in a global or national context. This issue is addressed by using a five-step approach that focuses on a national GHG budget and allocates a share of this budget to embodied carbon, as shown in Figure 1.

This procedure for downscaling from a global budget to an activity in a country is applied to the Danish and Finnish building sectors. In the proof of concept provided in this report, a combination of different allocation principles for the GHG budget to countries is applied. Global emissions are allocated to countries based on an equal per capita (EPC) principle. The share of embodied carbon resulting from new construction is determined in two ways. First, allocation is based on a utilitarian (U) principle that assesses the contribution to national welfare through

1. Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, maintenance, repair, replacement, refurbishment, deconstruction, transport to end-of-life facilities, processing and disposal.

2. Reports: #1: Facing the data challenge; #2: Setting the baseline; #3: Defining a carbon budget; #4: Bridging the gap.

multi-regional input-output (MRIO) models. Second, a grandfathering allocation (GF) based on the current share in the national emissions inventory is undertaken. Future construction is forecasted based on national economic activity (EA) in the construction sector. As this combines all building construction activity, a differentiation between building purposes (e.g. residential, non-residential) is not possible in this approach. Rather, all buildings are included in the resulting targets.

Figure 1: Downscaling from global budget to embodied carbon in buildings - a concept to set targets for embodied impacts in new buildings per m².

Results – What did we find?

Existing methodologies for budget calculation and target setting are designed for purposes other than addressing embodied carbon. This is due to several factors that can be summarised in two points:

- First, the characteristics of embodied carbon differ from operational carbon emissions. This is because of the cross-sectoral and international nature of the value chain along which embodied emissions occur. Neither a definition of emission scopes used in corporate GHG accounting nor the territorial GHG inventories used by governments and cities are fully able to capture all relevant embodied emissions.
- Second, important elements for setting a budget-based target are not available on a commonly agreed basis. Notably, agreement on a carbon budget specific to the building sector or embodied carbon, and a decarbonisation scenario or trajectory that is aligned with the global carbon budget are needed. There is therefore a pressing need to develop a shared trajectory that contains the reference information for reducing embodied emissions.

Applying the proposed approach for downscaling the global budget to upfront embodied carbon from national construction activity in Denmark and Finland shows that the Paris-aligned budget and related targets in line with global warming of 1.5°C are substantially lower than current levels of embodied carbon and existing legislation.

Table 1 presents a comparison of the targets per m2 with the baseline established in report #2 "Setting the baseline", which includes all life cycle stages but finds that the largest share is caused by upfront emissions. In Figure 2, the curves of the carbon budget as targets over time are shown for Denmark in comparison to the baseline and national legislation on maximum embodied carbon levels for new buildings. Both apply to new constructions, assuming a constant construction rate based on past construction trends from 2018 to 2020.

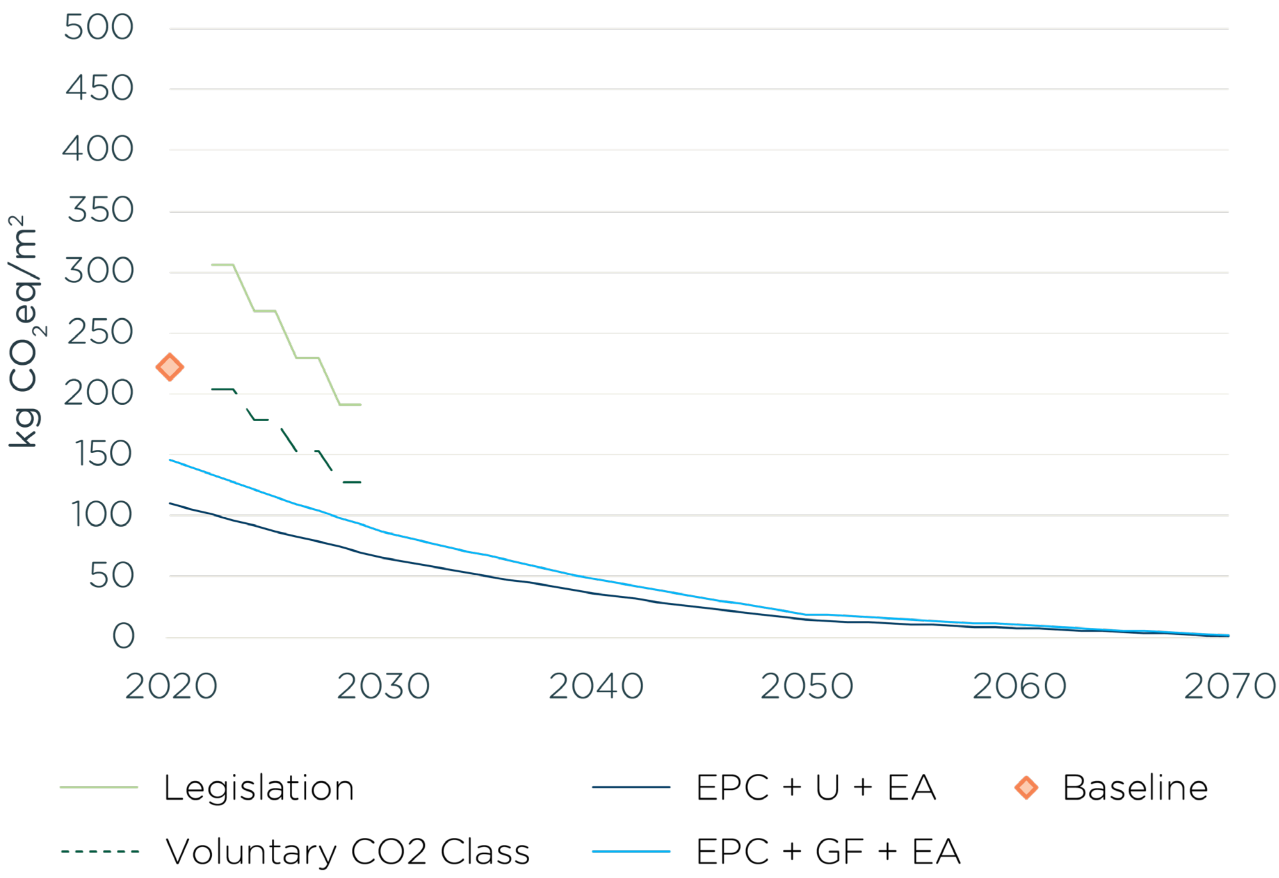
This approach, as with any allocation of the carbon budget among countries or sectors, relies on a choice of allocation principle. Depending on this choice, and because of the multitude of national or even more regional targets needed, an overshoot of the GHG budget is still a probable scenario. Additionally, the data for sectoral allocation of the budget to (upfront) embodied carbon requires data on the type of activity within the construction sector, which proves difficult to obtain. For these reasons, the concept would benefit from further progress on agreeing on allocation principles, data collection and availability, or the establishment of a global budget for embodied carbon to reduce differences between countries.

3. For these countries, the necessary data was available.

Table 1: Comparison of whole-life embodied emissions (in kgCO2eq/m²) according to empirical baseline and budget-based targets

Year	Denmark	Finland
Baseline	222	333
2025	87-116	52-213
2030	66-88	39-168
2050	15-19	8-35

Figure 2: Upfront embodied emissions (in kgCO2eq/m2) for Denmark



Conclusions – What does this mean?

Our assessment, concept and the resulting target levels highlight the following aspects:

- **Budget-based targets communicate the amount of embodied carbon that can be emitted in line with the carbon budget and are therefore consistent with the Paris Agreement on limiting global warming. Such targets set at building level are highly relevant** as a reference for the speed and scale of decarbonisation efforts in the construction sector. Considering the complexity of the value chain at play, they would constitute a strong signal for the demand side (investors, owners), and would subsequently be passed on further down the value chain (designers, producers).

- **There are challenges when defining a carbon budget and budget-based targets for embodied carbon emissions in buildings.** Fundamental elements of such targets, such as a specific carbon budget and a Paris-aligned decarbonisation trajectory needed for embodied carbon in buildings, are not yet available. Existing initiatives on GHG emissions reduction targets in the building sector have so far focused on operational carbon, and because of the specific characteristics of embodied carbon. Developing targets based on the carbon budget for embodied carbon will be crucial to more widespread target setting.

- **It is possible to overcome these challenges.** The concept of downscaling from global budget to building leads to ambitious targets that can only be achieved through a fundamental transition of the industry. Reducing the embodied carbon per m2 is essential in the industry and at construction project level. As this is not likely to be sufficient to stay within the carbon budget, action from policymakers is needed to reduce the number of m2 built. Therefore, in addition to an embodied carbon target per square metre, a target per capita may be needed.

- **The gap between the current levels of embodied carbon (see report #2 "Setting the baseline") and the levels required by the carbon budget is substantial.** The proposed concept for targets shows that Paris-aligned values lie well below the current baseline. Existing target initiatives do not specifically capture this gap for embodied carbon, while existing legislation falls short of closing it. This calls for immediate and ambitious action to reduce the embodied carbon of new buildings.

Call to action – What should we do?

Based on these conclusions, a set of recommendations emerges:

- **Setting budget-based targets for the embodied carbon of buildings needs to become more common.** For this, accessible data is needed, together with internationally recognised initiatives to define a target-setting methodology that is based on a widely agreed Paris-aligned carbon budget for the building sector, while also developing decarbonisation pathways for the sector, including embodied carbon.

- **The targets will need to be supported by ambitious benchmarks** for new buildings to be defined in regulations. To the extent possible, these benchmarks should be aligned with the budget-based targets. A framework for establishing such benchmarks is developed in report #4 "Bridging the performance gap".

- **Closing the gap between current and required levels of embodied carbon also calls for additional policy measures.** While embodied carbon limits per m2 are one element, further instruments such as reducing the rate of new construction or support for building materials with negative emissions should be considered. In addition, these elements need to be coordinated with renovations of existing buildings and the reduction of operational emissions.

- **To enable investors, building design professionals and spatial planners to set targets at building and local level, globally appropriate standards for a budget and decarbonisation trajectory for embodied carbon could be highly beneficial.** This would reduce barriers for such actors and ensure a higher level of overall consistency with the global budget. This exercise could be undertaken by an internationally accepted body like the SBTi, as part of its work to develop corporate targets in line with the Paris Agreement and the latest climate science, and necessitates collaboration with the public sector, the industry and academia, to get access to the necessary data on buildings' life cycle assessment (LCA) and construction activities.

Contents

1. Introduction

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

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

Altogether, the sum of embodied and operational emissions is referred to as whole-life carbon emissions. Reducing this total sum of a building's emissions is the highest priority, to which this work aims to contribute.

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 related to construction material production and processing. "Embodied carbon" consists of all the greenhouse gas (GHG) emissions associated with materials and construction processes throughout the whole life cycle of a building[4].

These embodied emissions of buildings are rarely addressed in policy strategies and instruments. However, if embodied carbon is not included in building decarbonisation targets, 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 require attention and alignment as part of European and global efforts to combat climate change. It was against the backdrop of increasing efforts to understand and reduce the whole life cycle carbon of buildings that the project "Towards Embodied Carbon Benchmarks for the European Building Industry" was established.

In particular, setting a performance system for embodied emissions at 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", established by Ramboll and Build AAU - Aalborg University, with the support of the Laudes Foundation. This includes a baseline for current embodied carbon levels in new buildings, as well as considerations of the available carbon budget for these emissions. Together with a review of data availability and quality, these elements form the basis for a performance system in the form of benchmarks for reducing embodied carbon.

The focus of this project was placed on the EU. This is grounded in its position as a pioneer in GHG emissions reduction policies with instruments such as the Energy Performance of Buildings Directive, its Taxonomy for Sustainable Activities, or the EU Climate Transition Benchmark Regulation. Additionally, there is increasing policy awareness of the life cycle perspective of buildings. These instruments and initiatives will have an increasing impact on the building industry. This project seeks to inform the debate among policymakers and industry alike and stimulate the development and application of benchmarks for embodied carbon in the EU and beyond.

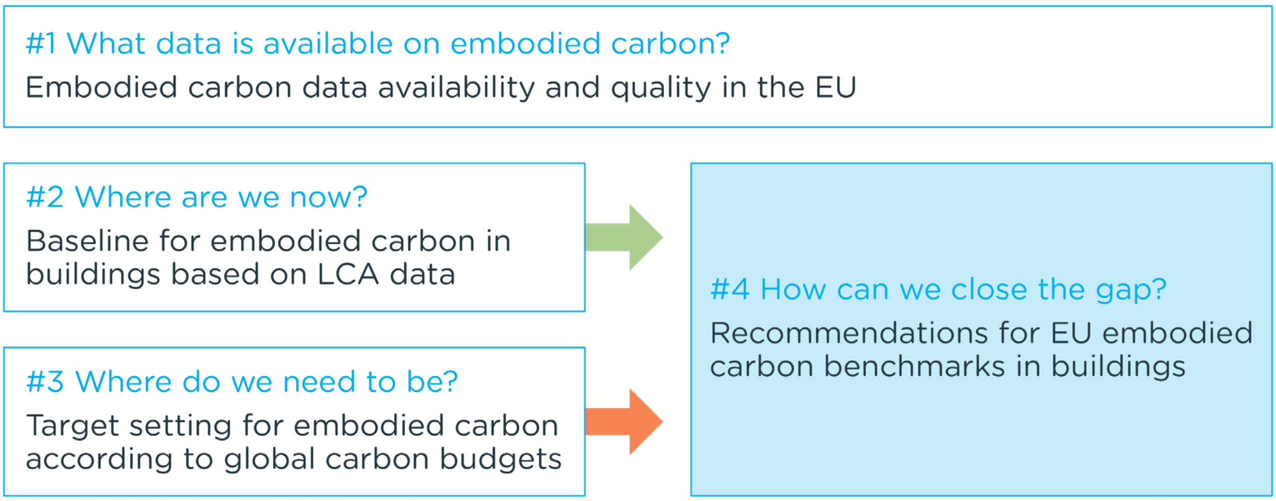
4. Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, use phase, maintenance, repair, replacement, refurbishment, deconstruction, transport to end-of-life facilities, processing and disposal

The series of reports produced in this project provide insights and advances 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 embodied carbon benchmarks be set for reduction?

This is the third report in this series.

Figure 3: Overview of report series for the project "Towards Embodied Carbon Benchmarks for buildings in Europe"



The purpose of this report is to present a proposed concept of how a carbon budget for embodied carbon can be determined and how targets aligned with this budget can be set for buildings. To do this, the report defines the necessary elements of a target, investigates the applicability of existing approaches for target setting to reduce the climate impact of embodied carbon in buildings, and proposes a methodology for setting embodied carbon targets.

This methodology is applied and tested for Denmark and Finland. Building on the Baseline Report that calculated current levels of embodied carbon, the application of the proposed approach for budget-based targets shows a huge performance gap in efforts to mitigate climate change. Not least because of the increasing share of embodied carbon (in relative and absolute terms) determined in the Baseline Report, this calls for rapid and ambitious action on target setting and benchmark development.

2. What is needed for a budget-based target?

Defining budget-based embodied carbon targets requires that the necessary foundations are established. This section lays out the fundamental elements of targets set in a budget-based process. These elements are:

- The global carbon budget
- Pathways for future emissions, to stay within this budget
- Approaches to scaling down global emissions to countries, sectors, companies or activities

2.1 Global carbon budget

The Paris Agreement sets out a global framework for averting climate change by limiting global warming. Climate change mitigation efforts and targets have increasingly emerged since the adoption of the Paris Agreement in 2015. In the Paris Agreement, the vast majority of countries around the world have expressed the ambition to limit global warming to 1.5°C or, at most, 2°C above pre-industrial levels [2]. To stay within the limit, the end-of-century radioactive forcing must be kept at 1,9 W [3]. Variations in radiative forcing are caused by changes in the atmospheric concentrations of greenhouse gas emissions, strongly driven by CO2 and other gases emitted by human activities. The relationship with radiative forcing having been established, the number of greenhouse gases (GHG) already emitted into the atmosphere have been identified and remaining global carbon budgets have been estimated [4].

The global carbon budget determines the remaining amount of GHG that can be emitted until the targeted global warming limit is reached. Because of the different global warming targets formulated in the Paris Agreement, varying levels of ambition between 1.5°C and 2°C are possible and result in different carbon budgets. The latest IPCC report published in September 2021 [5] contains updated budgets considering emissions up to 2019. These budgets cover CO2 emissions and are presented in Table 2. A CO2-equivalent budget for non-CO2 emissions has to be added, which is taken into consideration in the decarbonisation scenarios cited and referred to in this report.

Table 2: Estimated remaining global CO2 budgets from the beginning of 2020 in GtCO2 [5]

Global warming target relative to pre-industrial levels [°C]	Additional global warming relative to 2010-2019 average [°C]	Estimated carbon budget in GtCO2 by likelihood of limiting global warming to temperature limit					Variations in reductions of non-CO2 emissions
		17%	33%	50%	67%	83%	
1.5	0.43	900	650	500	400	300	Higher or lower reductions of non-CO2 emissions can increase or decrease the values on the left by 220 GtCO2 or more.
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

This global budget forms the top-level consideration that any relevant target has to reflect in order to keep emissions within this budget. Through this mechanism, the target can be considered science-based and Paris-aligned.

2.2 Global and sectoral pathways

In addition to the total carbon budgets, pathways are needed to define levels of emissions over time that result in a transition compatible with the carbon budget. These pathways or scenarios help to understand the necessary future development of emissions from industrial sectors and activities that ensure levels stay within the global warming target.

Pathways model the impact of expected changes to technologies, behaviour and policies on emissions reduction over time. In this way, pathways also provide a context for an emissions reduction target by illustrating certainties and uncertainties around political, economic, and technological developments. Ultimately, pathways reach an emissions level that can be sustained while staying within the global warming limit.

The IPCC Special Report identifies such mitigation pathways compatible with the 1.5°C target [6]. A set of transition pathways consistent with an increase of 1.5°C in 2100 were explored through six integrated assessment models (IAM) and a simple climate model. To systematically explore the impact of different socio-economic responses to the mitigation pathways, the IAMs have adopted the five Shared Socio-Economic Pathways (SSPs) [7]. The SSPs provide different narratives of the future world in terms of socio-economic indicators such as technological developments, and population growth and economic growth. By integrating the SSPs into the IAMs, GHG emissions scenarios can be derived for different climate policies.

The International Energy Agency (IEA) develops and updates scenarios for different global warming thresholds. The IEA report on net zero by 2050 [8] provides scenarios for limiting global warming to 1.5°C. In these scenarios, future energy emissions are divided into the following sectors: industry, transport, energy and buildings (operational energy use). The industry and transport sectors are further broken down[5] and the building sector is also further divided into direct and indirect energy use for residential and non-residential buildings respectively. The remaining sectors, including direct emissions from the construction industries, are in other IEA publications [9] summarised in “other industries”, which are considered mainly non-energy intensive[6]. Using these scenarios creates a complete and consistent framework for all sectors and entities, in which all GHG emissions can be attributed to one of the sectors. **However, this division also means that transversal categories like embodied carbon in building materials cut across several sectors, and the necessary emissions reduction for this category cannot be forecasted in these tools.** This key challenge is discussed in Chapter 2 below.

2.3 Downscaling the global budget

The carbon budget presented in the latest IPCC report (Table 2) is global and therefore needs to be broken down further to be operationalised for emissions reduction targets at country and economic activity levels. Assigning a share of the global carbon budget to a country, building or any other service is a matter of subjective opinion on what is fair. Different normative principles and underlying justifications exist on this matter.

Applying “equal per capita” (EPC) is one way of dividing the budget into equal shares to all individuals that can easily be translated into a country’s budget. However, some might also argue that developing countries should have a relatively larger share in the future, to make up for industrialised countries that have emitted large amounts of CO2 in the past. This would be an example of applying the “ability to pay” allocation principle. **Therefore, a distributed budget should always be communicated with transparency around the allocation principles applied,** to allow the reader to endorse or disagree with the ethical principles behind the resulting budgets. Allocation principles are also sometimes referred to as sharing principles.

Table 3 presents the commonly used and described sharing principles and their respective distributive justice principles as they are found in the literature [10–13].

5. For industry, this is cement, iron and steel, chemicals, aluminium, and pulp and paper; for transport it is aviation, maritime, rail, light vehicles, medium and heavy vehicles and two/three wheelers.
6. This category also includes the production of transport equipment, machinery, mining and quarrying, food and tobacco, wood and wood products, textile and leather, as well as miscellaneous sectors

Table 3: Sharing principles and underlying principles of distributive justice.

Allocation principles	Description	Underlying principle of distributive justice	Examples of application [14]
Equal per capita (EPC)	All individuals in the world have an equal right to emit GHGs. The individual carbon budget is the same for all.	Egalitarianism: All individuals should be equal in terms of, for example, welfare or resources.	N/A
Ability to pay, capability (AP)	Ability to pay allocates a larger share of the remaining budget to those who have fewer means, for instance by allocating a lower reduction target to a country with a low GDP. The individual carbon budget differs and favours poorer and less developed economies.	Prioritarianism: A benefit has a greater moral value the worse the situation of the individual to whom it accrues.	EU Effort Sharing Regulation
Final consumption expenditure (FCE)	The carbon budget is split by assigning individual shares which are proportional to the final consumption expenditure of an economy.	Utilitarianism: Maximising the sum of welfare should be the priority.	N/A
Grandfathering (GF)	The GHG budget is allocated and spread over time based on the status quo of emissions. Current high emitters also have relatively higher carbon budgets.	Acquired rights: No theoretical justification, as the share, is based on historical data on how large a share the system/country has previously acquired.	SBTi Absolute Contraction pproach, Sectoral Decarbonisation Approach

Implementing the allocation principles for the global carbon budget requires different levels of data and therefore also faces practical restrictions. For instance, to create sharing principles for a sector based on contribution to welfare, it is necessary to quantify the impact of the specific sector on welfare through available data. In general, a review of downscaling the planetary boundaries found that it appeared easier to assign shares on large scales, such as at country level or for industrial sectors, as larger scales require fewer normative decisions [11]. Setting more granular targets (e.g. at company or spatial planning level) requires more assumptions and notable efforts for data collection and quality assessment.

In practice, an allocation principle rarely stands alone as they are often applied together. An example is the most commonly applied sharing principle "equal per capita" (EPC) to scale down to country or individual level and then combined with utilitarian principles for sharing among industrial units [11]. Utilitarian sharing principles are based on currencies reflecting welfare such as economic value, contribution to happiness, or fulfilment of human needs. The share is then distributed according to the systems' contribution to utility compared to other systems. There are no commonly agreed standards for allocation, and thus it is a question of what is practically possible and ethically reasonable. A study investigated an annual carbon benchmark per m2 dwelling and applied six different allocation principles [15]. The study showed that applying different allocation principles affected the result by a factor of up to 6.2. This highlights the importance of the decision on the allocation principle and the potential ethical implications of such a decision.

Box 1 below describes the process of setting national GHG emissions reduction targets in the EU, including the allocation principles used for the division of reduction efforts between the Member States. In continuation of the work in work package 1 of this project, the same countries have been included in this overview.

Box 1: How national carbon budgets and targets work in the EU, and what they do to establish a sufficient basis for setting embodied carbon budgets and targets

The political context of allocation principles is dominated by considerations about capabilities and grandfathering. At international level, the allocation of efforts for reducing GHG emissions follows a categorisation of countries into developed, developing, and least developed countries along with their economic performance (e.g. measured in GDP per capita). This approach is referred to as "common but differentiated responsibilities" [16]. Developed countries with high economic development based on past GHG emissions should lead efforts to combat climate change. This principle paved the way for the Kyoto Protocol, in which only developed countries were obliged to reduce emissions, and is still reflected in the Paris Agreement (Articles 2 and 4). This is, however, not translated into specific pathways, carbon budgets or similar, as the contributions are self-determined.

The clearest example of allocating emissions reduction targets to a group of entities is the European Union with its Effort Sharing Regulation (Regulation (EU) 2018/842, abbreviated to ESR). The EU has been setting increasingly ambitious political targets for the reduction of emissions since 2009. As the EU has some, albeit only limited, legislative competence to regulate emitting activities in its member countries, it "distributes" the achievement of the target to the Member States and certain industrial sectors.

In response to increasing scientific understanding of the urgency of climate action, the EU has committed to a target of reducing GHG emissions by 55% by 2030 compared to 1990. This has been transcribed in the EU Climate Law and also submitted as the EU's Nationally Determined Contribution (NDC) to the UNFCCC in compliance with the Paris Agreement. The long-term objective is to reach climate neutrality for the EU by 2050 [17].

The general increase in ambition for this target was defined by the European Commission in the European Green Deal [17]. It was a result of the long-term climate neutrality commitment for 2050 that was set in response to the findings communicated in the IPCC Special Report published in 2018 [18]. To present a pathway that underlines the leading ambition of the EU, the intermediate reduction target of 55% was set after assessing the potential contributions of and impacts on society and the economy [19].

Different policy measures are put in place to achieve the necessary reductions. The measure of primary relevance to the allocation of reduction targets is the ESR. It sets the levels of national targets for the EU Member States to contribute to the overall EU target. The national targets are measured in relation to 2005 emissions levels in the EU Member States. The version of the ESR currently in force still reflects the previous level of ambition of a 40% reduction at EU level. In line with this, the Member State targets vary between reductions of 0% (Bulgaria) and 40% (Luxembourg). With the recent agreement to increase the EU target to 55%, and a proposal for a revised ESR published as part of the Fit-for-55 package, the Member State targets will also be increased. Table 3 shows the current and proposed future targets for the five countries covered in the project. These reduction targets are part of the NDCs for the EU countries as submitted in response to the Paris Agreement by the EU Commission. Further GHG reduction measures such as the EU Emissions Trading System (EU ETS) further contribute to the NDCs.

Table 4: National reduction targets for selected EU Member States by 2030

National reduction targets in accordance with the proposed revision of the Effort Sharing Regulation (COM(2021) 555 final).	
Denmark	50%
Finland	50%
Netherlands	48%
Belgium	47%
France	47.5%
For comparison	
EU	55% NB: This target encompasses all types of GHG emission sources, including those addressed by the EU, in particular through the EU Emissions Trading System (ETS), which are not part of a country's ESR reduction target. For this reason, EU reduction targets are higher than those for Member States under the ESR.

The EU also, to a large extent, bases the sharing of GHG emissions reduction efforts on the economic ability of Member States, by allocating efforts according to GDP per capita. The considerations of fairness and cost effectiveness have been key principles in the decision to set national targets. The impact assessment [20] of different options to distribute the targets describes the process and parameters in detail. Fairness reflects the economic development and abilities of Member States. Countries with low GDP per capita are allocated substantially smaller reduction targets than so-called rich Member States. Considerations of cost effectiveness are then applied to the group of rich Member States, taking the cost impacts of policies in the reduction curve of those countries into account.

In relation to embodied carbon, it is very important to understand that countries typically report on territorial emissions also sometimes referred to as production-based emissions. Territorial emissions account for activities within the country's borders, thus omitting all imported materials consumed by the country's activities. Research from **the UK** Green Building Council (UK GBC) shows that, of UK Manufacturing and Construction, 30% were related to non-territorial emissions, revealing a significant proportion of emissions coming from imported materials [21]. For the EU, with a large and diverse economy, this share may be lower. However, with high global interconnection, imports of steel, for example, still make up 20–25% of EU consumption [22]. Notable parts of embodied emissions are not therefore included in EU emissions inventories and are not addressed by the EU and national reduction targets.

3. What characteristics shape targets for embodied carbon?

Defining a relevant approach to target setting for the reduction of embodied emissions in the building sector has to reflect the characteristics of these emissions and the industry context. Applying the methods and defining the elements described above (budget, pathway and allocation principles) must address the characteristics and overcome the challenges of aligning the challenges with existing accounting practices. Chapter 3 will describe the approach of current target-setting initiatives that can be used to inspire budget-based targets for embodied carbon in buildings.

This chapter describes key considerations that must be addressed for developing budget-based targets for embodied carbon in buildings, which have been at the core of the concept presented in Chapter 4. The characteristics relate to the multiple sources of embodied emissions, the multiple market actors that share responsibility for the amount of embodied carbon, and the limited applicability of existing emissions accounting principles to embodied carbon.

3.1 Embodied carbon is cross-sectoral and international

The emissions that constitute embodied emissions in a building's life cycle cut across several sectors [12,23]. Construction materials in the production of steel, concrete, glass, etc. would belong to the industry sector, transport of these materials to the transport sector and construction energy to the energy sector, etc. Thus, mitigating the environmental impacts related to embodied emissions cannot be linked directly to one of the sectors normally used in national emissions inventories or future emissions scenarios. Furthermore, existing policy targets like the ones mentioned in Box 1 do not cover embodied carbon in any specific sector. Rather, parts of the mentioned sectors would have to be combined. In many cases, inventories and scenarios include a sector referred to as "buildings". This category, however, describes the emissions generated during the use of the building through fuel consumption, heating, cooling or electricity. **From a building perspective, it is nonetheless important to also address the embodied emissions, as it is the responsibility of the developer or building owner to increase demand for a more sustainable design in terms of materials and the square metres needed.** Leaving the issue of decarbonising embodied impacts to the material industry would fail to address demand.

Additionally, with embodied carbon largely stemming from emission sources upstream in the supply chain, i.e. caused by the production of materials that are used in the construction project, the reporting boundaries for emissions become highly important. Key materials such as steel or cement can be produced in different locations around the globe and transported to the construction site. This may result in different levels of embodied emissions, due to varying efficiency levels in the plants and energy sources used. Most importantly, however, the national carbon inventories and reduction targets do not account for emissions caused by the production of imported goods. This distinction is often referred to as reduction targets for territorial emissions. The target formulated in the EU policy framework, for instance, includes only GHGs emitted within the EU's borders. The extent of the issue of course depends on how much each country imports, but an example from the UK found that 30-40% of embodied emissions from construction relate to non-territorial emissions, i.e. production materials and products produced in other countries and imported to the UK [24].

In the context of highly globalised supply chains, cross-sectoral and international value chains represent a challenge when setting targets for the construction sector, companies, or building projects [21]. National carbon emissions inventories and targets do not include the full scope of emissions that a company or the sector must report on as soon as imported materials are used. The territorial targets in particular become inconsistent as a reference for companies with multiple building development projects in multiple countries, as the origin of all materials would have to be reflected and accounted for separately.

Therefore, targets for embodied carbon need to be based on a carbon budget that is consumption-based and includes the entire value chain. This can be achieved either by defining a global budget for embodied carbon or by assigning parts of national budgets to embodied carbon, which by definition include the emissions of the material value chain. This second concept will be presented and applied in Chapter 4.

3.2 Embodied carbon is determined by multiple actors in a building's value chain

In addition to the multiple origins of embodied emissions, the process of planning a building and taking decisions that determine the level of embodied carbon involves multiple actors [12,23]. These actors all have different levels of influence, depending on the set-up of a specific construction project and also encounter different types of reporting when it comes to carbon emissions, including embodied carbon. The relevant features of such reports include the type of building (e.g. residential, office space, warehouses), size (from small units to high-rise or large-area complexes), development approaches, ownership and occupation (e.g. owner-occupied or tenant-occupied). These all result in different considerations regarding the importance of embodied carbon.

Decision on the factors that determine embodied carbon, ownership of a building and use may involve multiple actors, each with different priorities[7]. A balance between these has to be struck when setting a reduction target. While embodied carbon represents some specificities, lessons from existing initiatives on corporate targets and the operational emissions of buildings can be learned. Such initiatives are presented in Chapter 3.

In addition to these considerations, policymakers determine some elements of embodied carbon as well. Building codes and local planning regulations may require certain design features or material characteristics, while spatial planning impacts the amount and type of development possible in a municipality. During permitting procedures for construction processes, these parameters are assessed and requirements for building design or use can be made. The result is a complex network of actors that shape the levels of embodied carbon at building level and in a municipality or governance structure [12,23].

This means that the optimal target addresses the demand side, with a target for a specific product unit like a square metre that can be scaled to a building, neighbourhood or owner. This signalling principle would then be passed on to the rest of the construction value chain to speed up the transition.

3.3 Existing emissions accounting principles are not designed to support embodied carbon targets

Carbon emissions can be calculated and reported in different ways, for which international standards have been developed. Corporate emissions accounting is one such way and is undertaken widely according to the GHG Protocol. At the level of a specific product like a building, LCAs are used to quantify, compare and report on emissions. However, both of these accounting approaches are designed for other purposes than setting budget-based targets for embodied emissions.

The GHG Protocol establishes a globally standardised framework to measure and manage greenhouse gas emissions at a corporate or organisational level, as well as for countries and cities. The purpose of the developed standards is to enable organisations to understand the sources of their emissions, create a comparable emissions reporting structure and allow for the tracking of corporate emissions reduction targets.

The framework defines three scopes: scope 1 emissions are direct emissions that are owned and controlled by the country, city, or company; scope 2 includes indirect upstream emissions arising from purchased energy, while scope 3 refers to other indirect emissions upstream and downstream, for which the company, country or city is responsible through its activities, but whose sources are not controlled by the company, city or country [25,26].

7. For example, an investor may develop a building with the support of building design professionals (e.g. architects and engineers) in order to later sell the property – or parts thereof. The new owner may still not be the occupant, in which case the property is rented out. The level of embodied carbon in such a case would be determined by the expectations of the developer (initial investor) and formulated by the architect and engineers. However, ownership and control over the asset would later be in the hands of other actors. In contrast, a company or an individual may decide to develop a new building for their own use. In this case, the chain of actors is substantially shorter (building designers will likely still be involved) and the decision over embodied emissions and subsequent ownership and use fall into the same hands.

As a challenge for the establishment of budget-based targets, the accounting of scope 3 emissions under the GHG Protocol is difficult to link with a specific budget, as it counts emissions generated by other actors. In the case of embodied carbon, the production of materials like steel, cement or glass would generally not be undertaken by the developer, builder or final owner of the building. Rather, the construction material industries would see the emissions in their direct GHG accounts, while for all the actors in the decision and planning process of a building, these emissions fall within scope 3. This is the case for all the actors previously described, who in almost all cases do not produce the materials that are the most significant sources of embodied emissions. A specific calculation of the global carbon budget for buildings, and within that for embodied emissions, would be needed to enable the use of the existing reporting data.

Additionally, the method of continuous (usually annual) emissions accounting means that recurring emissions from processes can be captured successfully. However, embodied emissions associated with the building occur at a specific time during production and construction, as well as maintenance and replacements, and finally during disposal of materials at the end-of-life (EoL) stage. On average, 64% of the embodied emissions occur at production and construction, 22% during use, and 14% at EoL [27]. Thus, emission peaks can be misleading if they are either misunderstood as re-occurring emissions and their magnitude will be overly emphasised, or even overlooked if the peak is lost among several yearly reports. One solution that could be considered is depreciating the emissions of the asset (building) over its life span by reporting annualised emissions values, as this is the current standard today. However, this approach falls short of capturing the reduction of the carbon budget during the time the building materials are produced. The result would be an increased likelihood of overshooting the budget.

Thus, because of these different purposes, reporting according to the GHG Protocol does not specifically support setting budget-based reduction targets for the building sector. This therefore becomes a challenge, as there is a risk of not incentivising decision makers to demand low carbon solutions if they fall within scope 3.

Basing such targets on building-specific emissions data could instead be achieved through the LCA of its materials and construction processes. However, using LCAs as a basis for a top-down target setting creates a different set of challenges. Similar to emissions reporting under the GHG Protocol, LCAs serve a purpose that differs from the intention to set reduction targets. An LCA enables comparison between products such as buildings based on the function or purpose they are fulfilling. LCAs are conducted according to a standard [28–30] and the same assumptions and rules are applied to both systems to enable comparison. An example of an assumption could be applying a reference study period of 50 years for all buildings. Although this may seem like a simplification, it is necessary for practical reasons, to make the task of conducting the LCA feasible within data limitations and nonetheless consistent across the different items of comparison. Using simplifications and assumptions for these items is useful for comparability purposes but reduces the ability to measure emissions reductions over time. When conducting building LCAs, the upfront emissions (A1-A5) are based on what actually happens today, whereas the rest of the buildings' life cycle is based on standard assumptions regarding life span, replacements and waste handling. These assumptions are reasonable to use for comparability, but do not necessarily reflect a realistic scenario and cannot for that reason be compared to a global carbon budget.

Unlike standardised products for high-volume consumption, most buildings are designed individually and have specific purposes and features. Thus, setting targets for embodied emissions in line with the global carbon budget requires specific methods that can capture the wide variety of buildings and the characteristics of the industry and value chain. **Because of this unique feature, more specificity for embodied carbon is needed to define the relevant carbon budget for embodied carbon, and the part a newly constructed building plays in it.**

The budget therefore needs to reflect the specificities of emissions related to the life cycle stages included, and to clarify whether new buildings, renovations or both are addressed in the budget and therefore the target. The work in this project concentrated exclusively on the new construction of buildings. This is reflected in the concept for target setting outlined in Chapter 4, which also focused on upfront embodied carbon from material production to construction (stages covered in modules A1-A5 of a building life cycle).

4. What initiatives exist for setting budget-based targets?

Various initiatives have had the objective of enabling organisations and sectors to understand the urgency and implications of climate change. The relevance and applicability of their approaches for embodied emissions in buildings will be analysed in this chapter. The Science-based Targets initiative (SBTi) provides guidance to entities from all sectors on setting GHG reduction targets in line with scientifically determined needs. The Carbon Risk Real Estate Monitor (CRREM) translates the necessary reductions in operational emissions into financial risks for buildings and real estate management. Additionally, the method used by the UK Green Building Council (UKGBC), which quantifies carbon budgets and reduction targets, will be presented, as it undertakes a different approach to determining future targets.

4.1 Corporate target approach by the SBTi

Science-based targets are a widely known approach to setting top-down targets based on external climate factors. The Science-Based Target Initiative (SBTi) develops standards, criteria and guidelines to achieve widespread and harmonised use of such targets. The initiative was created in 2015 through a collaboration between not-for-profit organisations as a response to the Paris Agreement.

The SBTi approach is aimed at individual entities, mainly businesses, that seek to commit to reducing their GHG emissions in line with the calculated need for reduction. The target is defined by the organisation and is based on a scientifically established need for reduction. Alignment is then checked by the SBTi and the target is approved. The vision behind the SBTi's approach is to enable all organisations to reduce GHG emissions. The organisational reductions are focused on emissions in scope 1 and 2, as organisations are considered to have the most influence on these. In this philosophy, scope 3 emissions have less ambitious requirements and offer more leeway to organisations, even though it is acknowledged that such indirect emissions can often be the largest contributor [31].

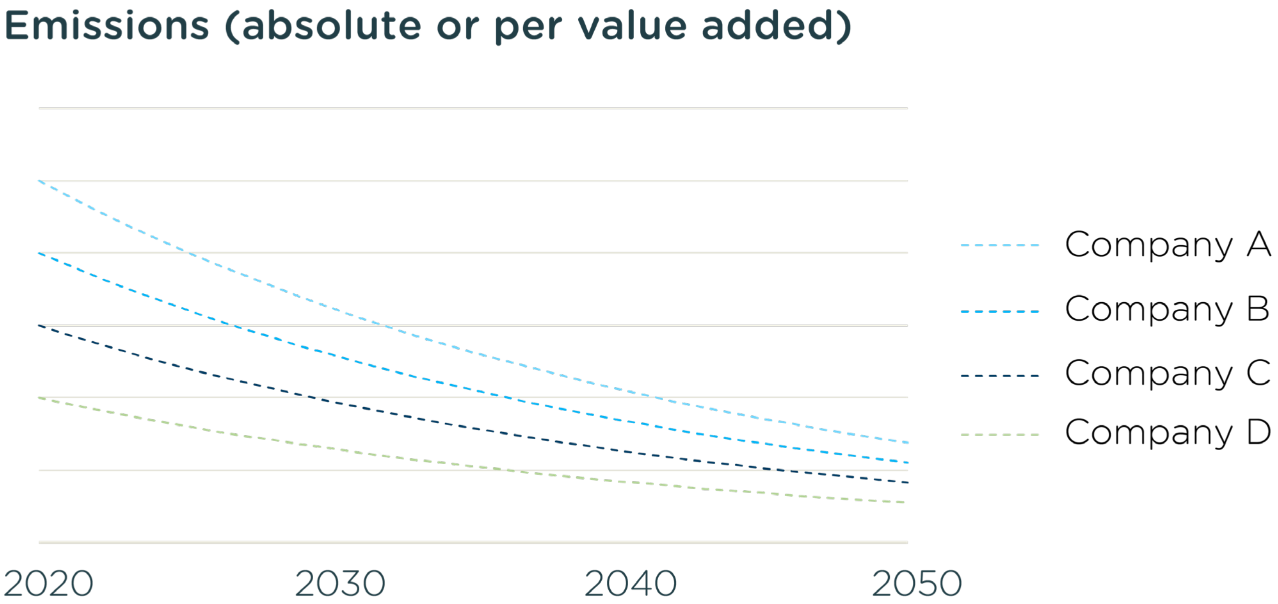
The need for reduction is determined according to three main elements, which constitute the science basis for setting the targets:

- A carbon budget defined by the IPCC (see Section 1.1)
- Scenarios on future emissions, developed by the IEA (see Section 1.2)
- An allocation approach to determining the reduction pathway of future emissions towards a target. This is connected to the allocation principles discussed in Section 1.3 but differs in the considerations it takes into account.

While the carbon budget and the emissions scenario are parameters set externally, the allocation approach determines the reduction contribution with targets and pathways for a specific organisation depending on the global warming target that is selected. Two main strands of allocation approaches are provided as options by the SBTi.

The first strand of allocation options is a contraction: a target for reducing GHG emissions that is set based on the specific emissions of the organisation and without resulting in an associated carbon emissions intensity for the sector. The contraction can be defined in terms of absolute emissions or emissions intensity per unit of value added. A graphical illustration of the emissions pathways of several organisations is presented in Figure 4.

Figure 4: Illustration of emissions reduction targets for four companies using contraction approaches.



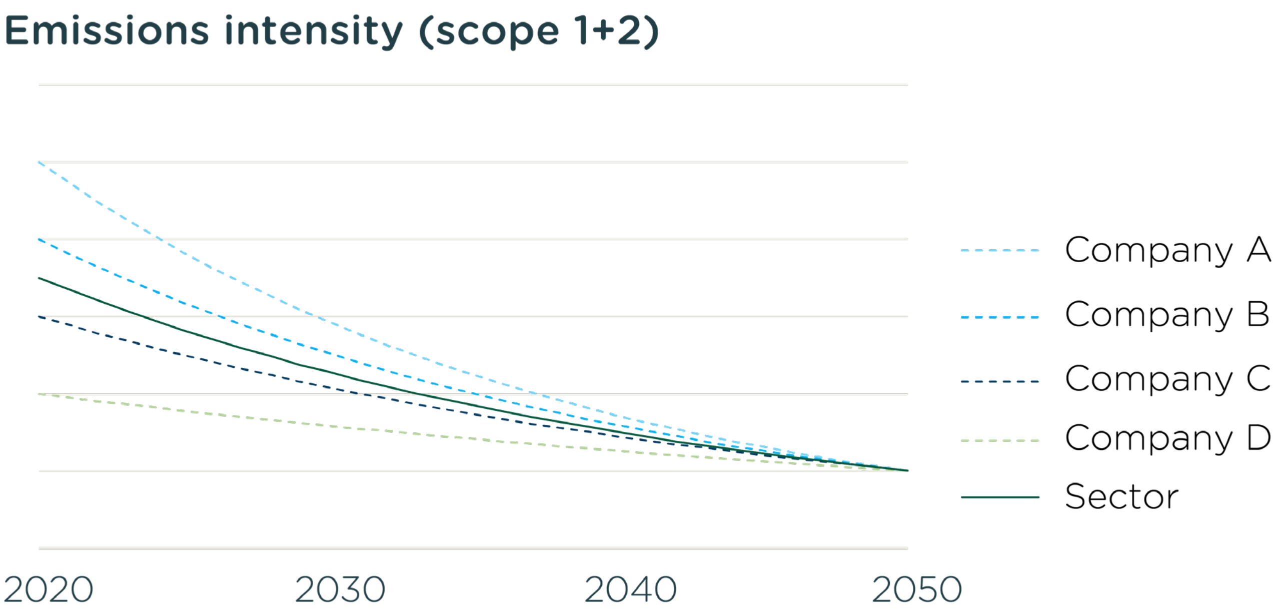
The reduction of absolute emissions is called the absolute contraction approach (ACA) and represents the least data-intensive allocation approach. Only company-specific parameters such as corporate GHG accounting are needed for a recent base year together with a target year, for which the target can be calculated according to the relevant budget and scenario from the previous steps. This results in a reduction pathway for the organisation with the same year-on-year reduction. A target under this approach has to be a minimum of 4.2% annual reductions for scopes 1 and 2 to be aligned with the 1.5°C goal.

The reduction of emissions per unit of value added is determined according to the approach called Greenhouse Gas Emissions per Value Added (GEVA). Here, the emissions intensity of the economic activities is the metric for expressing the target. This approach requires information on the value added in the base year and projections about its development up to the target year. As the relative level of ambition also depends on the economic development of a sector that is not reflected in the target, this method is considered less robust than others and considered applicable primarily to scope 3 emissions.

The second strand of allocation options is convergence. In this method, the emissions of an organisation are placed in the context of the emissions intensity of the respective sector, the so-called Sectoral Decarbonisation Approach (SDA). As a result, the emissions intensity is supposed to converge at one global level that is aligned with the long-term limiting of global warming. This is illustrated in Figure 5 below and is applicable to scope 1 and 2 emissions. To calculate this convergence target and the contributions of specific organisations, more input data is needed, including for the sector as a whole – at present and in the future. This approach is suited to homogenous sectors with common output metrics and relatively transparent output quantities. First, this is shaped by the need for a sectoral scenario, as in the IEA Energy Technology Perspectives. Second, all organisations in the sector should be able to agree on a common physical metric per which the emission intensity is measured. If these features are in place, the SDA provides valuable benchmarks for a sector to establish science-based emissions intensity, and to provide guidance for all companies in that sector in respect to their scope 1 and 2 emissions.

Setting targets following the SBTi methods includes specific normative assumptions. Firstly, even though the term allocation approach used by the SBTi is similar to the concept of allocation principles described in Section 1.3, the SBTi target methods do not consider ethical parameters in the allocation of the carbon budget across the users of carbon. The allocation principle used in the ACA is based on the current levels of emissions, benefitting high-emitting organisations. This principle is referred to as grandfathering in Section 1.3. The SDA considers the current level of emissions and reflects this in the relative contribution, but also does not differentiate between the state of economies. As such, it fails to recognise the common but differentiated responsibilities between nations depending on their historic emissions and current development status [14,23].

Figure 5: Illustration of emissions reduction targets for four companies using a convergence approach such as SDA.



Secondly, it has to be kept in mind that the resulting target of all approaches is the "fair share" contribution that assumes all companies would do the same, specifically for scope 1 and 2 emissions. In this case, the sum of all targets being reached would result in a global emissions level that respects the global warming target. Keeping within the global budget is only possible if all companies commit and reduce, otherwise, reductions by certain companies may be countered by increased emissions from others. If the range of companies that commits to targets remains limited, an overshoot of the emission budget would be the likely result.

As a result of the discussion in Chapter 2, an approach and target metric would have to be targeted to an actor in order to be relevant. Given the influential role of investors in developing large-scale construction projects and the increasing requirements to report on the non-financial impacts of their investments and assets, setting targets for institutional investors could be a relevant path for embodied carbon targets. Considering the high quantity of scope 3 emissions from purchased materials in construction, a focus on scope 1 and 2 emissions in the target neglects the importance of development decisions on overall emissions, which fall within scope 3 of the building project. The argument of the companies having less control over the scope 3 emissions does not apply to buildings, as there are multiple design and construction techniques that offer strategies for mitigating these emissions, including a priority for renovation or notions of sufficiency in spatial planning. Moreover, given the importance of scope 3 emissions for construction, it would clearly be inconsistent with national and global mitigation goals to fail to consider these [23].

Under the SBTi, target-setting methods have been developed for specific industries and types of actors, but they focus on emissions related to operational energy consumption. An SDA methodology exists for financial institutions, and this also includes real estate assets and investments [32], including scope 3 emissions from the investor's perspective. However, the criteria only require calculating emissions in scope 1 and 2 of the real estate assets and exclude embodied emissions, as they make up scope 3 emissions from the building's perspective. This existing method therefore has a different purpose and would need further refinement to create guidance on embodied emissions, too.

As highlighted before, the private sector will have difficulty staying within an emissions budget, even if targets are set at the level of developers. This is because achieving the necessary reductions also depends on other developers, some of which may not develop construction projects as their primary focus, but also construct new buildings for their own operations or use. Targets at the municipality planning level are therefore highly relevant, too. The Science-Based Target Network, a group of organisations closely linked to the SBTi, has developed a guide for GHG emissions reduction targets at city level [33]. However, the methods proposed in this guide also limit their scope to direct emissions that are included in an inventory of emissions sources located within the city's boundaries, with the result that this approach cannot be directly applied to embodied carbon either.

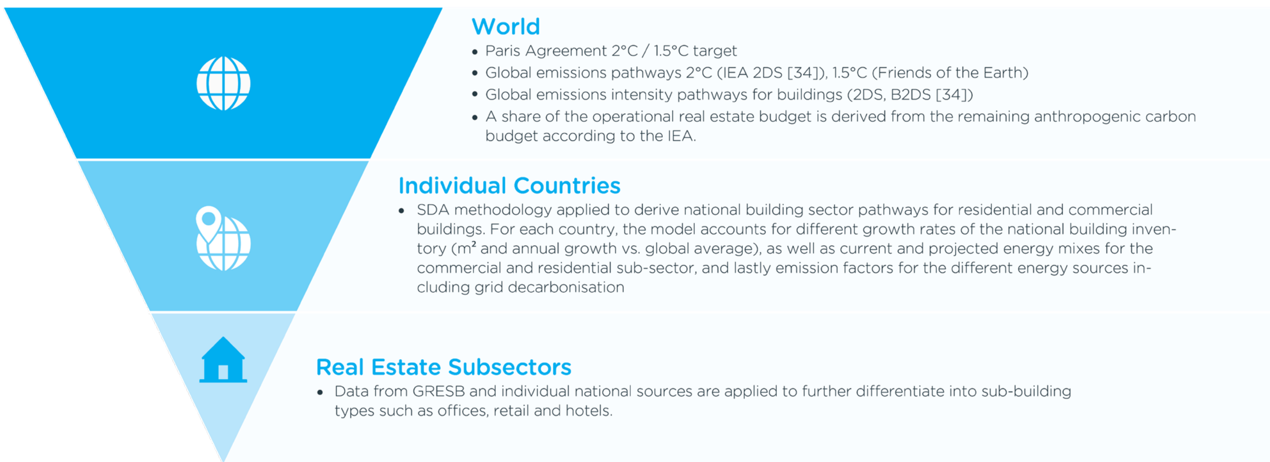
In conclusion, this is an approach that considers scope 3 emissions as secondary, falls short of the relevance of building development decisions on embodied emissions and the potential for savings from renovation, design and material choices. This underlines that a specific approach for target setting is needed for this type of emission.

4.2 Carbon risk approach for operational emissions for the real estate sector by CRREM

The Carbon Risk Real Estate Monitor (CRREM) has proven that a budget-based approach can be applied to a building perspective in relation to indirect emissions in scope 2. CRREM offers a tool for investors and property owners to estimate the risk and uncertainty associated with commercial real estate decarbonisation, with a focus on operational emissions related to a building's energy source and energy efficiency. To do so, CRREM has developed decarbonisation pathways (both in kWh and CO2e) that translate the ambitions of the Paris Agreement into pathways specific to countries and building types. The results enable investors with real estate portfolios to benchmark their real estate assets and use the pathways as proxies for "transition risk" that increase the chances of market obsolescence of an individual building, becoming a stranded asset. By illustrating the risk, the property owners are encouraged to renovate buildings to reduce operational energy use and/or switch their energy sources to renewables to stay below the decarbonisation targets.

"Paris-proof" pathways are established by downscaling from global mitigation pathways to property level, as illustrated in Figure 6.

Figure 6: CRREM pathways calculated by top-down downscaling



To scale down from global to building sector level, CRREM utilises the global emissions intensity pathways for buildings set by the IEA [34]. By applying the SDA at country level, the overall carbon intensity of each country's building sector converges gradually towards the global averages figure in the defined target year of 2050. All trajectories start at the actual emissions intensity of each country's building stock and converge around the same decarbonisation target. Pathways are calculated by taking country growth rates into account, which in practice means stricter target intensities for countries with larger floor area growth relative to the global floor area growth. Pathways for residential and commercial buildings are respectively based on the two baselines and the assumption of a constant ratio of carbon intensity for residential and commercial. Currently, CRREM covers the majority of global real estate markets – residential as well as commercial real estate. CRREM is aligned with other major initiatives such as SBTi, PCAF, and GRESB.

The initiative covers operational energy in buildings, but does not account for embodied carbon emitted in order to achieve the reduction in operational energy in the existing buildings. Through the SDA methodology, carbon intensity pathways converge around the global target (see Figure 5), which is suitable for tracking re-occurring emissions, such as operational carbon. However, it is not ideal for capturing peak emissions from new construction and renovations. Furthermore, the overall global target is based on the pathway for global buildings outlined by IEA, which only covers operational carbon and not embodied impacts in buildings. As previously described, embodied carbon is cross-sectoral and the IEA has no single pathway which describes the decarbonisation pathway needed for embodied carbon. Therefore, applying the approach developed by CRREM for embodied carbon is not currently possible.

4.3 National carbon budget for the built environment by the UK Green Building Council

The UKGBC released a pathway to net zero for whole-life carbon for the UK built environment in November 2021. The vision is to present “A Net Zero Scenario” with a calculated emissions budget and trajectory to 2050 for the UK built environment [21]. **The aim is to identify the role of the UK’s built environment in complying with the Paris Agreement. The initiative covers both embodied and operational carbon for buildings and infrastructure.**

The UKGBC refers to the Paris Agreement as the basis for the budget and follows the recommendations of the Climate Change Committee (CCC). The overall UK target recommended by the CCC is to reduce emissions by 78% by 2037 compared to 1990 levels. The CCC recommendations build on the NDC of a 68% reduction by 2030 compared to 1990 levels. In April 2021, the UK adopted the recommendation and made this legally binding.

Furthermore, the CCC sets out pathways for carbon reductions across sectors, and while some sectors need to decarbonise completely, Manufacturing and Construction are not projected to reach full decarbonisation but are left with some residual emissions, which will then need to be offset by GHG removals. Moreover, it should be noted that the CCC targets refer to territorial emissions, and imported materials are therefore not included. **In its report, the UKGBC acknowledges the large proportion of non-territorial emissions in the UK’s Manufacturing and Construction sector (c. 30%) and therefore reports on a consumption basis.**

Pathways are therefore calculated by identifying the lowest possible residual emissions by mapping historic emissions, identifying future demand and analysing mitigation potentials. To estimate the contribution from each activity, a comprehensive analysis including a multi-regional input-output (MRIO) model combined with an emissions model was used. The work involved mapping existing building stock, operational energy demand and the supply system, anticipated construction and renovation activities, while also identifying potentials from mitigation strategies within each area.

In the UKGBC report, GHG emissions reduction targets are set through a joint effort between all emitting activities: construction of new buildings, operational energy use, as well as renovation and maintenance of existing building stock. The result of the project reveals a trajectory for total GHG emissions for the built environment from 2018 to 2050. The total GHG emissions are shown as contributions from operational and embodied emissions from buildings (domestic and non-domestic) and infrastructure.

The trajectory is highly relevant as a roadmap for policymakers at national level, as it defines the necessary and possible contributions of the building sector as a whole, including specific targets for embodied emissions. Extensive efforts are needed to calculate and align the current activity levels of industrial sectors with elements of the embodied carbon and the climate change scenarios.

With a high level of aggregation, the trajectories do not, however, provide operational information for building developers and designers, because the trajectories do not give specific information at building level for embodied carbon. Specific targets on operational carbon at building level are, however, are provided. Rather, policymakers have to take the intermediate role of defining the measures for achieving the necessary reductions (e.g. targets for reduction through renovations, material efficiency, GHG targets for new buildings, etc.) for developers or investors, designers, and material manufacturers.

In summary, Table 5 presents the key characteristics of the target-setting approaches by the three initiatives.

Table 5: Summary comparison of existing target-setting initiatives

	SBTi	CRREM	UK GBC
Geography	Global	44 countries, with a focus on industrialised countries in Europe and North America	UK
Target group	Corporate and other organisations in all industries and sectors	Investors and property owners	All built environment stakeholders
Scope	All emissions, with a focus on scope 1 and 2 emissions according to the GHG Protocol	Building sector (operational energy)	UK built environment (infrastructure and operational and embodied impacts from buildings)
Trajectory	Depends on the selected method. Trajectories are generally based on Energy Technology Perspectives by the IEA	Global emissions intensity pathways for buildings set by the IEA	Climate Change Committee (CCC) trajectories for Manufacturing and Construction
Contribution to embodied carbon targets	Broadly recognised methodologies for corporate target setting with different emissions allocation principles Sectoral coverage, including material-producing industries and the financial sector as important building developers	Establishment of a carbon budget and Paris-aligned targets for indirect operational emissions addressed to building owners and developers Downscaling global emissions budgets for national targets	Creation of a national budget for the whole-life carbon emissions of buildings, including embodied emissions Input-output quantification of sectoral emissions contribution
Limitations in relation to embodied carbon targets	Priority is given to scope 1 and 2 emissions, where the influence of the target-setting actor is greater Embodied carbon not considered for financial institutions	Focus on operational emissions, as these create future carbon-related risks	Policy trajectories require further formulation for actors in the building value chain

The main requirement for such targets on embodied carbon would be a specific budget and trajectory that provide operational metrics to actors of building projects along the entire value chain. This specification can be undertaken at global or national level, depending on the targeted group of actors. The necessary steps to undertake will be outlined in the next chapter.

5. How can targets for embodied carbon in buildings be developed?

The previous chapters of this report have highlighted the ways in which embodied carbon in the building sector differs from other types of emissions, including operational emissions, that are often described in sectoral overviews of the building sector. The three initiatives presented in Chapter 3 pursue different purposes and approaches that each point to important features of the required elements for a budget-based target for embodied carbon in buildings.

This section presents a possible way forward for setting targets and discusses how the necessary elements can be developed. First, the lack of a science-based budget and trajectory for embodied carbon needs to be overcome. Second, these elements have to be applied at the relevant level in order to make them relevant and useful for policymakers, developers and building designers in specific geographical contexts. For this, exemplary calculations in the form of a proof of concept are undertaken for Denmark and Finland.

5.1 Develop a budget and emission reduction trajectory for embodied emissions based on the carbon budget

While the existing target-setting mechanism such as CRREM or the SBTi manual for financial institutions apply to operational emissions, specific methods and calculation tools need to be developed for the purpose of embodied emissions in buildings.

As discussed in this report, embodied emissions are a result of complex value chains, both in terms of products and in terms of decisions. Essentially, most buildings are unique in their size, material composition, intended use and ownership structure. Around the world, these features differ notably, as do the planning requirements and climatic conditions in which the building will be used. However, all building projects deplete the global carbon budget and therefore need to be aligned with the global carbon budget.

A Paris-aligned carbon budget and a decarbonisation trajectory for buildings that are aligned with this budget need to be established and must include specifications for the amount of embodied carbon emissions. This is a key challenge that needs to be overcome to enable setting budget-based targets for the reduction of embodied emissions from building projects.

A carbon budget serves as the basis for decarbonisation trajectories and also illustrates the climate impact of each building project or year of activity as the budget depletes. The First Report of this project has established a baseline of current levels of embodied carbon in building projects. Ensuring that global warming stays within the limits defined by political agreements and emphasised by scientific evidence necessitates a total amount of emissions that can be emitted this way. This has been highlighted in Chapter 1, by defining the carbon budget as a fundamental element of a reduction target that creates an adequate contribution to climate change mitigation.

A global trajectory for the decarbonisation of buildings that reflects the carbon budget serves as a reference point for the speed and extent of decarbonisation. As for other industrial sectors, the possible levels of GHG reduction and the necessary steps to take to limit global warming in line with the Paris Agreement need to be determined. There are existing reports on trajectories for the building sector or parts thereof. For example, the International Resource Panel has developed a climate trajectory for residential buildings [35]. However, agreement on a global emissions trajectory for the building sector and specifications for a broader range of building types is needed, to formulate a standard for the target setting. Ideally, such a scenario is aligned with the other trajectories and scenarios used in the methodologies for corporate bodies, municipalities, or countries. An established trajectory would then also enable effective communication of benchmarks as proposed in the third report of this series and the assessment of building projects over time against the remaining carbon budget.

This task will not be easy, as a highly heterogeneous sector would have to agree to the standards. In particular, the question can be raised of what effect the different demands and needs for buildings around the world have on embodied emissions, and how these differences may be reflected in the methodology. Nonetheless, considering the increasing urgency of reducing global emissions, this should be considered and is considered worthwhile by this study.

5.2 A concept for downscaling carbon budgets to national embodied emissions budgets

In the following section, a concept of how country-specific, top-down targets can be determined for embodied carbon in new buildings is presented. The concept of downscaling through sharing principles (allocation principles) is widely used in literature, and often follows the structure of scaling to a per capita budget, which is then translated to a national budget and then further down to a specific sector or activity [11]. At building level, there are also multiple examples of top-down targets for buildings [36–40], however, these still lack consensus around the global budget, sharing principles, the scope of life cycle stages included, etc. [12].

In this section, the concept of downscaling is presented step-by-step and the concept is then applied to Denmark and Finland as a proof of concept. Figure 7 illustrates the concept of downscaling from the global GHG budget to building level. The methodology can, in theory, be applied to any country with available data. The work presented in this study is based on a larger study on defining science-based targets for buildings. Thus, this section provides an extract of the approach used for downscaling, as well as the example applied to Denmark and Finland. Specific details can be retrieved in the planned publication of the larger study [41] or by contacting the authors of the study.

Figure 7: Downscaling from global budget to embodied carbon in buildings - a concept to set targets for embodied impacts in new buildings per m2.

The intended uses of the top-down targets are to enable developers and building designers to set ambitious climate targets for their new buildings, as well as to guide policymakers influencing legislation on GHG limit values and other measures to limit GHG emissions from construction.

The targets calculated in the proof of concept are consumption-based, thus include the imported materials consumed by the building. This is in line with how an LCA of a building is calculated. However, as previously mentioned, it is not in line with national budgets or NDCs declaring on a territorial basis.

1. Global budget and budget distribution

The global carbon budget depends on the level of temperature increase tolerated. The agreed limits in the Paris Agreement suggest 2°C, or preferably 1.5°C. The total budget (given in GHG emissions) is then distributed over the years by applying mitigation pathways calculated, for instance, in the IPCC report and which have been proven to keep warming below 2°C or 1.5°C by applying IAMs and climate models. The mitigation pathway used in this concept is based on the average of 13 Paris-aligned decarbonisation scenarios and expressed as net emissions [3]. The work of the referenced study is aligned with the IPCC Special Report [18] and the referenced article is produced by the same lead author as the chapter on mitigation pathways in the IPCC report. The pathways rely on net negative emissions from 2070 and comprise an average net total budget of 791Gt CO2eq over the 2020–2100 timeframe.

2. Defining a country share

The country share determines the budget for consumption-based emissions that the country can emit and should stay within. Determining the budget for a country can be based on EPC, allowing countries a share based on the population share relative to the global population. Other possible allocation principles take historical development and ability to reduce into account. This is applied, for example, by the EU Calculator [42], where it is possible to choose "capability". In the EU Calculator, applying capability means that, because the EU has an above-average GDP, the share of the budget is halved compared to an EPC distribution [43].

3. Defining a share for embodied impacts in buildings

The share for embodied impacts in buildings can also be determined in different ways, depending on the allocation principle applied. A grandfathering (GF) principle would base the share on historical emissions shares. In practice, this requires representative data from the respective country on the contribution of embodied emissions from materials relative to total emissions. Another example would be determining the share based on the direct and indirect contribution the buildings have on peoples' welfare, i.e. taking a utilitarian perspective. This requires estimating how construction affects peoples' welfare directly and indirectly. The method applied in this concept utilises a MRIO model of linking the global economy that considers flows between industries across supply chains. The method estimates direct and indirect contributions of the utility of the construction sector and was originally developed at DTU as part of a master's thesis [44].

4. Apply projections for future building activity

The budget share determined in steps "01-04" accounts for all construction activity. This means that if a country builds "x" new buildings in year "y", then the budget for embodied impacts in buildings in year "y" is divided among "x" buildings. Furthermore, the budget for embodied impacts in buildings needs to account for maintenance and renovation of the existing building stock. The projected future construction activity therefore needs to be mapped, to be able to create a budget for new buildings. For the proof of concept exemplary application for Denmark and Finland, construction activity is based on past construction trends from 2018 to 2020. However, it is acknowledged that realistic market projections could be beneficial to the accuracy of the targets.

5.3 Exemplary application of the concept for new construction in Denmark and Finland

The following graphics illustrate the process and results of applying this concept to Denmark and Finland. The countries selected are based on the availability of the data required to perform the downscaling. The procedure for downscaling presented in 4.2 requires country-specific data on population and construction activities, regarding both the amount of material that goes into new construction as well as the amount of new square metres. This data, especially the contribution of new construction, rather than the construction sector as a whole, has proved challenging to collect.

Budget-based targets for upfront embodied carbon

Downscaling global climate targets to embodied carbon of new buildings

01 Global GHG budget is identified and distributed over the years

The global budget was defined as the average of mitigation scenarios consistent with the 1.5OC target [3]. The work of the referenced article is in line with the work of the IPCC Special Report [18].

02 Defining a **country share**

To define a country budget, equal per capita (EPC) was applied, accounting for future population projections by the UN [48]

03 Defining a share for **embodied impacts** in buildings

The allocation to embodied impacts in buildings were based on two principles:

1. A grandfathering principle (GF)
2. A utilitarian (U) principle considering the utility the construction industry in Finland provides to people.

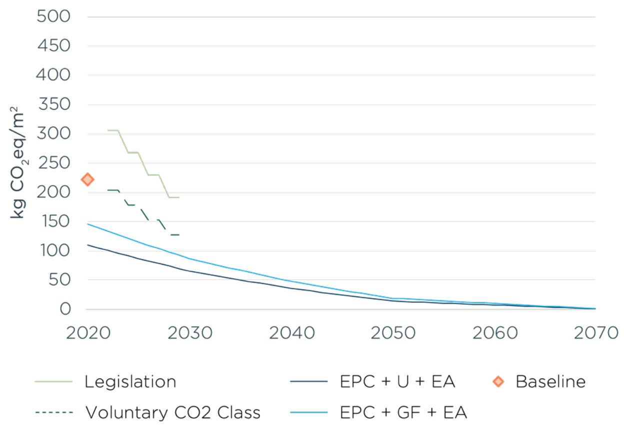
04 Apply projections for **future activities of the building stock**

To estimate the activity level of new buildings, maintenance and renovation, the study assumed status quo in construction activity, applying past construction trends from 2018 to 2020 [47]. For the distribution between activities, economic activity (EA) was used.

Budget-based targets for upfront embodied carbon emissions in Denmark

Figure 1: Budget for upfront embodied GHG emissions in Denmark.

GHG budget for upfront emissions per M2 of new buildings



To enable comparison between the national strategy and the calculated values of this study, the average contribution of upfront emissions according to a Danish study of 60 cases was applied [45].

The following numbers represent the targets for upfront embodied GHG emissions in Denmark in line with the established carbon budget.

[kgCO2eq/ m2]	2020	2030	2040	2050
GHG Budget (EPC+GF+EA)	146	88	48	19
GHG Budget (EPC+U+EA)	110	66	36	15

In 2021, a national strategy was proposed for new buildings in Denmark. The strategy consists of limit values for legislation and “a voluntary sustainability class”. Under the assumption presented, this study indicates that in 2023 the limit values of the legislation will exceed the carbon budget by between double and triple the amount, depending on the allocation principles applied.

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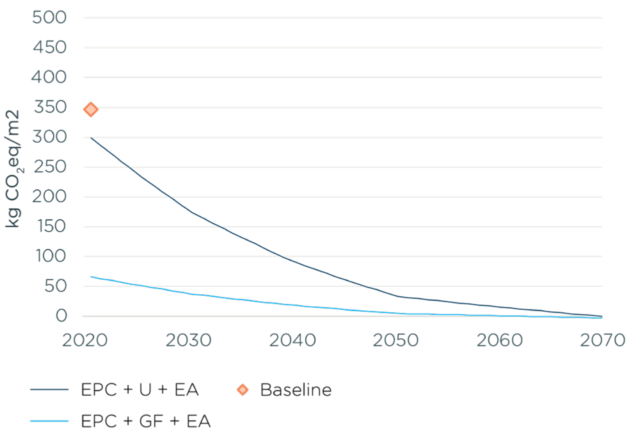
Budget-based targets for upfront embodied carbon emissions in Finland

Figure 1: Budget for upfront embodied GHG emissions in Finland.

GHG budget for upfront emissions per M2 of new buildings



The following numbers represent the targets for upfront embodied GHG emissions in Finland in line with the established carbon budget for the two sharing principles presented.

[kgCO2eq/m2]	2020	2030	2040	2050
GHG Budget (EPC+GF+EA)	288	168	89	35
GHG Budget (EPC+U+EA)	67	39	21	8

The proof of concept for the Danish and Finnish building sector outlines pathways for targets for up-front embodied emissions for the construction of new buildings. The calculated targets are the results of a downscaling procedure that first applies EPC to get a national budget and then assigns a share of the national budget to the construction sector by applying either the relative share of GHG emissions to total emissions (GF) or the results of an MRIO model, estimating the construction sector's direct and indirect contribution to the global economy (U). Lastly, the downscaling procedure applies past construction trends to estimate the budget for the construction of one new m2.

Differences in the budgets for the two countries can be observed and explained. As a result of the proposed downscaling procedure, the GHG budget depends on the population size as well as construction activity within the country. For Finland, the result is a lower budget per m2 than the Danish budget when applying the utilitarian principle. This is because the input-output (IO) model reveals that overall spending on the Danish construction sector relative to other industry sectors was higher than that in Finland. By using an IO model, a country's total GHG budget is distributed to the construction sector according to the money spent in that sector relative to other sectors, which is thus a proxy for prioritising what contributes to welfare within each country. Furthermore, the Finnish population is slightly smaller than the Danish, whereas the amount of new square metres built every year is almost the same for the two countries. When applying the grandfathering principle, Finland receives the largest budget per m2; this is because the GHG contribution from the Finnish construction sector relative to Finland's total consumption-based emissions is higher than that of Denmark.

Comparing the targets with the baselines calculated for Denmark and Finland in the Baseline Report shows a performance gap. The targets for 2020 are already significantly lower than the baseline. This means that buildings today create embodied emissions that exceed the carbon budget resulting from the Paris Agreement. As this depletes the budget even more and faster, the target becomes more relevant and urgent.

Several limitations apply to the concept as presented here. These concern the choice of allocation principles, the lack of granularity regarding building types, as well as data availability.

- First, the proof of concept applied to Denmark and Finland relies on the **choices of allocation principles** applied. As the results show, different allocation principles will result in different GHG budgets. As highlighted earlier in this report, the application of allocation principles has so far been a matter of subjective opinion. Since there is no broad agreement on the principles of a fair allocation of emissions, the choice of principles requires justification and the results must be interpreted with the principle in mind. The choice for EPC, for instance, builds on an equal right for all humans. This avoids grandfathering in the global allocation step, but also falls short of accounting for historic inequalities. The differences in historic emissions and development statuses of the building sector around the world call for further research to introduce global equity into carbon budgets, particularly for a sector as essential to basic needs as housing. Given this limitation of the downscaling method, it is also important to acknowledge that there are multiple ways of applying allocation principles, and that this report exemplifies two possible methods for a sectoral allocation but acknowledges that the targets cannot be interpreted as objective final results. Thus, the method also comes with a risk of overshoot if every target-setting actor (e.g. national government, municipality, investor) chooses the allocation principle most beneficial for their case.
- Secondly, the proposed method does not allow for **granular budgets for specific building types**. The sectoral data comprises all building construction activity, without specifying the type of building (e.g. residential, non-residential). As these buildings have different requirements and use patterns, which again vary substantially between different types of non-residential buildings – more specific budget calculations and related targets could have benefits. Such advances should be considered and could be based on combinations of building stock models combined with material flow data for different building types. Bringing together the sectoral pathways for key building materials may be another alternative approach to calculating more specific budgets. However, these approaches need to consider that embodied carbon comprises a wider range of emissions than those of materials.

- Lastly, the method **relies on data** that has proved difficult to obtain in this project – especially data describing the proportion of activities that contribute to embodied impacts, i.e. renovation, maintenance, and new buildings were difficult to obtain. Therefore, the application of this approach needs to be preceded by ensuring that this data is available and accessible.

The results of this report need to be read with these limitations in mind. Another major limitation is future uncertainty. It is the purpose of this report to set targets per m2 for new buildings, however, as the overall goal is not to overshoot the total GHG budget, the targets per m2 depend on the number of m2 to be built. Likewise, will renovation and maintenance activities of the existing building stock also consume embodied carbon, and it could be argued that if renovation activity increases, the share for new buildings should be lower. For this proof of concept, status quo for construction activities, including the number of newly built square metres has been assumed. However, the method would greatly benefit from applying projections for future activities in the building stock.

5.4 Target audiences and metrics

Approaches to top-down target setting for buildings also require consideration of the target audience. In existing initiatives, different examples of the target audiences addressed are investors and other actors that commission and oversee construction projects for the SBTi, portfolio owners for CRREM, as well as policy recommendations for central and local governments by the UKGBC. In this proof of concept, an example has been developed of a budget-based target set at building level for a specific country.

From a real estate developer or investor perspective, budget-based targets inform the climate impacts of investment decisions in new assets. In a context of increasing awareness among stakeholders as well as requirements for non-financial disclosure, the closest possible alignment with the carbon budget becomes a highly relevant consideration. With assets often dispersed over different countries, a global budget and related pathways would be highly beneficial to defining the budget share of an investor, similar to the approach used by the SBTi.

From a policymaker's perspective, budget-based targets can be used to guide ambitions for a combined strategy for implementing GHG limit values in regulations, in combination with other measures to limit GHG emissions from embodied impacts in buildings. For this, a local budget is highly appropriate as it informs the overall reduction need from embodied carbon. The assessment of the proposed target approach for Denmark in comparison with existing Danish legislation makes it clear that either the impacts per m2 need to be substantially reduced or the total new construction activity will have to decline, which requires planning efforts at public levels. In the context of deciding on scenarios for the future building stock, it is therefore relevant to discuss mitigation strategies for the built environment. While there is a need to reduce impact per m2, it might also be necessary to build fewer new square metres than has been done in the past.

While targets meant to guide developers and building designers should reflect society as it is, targets for policymakers can reflect other measures which can be taken in addition to reducing the impact of embodied carbon per m2. These measures can be a vital element of efforts to reduce the overall climate impacts from buildings – existing as well as new construction. Here there is a need for a **discussion on the sufficiency and utilisation of the existing building stock**. This would involve discussions on utilising the existing building stock better, to avoid new construction. Examples could be to transform a vacant office building into residential use, to offer less living space per person, or to introduce flexible use of building space (for example, utilising school facilities for evening classes). Embedding these kinds of outcomes as results of policies should then be reflected in step 5 of the proposed concept, where projections for future activity in the building stock are applied. The target values for new construction would thus reflect the combined effort of optimising existing buildings as well as reduction targets for new buildings.

Lastly, it is important to keep in mind that, since the targets set in this report relate to a country perspective, they are not directly comparable to the accounting principle applied in the NDCs. This is because NDCs cover territorial emissions only, while the proposed concept for target setting in this project takes a consumption-based approach, to account for all emissions, including those from imported materials.

Combining the two levels of asset portfolios and the policy mix, the budgets and corresponding target pathways can be used to guide the level of ambition for the design of new buildings and have practical relevance for building designers. The budget pathway represents benchmarks for embodied carbon that are Paris-aligned and define the scientifically necessary need for decarbonisation. To enable operable and comparable targets for buildings across use types, the targets are given per m2. However, targets could also be set according to the purpose that it is fulfilling – kgCO2eq per full-time employee, per resident, etc., to incentivise designing efficient square metres. This has to be considered in a benchmarking system. A concept for such a system is developed and presented in report #4 “Bridging the performance gap”.

6. Conclusions and recommendations

6.1 Conclusions

Existing example initiatives by the SBTi, CRREM and the UKGBC have all developed approaches to climate targets in buildings. However, with the exception of the UKGBC, these have all focused on operational emissions. This is primarily the case because these emissions were considered more relevant in the past, can be measured more directly and, for those and other reasons, decarbonisation pathways have already been developed.

Furthermore, developing targets for embodied emission that are in line with the reduction needs as expressed in the global carbon budget is a complex exercise. This is due to the nature of embodied carbon as indirect emissions, the multitude of sources for the relevant actors, the shared responsibility between these actors, and difficulties in calculating embodied emissions accurately with common GHG accounting standards because of the different purposes of these standards.

However, with additional efforts to develop the elements necessary for budget-based targets, in particular a Paris-aligned decarbonisation trajectory, it is possible to set targets that reflect the available carbon budget. This paper demonstrates that a budget can be determined by applying allocation principles and current market trends. This, however, requires a line of normative assumptions on how the budget could be split and allocated to an activity.

By applying the proposed concept to Denmark and Finland, this paper finds that the budget-based target for embodied emissions is substantially lower than the baseline established in report #2 of this project "Setting the baseline" and lies far below current legislative targets (where existing). This result calls for increased action across the EU and beyond to focus attention on embodied carbon, determine Paris-aligned targets for these emissions and accelerate the decarbonisation of this sector.

Targets will have different audiences: developers and investors can use the targets to guide the level of ambition for the design of one new m2. The targets can be used to set Paris-aligned targets for upfront embodied GHG emissions in new construction projects and offer relevant information for building designers such as engineers and architects. **Policymakers** at local, national, or supranational levels can use the calculated targets to guide ambitions for a combined strategy in implementing GHG limit values in regulations, in combination with other measures to limit GHG emissions from embodied impacts in buildings. In the strategies, policies and local plans, consideration of the total embodied carbon per individual building project will also be needed to stay within the carbon budget.

As a consequence, multiple metrics will be needed as benchmarks for building design and to ensure that mitigation efforts are driven both by reducing the embodied carbon per m2 and by building fewer but more efficient building spaces per capita. This also calls for discussion on the current demand for new buildings and a need for rethinking how we meet society's needs with an increased focus on sufficiency through better utilisation of existing buildings as well as on the material side, applying reuse or recycling possibilities.

6.2 Recommendations

Setting budget-based targets for buildings' embodied carbon needs to become more common and be reflected in a benchmarking system. This need to close the gap between current and required levels of embodied carbon also calls for additional policy measures.

Targets per square metre are a relevant metric to enable investors, building design professionals and spatial planners to make decisions at building level that ensure staying within the global budget. This would reduce barriers for such actors and ensure a higher level of overall consistency with the global budget. This exercise could be undertaken by an internationally accepted body like the SBTi as part of its work to develop corporate targets in line with the Paris Agreement and the latest climate science.

Work is needed on the creation of the necessary data that would allow for allocating the carbon budget to industry sectors and thus to embodied carbon. Efforts should be undertaken to produce more granular data on construction activities in relation to different building types. In addition, future projections of construction activity scenarios are strongly recommended, to improve the accuracy of carbon budget pathways, reducing the need to frequently revise such pathways and ideally limiting budget overshoot. Similar to recommendations in the Baseline Report and the Benchmark Report, a combined effort is needed from public institutions such as statistical offices, building sector associations and observatories and academia, along with a common language and shared methodological foundations.

Further policy instruments such as a reduction in new construction rate or support for building materials with negative emissions should be considered. For this, additional metrics to define targets per capita may prove relevant to ensure staying within budget at local and regional spatial planning levels.

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Towards embodied carbon benchmarks for buildings in Europe

#4 Bridging the performance gap: A Performance framework

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Laudes Foundation

Towards embodied carbon benchmarks for buildings in Europe

#4 Bridging the performance gap: A Performance framework

Project name	Towards EU embodied carbon benchmarks for buildings
Date	March 2022
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Disclaimer

In this report, the widely used term 'embodied carbon' is applied. Herein it is considered synonymous with 'embodied GHG emissions'. The data and values presented in the following consider both CO_2 and non-CO_2 GHG emissions, the reference unit applied is kilogram CO_2e (equivalent) expressed per m², per capita, or m² and year, respectively.

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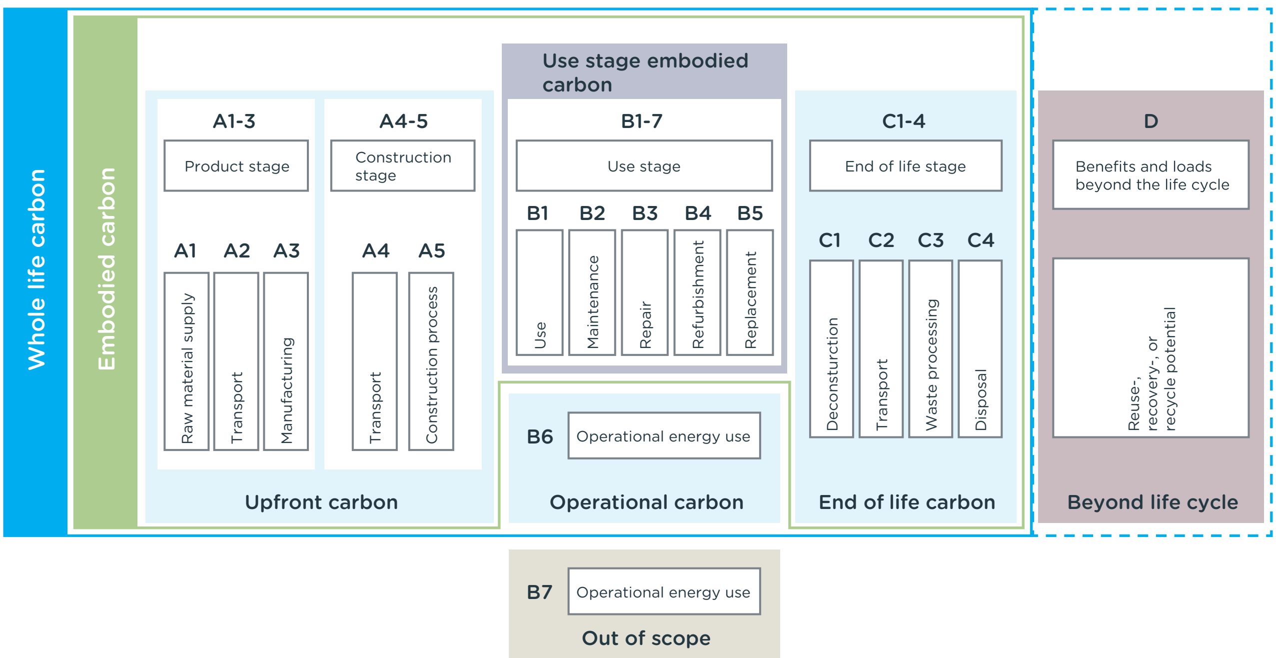
Executive summary

Rationale – Why is this important?

"Embodied carbon" consists of all the greenhouse gas (GHG) emissions associated with the construction products (materials, products, and building components and systems), construction processes, use and end of life of the whole life cycle of a building[1]. While past efforts have mostly focused on increasing energy efficiency in building operation, 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 products. The urgent state of climate change requires rapid action without any further delay.

The "Towards Embodied Carbon Benchmarks for buildings in Europe" project was set up by Ramboll and BUILD AAU - Aalborg University 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 particular, the focus lies on upfront embodied emissions which represent the largest share of embodied carbon and can be addressed at the design stage (Figure 1). In order to do so, the project explores the concept of embodied carbon baselines, targets and benchmarks for buildings in Europe.

Figure 1: Definition of whole life carbon based on the life cycle stages and modules from EN15978:2012



1. Embodied carbon therefore includes: material extraction, transport to manufacturer, manufacturing, transport to site, construction, maintenance, repair, replacement, refurbishment, deconstruction, transport to end-of-life facilities, processing, disposal.

To drive embodied carbon emissions reduction, a performance framework is needed. This performance framework is based on reference values built on a solid data foundation and combining the status quo with the embodied carbon levels required to limit global warming to 1.5oC. This report outlines how such a performance system could be created, what building blocks are needed and how the remaining gap between reality and climate necessity can be bridged.

Sustainability benchmarks for buildings – How do they work?

A benchmarking system defines reference values to measure and manage performance in relation to a key parameter: embodied carbon. In accordance with ISO 21678:2020, two types of reference systems are possible:

- Bottom-up benchmarks relate to the values of the existing level of embodied carbon based on an empirical dataset. Possible bottom-up reference values can, for instance, remain below the average for current buildings or not cause more emissions than the best-in-class buildings.
- Top-down benchmarks relate to values determined by external factors, such as the global carbon budget. The relevant top-down benchmark is to limit embodied emissions below the levels required by downscaled budgets for the building sector.

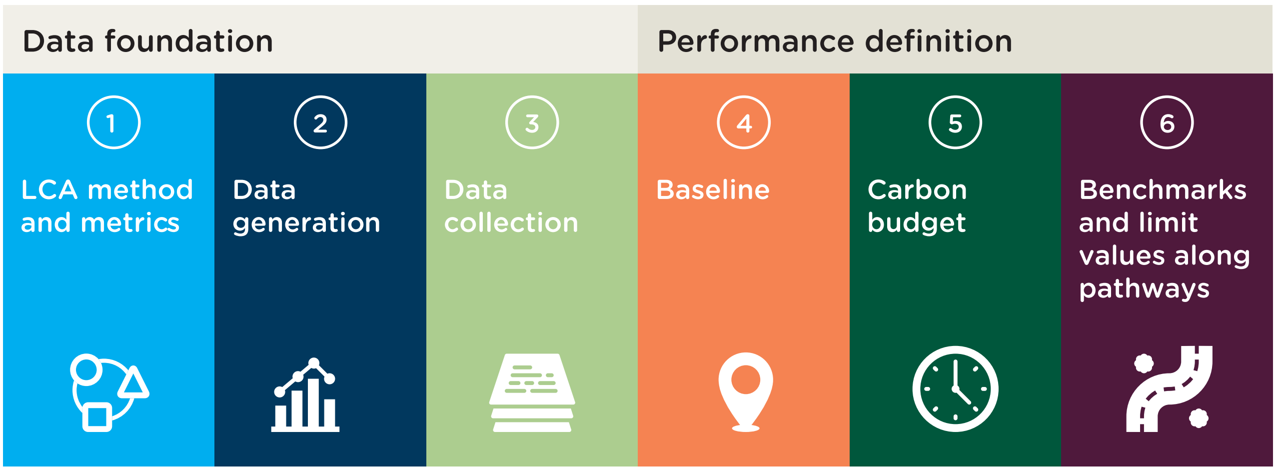
In existing sustainability performance systems, benchmarks for embodied carbon in buildings are rare. Only a few initiatives such as DGNB, BNB and national legislation in Denmark and France define reference values. These benchmarks are all based on bottom-up methods and relate to national building samples or a business-as-usual scenario for the building project.

The comparison of the baseline on embodied carbon in new buildings in five EU Member States (see report #2 “Setting the baseline”) and the calculation of a carbon budget and pathway (performed in report #3 “Defining budget-based targets”) reveal a gap between the reality of the building sector and the necessity of climate science. The embodied carbon performance gap **benchmarks are a useful tool for closing this gap gradually with efficient but ambitious reference values**.

A performance system – How can we close the embodied carbon performance gap?

A successful and efficient performance system for embodied carbon from new buildings needs to first build the data foundation on new constructions and subsequently set a framework consisting of a baseline, a carbon budget and decarbonisation pathways that translate into intermediate benchmarks or limit values.

Figure 2: Overview of the proposed benchmarking system



In detail, the elements of the performance system are the following:

Table 1: Elements of the performance system for embodied carbon

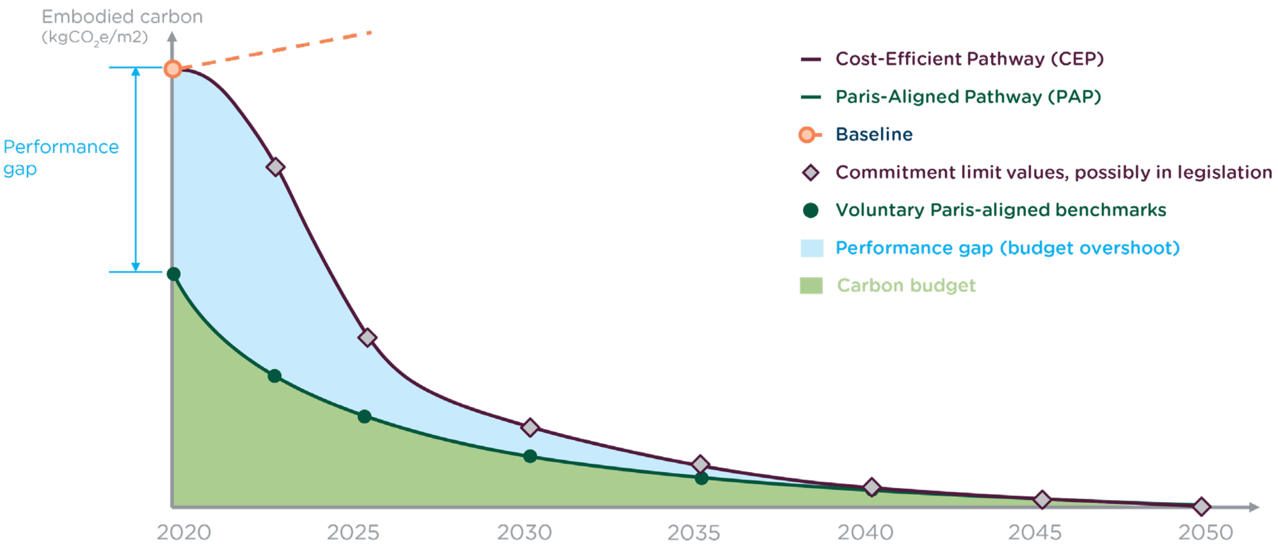
Performance system for embodied carbon	
Data foundation	
LCA method and metrics	• Nationally standardised LCA methods following the ISO and EN standards • Environmental data on building products and materials based on the EN standards. Data should be both industry and product specific. • Clearly defined parameters for the LCA calculations (including life-cycle scope, building elements, service life of buildings, handling of biogenic carbon and re-used and recycled materials.) • Reporting metrics (per m2 and per capita) • Includes extended documentation requirements, e.g. supported by the Level(s) framework or Digital Building Logbooks
Data generation	• Obligation or strong incentives to conduct LCAs for new buildings • Based on extended documentation requirements of contextual factors • Obtain a representative sample of new buildings for developing a baseline
Data collection in databases and software tool	• Centralised collection of LCA data for new buildings • Central database for calculating and comparing future buildings • Supported by a software tool for LCA calculations and data input • Aligned with a national LCA method • Open data available to stakeholders
Performance framework	
Baseline	• Baseline/reference value of status quo building practice • Calculated based on data collected in steps 1-3 • Expressed in embodied carbon levels per square metre and per capita • Updated regularly based on data on new buildings
Carbon budget	• Paris-aligned emission levels for embodied carbon • Calculated based on downscaled global budgets • Expressed in embodied carbon budgets per square metre and per capita • Representing target values for decarbonisation that should be reached as soon as possible • Updated regularly based on revisions of the global carbon budget and sectoral overshoot

Benchmarks and limit values along pathways	• Two sets of reference values along two pathways:
	  • Voluntary benchmark values in a Paris-Aligned Pathway (PAP) based on the carbon budget pathway
	  • Limit values in a Cost-Efficient Pathway (CEP) based on a shared commitment by the industry after consultation

The resulting performance framework is illustrated in Figure 2. The Cost-Efficient Pathway should be ambitious so as to minimise, as much as possible, the overshoot of embodied emissions over the budget limit. However, as this will not eliminate the overshoot completely, further considerations are required.

- Firstly, it highlights the **urgency in taking action** to reduce embodied emissions per built square metre. Any delay in starting the reduction will increase the overshoot and mean that the budget is depleted even faster, thus decreasing the likelihood of limiting global warming.
- Secondly, a **reduction in new construction activity** increases the budget available for new square meterage. Therefore, strong emphasis on renovating existing buildings and promoting sufficiency in building space use will reduce the budget overshoot.
- Thirdly, **carbon removals** created by removing carbon from the atmosphere and capturing it in building materials, for example in biogenic substances, may balance some of the emission overshoot in the future if the carbon can be captured at the end-of-life stage. However, this perspective comes with a high number of limitations, which means that relying on carbon removal can only be one supportive measure in a combination of actions to reduce the budget overshoot. Additionally, from a life cycle perspective, the carbon emissions associated with the end-of-life stage must be considered and might not result in negative emissions.

Figure 3: Embodied carbon performance framework



Call to action – What should we do?

Implementing this performance framework will require a combined effort from the whole value chain in the building industry, certification bodies, researchers, and policy makers. A national approach is suggested here, as many existing sustainability certification schemes are operating at the national level and some countries have already adopted legislation on whole life carbon emissions in buildings. However, the EU also has a highly relevant role in facilitating the harmonisation of calculation methods for LCA baselines and carbon budgets through instruments such as the Level(s) framework, as well as defining a European roadmap to steer the sector across the whole of the EU. The key responsibilities for actions in each step are summarised in Table 2.

Table 2: Call to action on combined effort for establishing a performance framework

Call for action	Who?	What?
Foundation		
LCA method and metrics	Policy makers Researchers Product manufacturers Building designers Certification bodies Non-profit organisations	• Develop a robust national LCA method and develop environmental product declarations applicable to the country, both industry-specific and product-specific • Create basis for harmonising national methods
	Policy makers	• Integrate LCA method into national building regulations or otherwise promote the use of the method
	Building designers Real-estate investors	• Adopt whole life cycle thinking and the national method and integrate into everyday practice
Data generation	Policy makers	• Create obligations or other strong incentives to use the LCA method developed in step 1
	Researchers Product manufacturers Certification bodies Building designers Non-profit organisations	• Use the method to monitor embodied carbon and publish reports regularly
Data collection in databases and software tool	Researchers Certification bodies Building designers Non-profit organisations	• Initiate and maintain national data collection for LCA data
	Policy makers Certification bodies	• Develop a software tool for LCA calculation, data collection and analysis • Create open-source database for LCA data
	Building designers Real-estate investors	• Use data and tool to assess and compare projects

Performance framework		
Baseline	Policy makers Researchers	• Determine the baseline based on the current building practice compiled in the database • Monitor progress and regularly update the baseline
Carbon budget	Policy makers Researchers Building industry NGOs	• Define carbon budget based on data and support from the industry, researchers and certification bodies
	Policy makers	• Publish carbon budget in a policy document
Benchmarks and limit values along pathways	Policy makers Researchers Building industry NGOs	• Agree on and commit to a Cost-Efficient Pathway
	Policy makers	• Define Paris-Aligned Pathway based on carbon budget distribution over time and Cost-Efficient Pathway based on sector agreement • Set reference values for limit values and voluntary benchmarks at intervals of 3-5 years • Monitor progress and regularly update the pathways and reference values
	Certification bodies	• Align with voluntary benchmarks, go beyond limit values

Contents

1. Introduction

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

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

Altogether, the total amount of embodied and operational emissions is referred to as whole-life carbon emissions. Reducing this total sum of a building's emissions is the highest priority, to which this work aims to contribute.

While past efforts have mostly focused on increasing energy efficiency in building operation, recent research on 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 material. "Embodied carbon" includes all the greenhouse gas (GHG) emissions associated with materials and construction processes, use and disposal throughout the whole lifecycle of a building[2].

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 require attention and alignment as part of European and global efforts to combat climate change. It was against the backdrop of increasing efforts to understand and reduce the whole carbon life cycle of buildings that the project "Towards Embodied Carbon Benchmarks for the European Building Industry" was set up.

In particular, setting a performance system for embodied emissions at 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 for current embodied carbon levels in new buildings, as well as considerations of the available carbon budget for these emissions. Together with a review of data availability and quality, these elements form the basis for a performance system in the form of reference values for reducing embodied carbon.

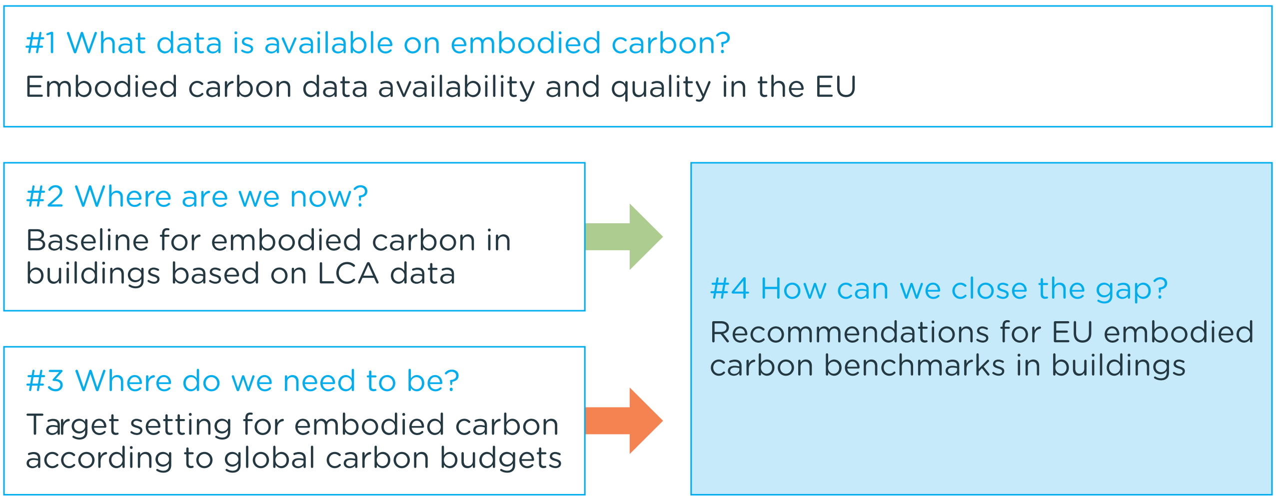
The project focused on the EU. This is due to its position as a pioneer in energy use reduction initiatives such as Energy Performance of Buildings Directive, and in GHG emission reduction policies with instruments such as the Taxonomy for Sustainable Activities and the EU Climate Transition Benchmark Regulation. Additionally, there is increased policy awareness of the life cycle perspective of buildings. 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 reference values for embodied carbon in the EU and beyond.

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

The series of reports produced as part of this project provide 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?

Figure 4: Overview of the series of reports produced for the "Towards Embodied Carbon Benchmarks for buildings in Europe" project



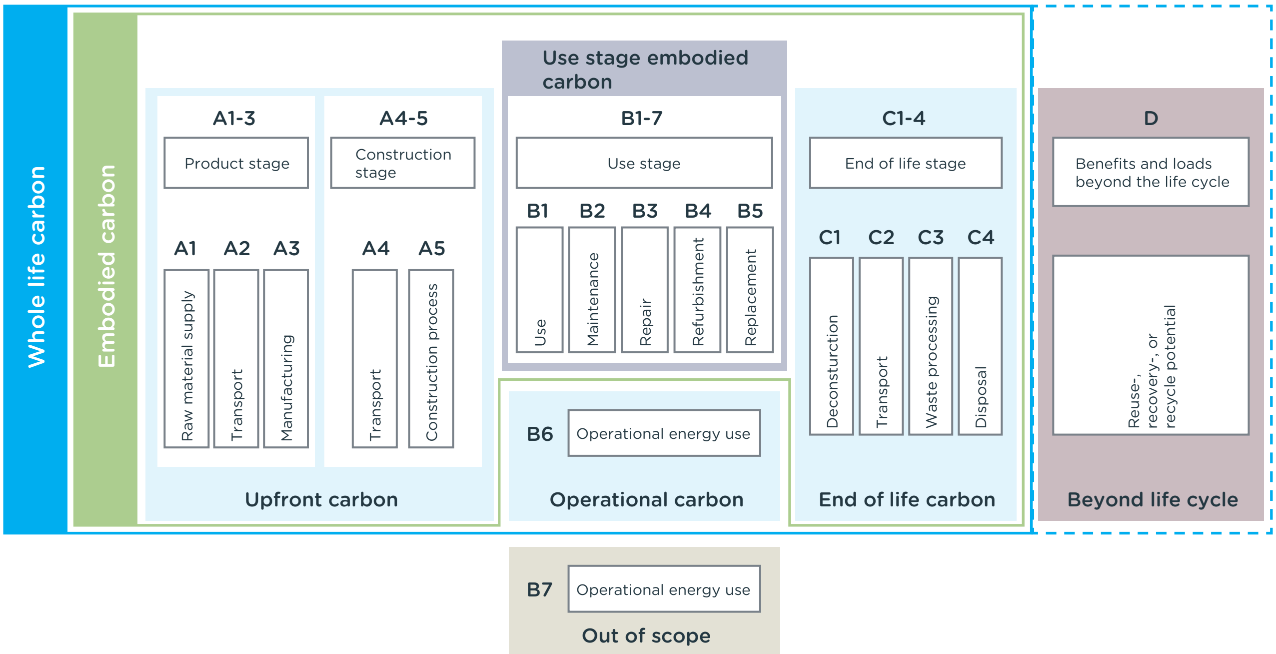
The purpose of the report herein is to outline how a performance framework for embodied carbon, that is based on bottom-up data as well as top-down climate science, can complement existing initiatives on sustainability in buildings. For this purpose, **the insights gained in the three previous reports are combined in a proposal for a performance framework** that is able to address the data challenge and minimise the embodied carbon performance gap between the embodied carbon in the baseline data and the levels required by the carbon budget.

2. What are benchmarks and what is the challenge for embodied carbon?

2.1 Embodied carbon from new buildings

To determine the embodied carbon emissions in a new building, a life cycle assessment (LCA) must be conducted. The life cycle of a building is divided into different life cycle stages and into several life cycle modules, in accordance with EN15978:2012. The embodied carbon emissions from buildings are associated with the product stage (Modules A1-5), which is referred to as upfront carbon; the use stage associated with the materials and construction products (Modules B1-5), defined as the use stage carbon; and finally the end-of-life stage (Modules C1-4), denoted as end-of-life carbon. Carbon emissions associated with operational energy use (Module B6) are not taken into consideration in the embodied carbon. An illustration of the carbon emissions throughout a building's life cycle is provided in Figure 5. Module D indicates the potential carbon benefits from reuse, recycling or recovery which can be taken into consideration, but which are not usually included in the total embodied carbon emissions due to the system boundaries.

Figure 5: Definition of whole life carbon based on the life cycle stages and modules from EN15978:2012 [2]



Several environmental impacts are usually considered in the life cycle assessments of buildings as defined in EN15978:2012. The focus here, however, is on the global warming potential of embodied carbon emissions.

2.2 Benchmarking approaches for buildings

In general, benchmarks are reference points for a comparison that allows the performance of a process, product or result to be assessed. This principle can be applied to carbon emissions from buildings, and embodied carbon more specifically, as part of assessing the sustainability performance.

A standard by the International Organisation for Standardisation (ISO) exists for Sustainability in buildings and civil engineering works – Indicators and benchmarks (ISO 21678:2020). In this standard, benchmarking is defined as the process of collecting, analysing, and relating performance data of comparable buildings or other types of construction works.

Various types of benchmarks exist, which are described in ISO 21678:2020 and summarised in Table 3. In the benchmarks, the reference values are set on the basis of a performance level. The performance level is defined as the value indicating the relative performance required (or provided) for a particular attribute on a relative scale, from the level of the least (performance) to the level of the most (performance) pursuant to ISO 21678:2020 [3].

Table 3: Elements of the performance system for embodied carbon

Type of benchmark	Statistical analysis	Determination of reference level
Upper limit values	10th or 25th percentile	• The upper acceptable performance level on a performance scale. 10% or 25% of all values shall be below this limit.
Reference value/ Baseline	Median, mean, or modal value	• The present state of the art based on relevant statistical information that describes the performance of buildings.
Lower limit value	90th or 75th percentile	• The minimum acceptable performance level on a performance scale. 90% or 75% of all values shall be below this limit.
Best practice	N/A	• The level representing the best available real performance
Target value	N/A	• This value is set by e.g. policy makers to set targets for varying performance aspects.

The previous reports for this project have laid the foundation for a baseline, as well as a budget for embodied carbon. The former constitutes a **bottom-up approach based on empirical data** from current new buildings. The latter **takes a top-down perspective of the decarbonisation** required to achieve global targets.

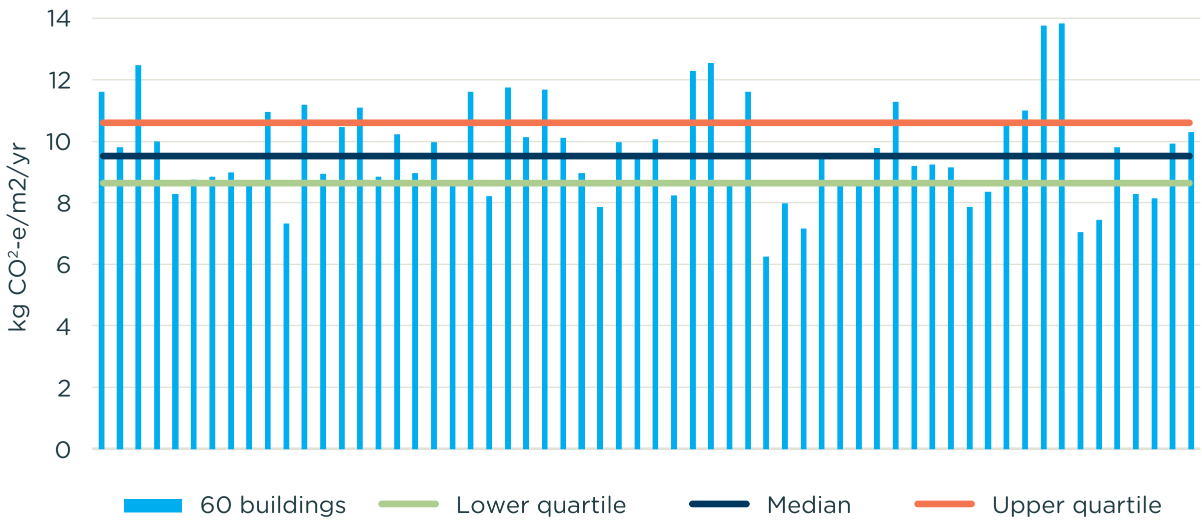
Both approaches can be translated into benchmarks. Bottom-up benchmarks can be defined and oriented on the best-in-class cases. In respect of the types of benchmarks defined in ISO 21678:2020, the top four types are defined on the basis of empirical data and only the last one has an external target value as the reference level.

Bottom-up benchmarks have the benefit of being relatable to practitioners because current cases of buildings at the reference level exist. This facilitates communicating the required actions and providing practical examples. Box 1 illustrates the underlying mechanism of whole-life carbon benchmarks for buildings, on which the Danish legislation is based (see also Chapter 3).

Box 1: Exemplary case of whole-life carbon benchmarks in Danish legislation

In **Denmark**, in 2020, a report documenting bottom-up based reference values for Danish buildings based on 60 new buildings (mainly residential and office buildings) was published by BUILD [4]. Based on those reference values, in 2020 the Danish climate partners, who advise the government, recommended introducing CO2-limit values. It was suggested that the limit value should be 12 kgCO2e/m2/year and tightened from 2023 to 2030, and that the voluntary CO2-limit value should be 8.5 kgCO2e/m2/year tightened from 2023 onwards. Based on these recommendations, in March 2021, the government introduced a plan for sustainable construction including the mandatory CO2-limit value of 12 kgCO2e/m2/year and the voluntary value of 8 kgCO2e/m2/year, which will become effective in 2023.

Figure 6: The reference values for carbon emissions from 60 Danish buildings



However, establishing benchmarks based on the empirical baseline data requires such data to be available, accessible, of high quality and comparable between the cases. This project has encountered the challenges of obtaining such data at national level in many forms. The experiences, limitations and possible solutions are summarised in the first report "Facing the data challenge".

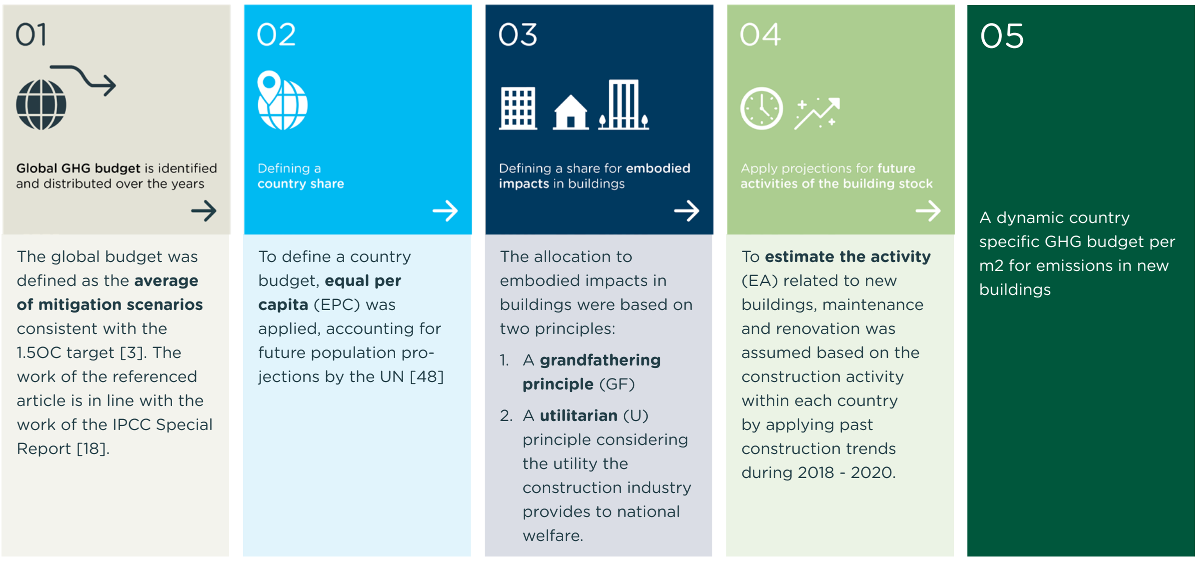
Top-down benchmarks, on the other hand, can steer the sector quickly towards the necessary decarbonisation for Paris-aligned emission limits by aligning with the available carbon budget as rapidly as possible. In the context of the increasing urgency of GHG emission reductions, an orientation based on target values provides the benefit of stressing the scale of transition needed.

The results of the report on top-down budgets for embodied emissions are illustrated in Box 2. They highlight the difference between the baseline and the budget, including a breakdown of the embodied carbon share of the Danish legal limits. This performance gap on embodied carbon calls for increased decarbonisation action, but may also result in purely top-down, budget-based upper limit values for embodied carbon to be dismissed as unrealistic by the industry, at least in the short term. Additionally, the necessary methods and data for establishing an embodied carbon budget – be it at global, national, municipal or portfolio level – are still underdeveloped. Our concept for embodied carbon budgets provides one possible solution, but wider application is also limited by data challenges.

Box 2: Example of top-down targets derived from the global carbon budget

In this project, a target pathway based on the carbon budget was calculated in the carbon budget report (#3 “Defining budget-based targets”). For this purpose, the global budget was downscaled to the Danish national level based on the population share (equal per capita, EPC), and further-specified for new construction activities based on past emission levels (grandfathering, GF) or welfare contribution (utilitarianism, U) and projected figures based on recent economic activity (EA). Figure 3 illustrates this applied process.

Figure 7: Approach to top-down carbon budget pathways for embodied carbon



Summary

In summary, a performance framework for embodied carbon has to rely on both, bottom-up and top-down considerations in order to rapidly, but feasibly, bridge the gap between reality and necessity. In particular, for the bottom-up elements a high-quality data foundation is needed first. All these elements will form part of the performance framework proposed in Chapter 4.

3. How are sustainability benchmarks currently used for buildings?

Before proposing a framework for comparing and reducing embodied carbon, it is important to understand the existing landscape of sustainability performance frameworks for buildings. Benchmarks, following the idea of reference values and relying on the types cited above, are crucial in four categories of initiatives aiming to foster sustainability in the building sector:

- Certification schemes that incentivise sustainable building design by offering recognition for voluntary ambition. To this end, a set of requirements defined by benchmarks need to be met
- Reporting frameworks that develop voluntary guidelines for collecting and presenting sustainability parameters of buildings to increase transparency and, consequently, raise ambition
- Regulation specifying legal, mandatory requirements for building design, emission levels or reporting
- Other local or public initiatives which frame mandatory requirements for either new public buildings or all new buildings within cities

In the initiatives in these three categories, benchmarks are already used to a varying extent for operational carbon, embodied carbon or whole life carbon. The key initiatives and their consideration of embodied carbon are presented below and summarised in Table 4.

Certification systems

Sustainability certification systems provide voluntary guidelines that motivate the industry to design and construct more sustainable buildings. The use of certification systems has paved the way for the use of LCAs in the construction sector. Several of these systems are in use in Europe, including LEED, BREEAM, and national initiatives such as the German DGNB which has been adapted in other countries like Denmark as well, and the French HQE. A large portion of the voluntary sustainability systems is organised by the different national Green Building Councils.

However, the scope, methods and level of ambition varies between each of these initiatives. Some certification systems, such as DGNB, require a full life cycle assessment (LCA) for a building in accordance with a specific methodology in order to be certified, while other systems, such as LEED and BREEAM, have used a life cycle approach to evaluate materials or building elements and not necessarily a full LCA of a building [5]. Level(s) on the other hand requires a holistic LCA to be performed, but does not prescribe a specific methodology [6] or reference points.

As indicated in Table 4, only the LEED and DGNB schemes set any form of limit values or other reference points for embodied carbon. **Where they exist, the current benchmarking schemes are voluntary and the reference values are not aligned with the ambition of the Paris Agreement.** Significant reductions in the environmental impacts from buildings have so far not been observed [7]. In order to achieve significant decarbonisation in the building and real estate sector, embodied carbon benchmarks with a sufficient level of ambition are, therefore, urgently needed.

Table 4: Relevant existing sustainability initiatives for buildings and their use of benchmarks for embodied carbon

	Purpose	Building coverage	Emission scope	Existence of embodied carbon benchmarks
Certification schemes				
BREEAM	Promotes sustainability considerations in construction by certifying robust assessments of impacts from material choices.	• All types of buildings • Different standards for new construction and retrofits.	Requirements for material inputs and construction stage, optional inclusion of other life cycle stages	No benchmark or limit value used.
LEED	Promotes sustainability considerations in construction by certifying robust assessments of impacts from building life cycles.	• All types of buildings • Different standards for new construction and retrofits.	Cradle to grave life-cycle stages.	Reduction of whole-life carbon emissions compared to baseline scenario receives higher scores.
DGNB	A sustainability scheme for new and retrofitted buildings which, amongst other things, has brought attention to life cycle assessments for buildings.	• All types of buildings both new, renovations and existing buildings.	Upfront carbon (A1-3), Use stage embodied carbon (B4), Operational carbon (B6) and End of Life carbon (C3-4).	Benchmarks for embodied carbon is a fixed reference value based on the bottom-up approach that applies for all building types.
HQE	Certification scheme for buildings that primarily focuses on the occupants' health and comfort.	• New buildings, renovations and existing buildings.	Assessment of emissions is carried out on construction product-level and not building level. No required scope.	No benchmark or limit value used.
Reporting frameworks				
Level(s)	Common framework for more sustainable buildings in Europe. Specific criteria for quantifying GHG emissions for different experience levels in the construction industry.	• All types of buildings.	Upfront carbon (A1-5), Use stage embodied carbon (B1-5), Operational carbon (B6) and End of Life carbon (C1-4) – also denoted as cradle to grave.	No benchmark or limit value used.
Global Real Estate Sustainability Benchmarks (GRESB)	GRESB systematically reports and evaluates the disclosure of environmental, social and governance (ESG) data from listed real-estate companies.	• All real-estate elements of companies' portfolios.	All life cycle stages can be included.	Disclosure of embodied carbon emissions can be included, if available. No benchmark or limit value used.
Carbon Disclosure Project (CDP)	The Carbon Disclosure Project (CDP) runs a global disclosure system for companies or cities to manage their environmental impacts.	• No specification of the building coverage.	Primary focus on scope 1 and 2, but scope 3 can also be disclosed.	Using their system, CDP members can achieve science-based targets. No benchmark or limit value used.
Taskforce on Climate-related Financial Disclosure (TCFD)	The Task Force on Climate-related Financial Disclosure supports organisations to improve and increase their reporting of climate-related financial information.	• No specification of the building coverage but can be included if scope 3 is disclosed.	The framework suggests that organisations in general should provide emissions associated with scope 1 and 2 and, if possible, scope 3 GHG emissions. Should be reported in alignment with the GHG protocol.	No benchmark or limit value.

Principles of Responsible Investment (PRI)	The Principles for Responsible Investment (PRI) work to encourage investors to use responsible investment. The strategy here is to incorporate environmental, social and governance (ESG) factors.	• Buildings occupied by organisations using the framework can be reported.	The recommendations of the TCFD are integrated in PRI, which allows organisations to voluntary report scope 1, 2 and 3.	No benchmark or limit value.
Science-Based Targets Initiative (SBTi)	Standardises an organisation's approach to emissions reduction targets.	• No specification of building coverage.	Focus on scope 1 and 2 emissions, which relate predominantly to operational emissions. No specific criteria for embodied carbon as part of scope 3 so far.	No benchmark or limit value used.
Building System Carbon Framework by WBCSD	Framework to transparently report, account and measure whole life carbon	• Whole life carbon emissions. New buildings and construction work, major retrofitting and system emissions.	Reporting and accounting of whole life carbon: Upfront carbon (A1-5), Use stage embodied carbon (B1-5), Operational carbon (B6) and End of Life carbon (C1-4) and beyond life cycle (D). Also, scope 3 in accordance with the GHG Protocol.	No benchmark or limit value used.
Regulation				
EU Taxonomy for sustainable activities [8]	Defines criteria for sustainable economic activities in the EU.	• New construction (separate criteria for renovations).	Operational emissions in detail, plus whole-life carbon.	Requirement for reporting on whole-life carbon for all new buildings. No limit or reference value is fixed.
EU Energy Performance of Buildings Directive (EPBD, proposal for revision of December 2021) [9]	Part of the Fit for 55 package which sets the vision for zero-emissions building stock by 2050. EPBD focuses on the operational carbon from buildings, but recently expanded to embodied carbon for new buildings.	• The whole life carbon of all new buildings shall be calculated as of 2030, while new buildings with floor area greater than 2000 m2 must be calculated as of 2027.	The whole life carbon shall be reported in accordance with the Level(s) framework.	No benchmark values are provided yet.
Danish legislation in the National Strategy for Sustainable Construction [10]	Places focus on carbon emissions from Danish buildings with LCA and aims for reductions in the future.	• All new buildings to report whole life carbon emissions.	Upfront carbon (A1-3), Use stage embodied carbon (B4), Operational carbon (B6) and End of Life carbon (C3-4).	Buildings larger than 1000 m2 to fulfil limit value of 12 kgCO2e/m2/year. Voluntary limit value of 8 kgCO2e/m2/year. Limit values will be tightening up in the period 2023-2029.
French legislation in Décret n° 2021-1004 [11]	Reducing the climate impact from new buildings by integrating energy and carbon requirements.	• Residential buildings in the form of detached and attached houses and social housing.	Upfront carbon (A1-5), Use stage embodied carbon (B1-4), Operational carbon (B6), End of Life carbon (C1-4) and beyond life cycle (D).	From 2022 CO2-limit values will be introduced and tightened up until 2030 starting from 640 to 415 kg CO2e/m2 for detached and attached houses, and from 740 to 490 kgCO2e/m2 for social housing, respectively.
Finnish proposal for a Method for a whole life carbon assessment of buildings [12]	The proposal contributes to developing legislation that aims to achieve low-carbon construction.	• New buildings and extensive repairs.	Upfront carbon (A1-5), Use stage embodied carbon (B4), Operational carbon (B6) and End of life carbon (C1-4).	No benchmark or limit value provided, however this is planned to be implemented by 2025.

Reporting frameworks

Reporting frameworks also create voluntary mechanisms to increase transparency on climate-related parameters for building construction and operation. In contrast to certification schemes, reporting usually happens at an organisational level, and is aggregated for the portfolio of buildings owned by an organisation. Such frameworks provide support and recognition for the standardised measurement of climate impacts so as to be able to manage and mitigate them.

The frameworks define elements, on which reporting is mandatory to obtain the approval, or on which disclosing data can be optional. As can be seen in Table 4, most reporting frameworks cover a wide range of economic activities and focus on emissions in scopes 1 and 2, while indirect emissions from the value chain in scope 3 are often voluntary. **Therefore, embodied carbon emissions are less specifically addressed, and no reference values are provided.** Only GRESB targets the real-estate sector specifically, but does not define benchmarks in its requirements.

A framework that is specially made for buildings is Level(s). **Level(s) has great potential to encourage the construction industry in Europe to think sustainably,** since it provides a holistic method that considers every aspect of sustainability. It gives guidance on how to design and construct more sustainable buildings, although it does not provide a benchmark value yet [13].

However, the purpose of reporting frameworks is to be able to compare an organisation or building asset to others in the market. This is strongly supported by these frameworks, even though the embodied carbon, as indirect emissions in the value chain, does not take a prominent role. This concept of benchmarks also uses a bottom-up approach based on the reported data from companies, buildings or portfolios and does not include reference to the carbon budget.

Regulation

In contrast to most certification systems and reporting frameworks, regulations create legal obligations. In relation to embodied carbon, these can relate to limit values for the quantity of emissions from buildings or spatial development, requirements for building design, or emissions reporting.

The **European Union** has adopted a taxonomy for sustainable activities, which specifies sustainability requirements for a wide range of sectors. Reporting on alignment with these criteria will become mandatory for many EU companies in the future. For Construction and Real Estate, benchmarks are set for operational carbon, while whole-life carbon emissions have to be calculated for buildings larger than 5000m2 [8]. Reference values for whole-life or embodied emissions would improve the ability to be able to interpret the reported data and enable limits to be set in the future. However, such benchmarks are not included in the current list of criteria.

Additionally, the EU Commission has proposed revisions to the Energy Performance of Buildings Directive (EPBD). The Directive has required national benchmarking frameworks for operational energy use for a long time, expressed in Energy Performance Certificates (EPC) for buildings. The proposal aims to introduce the obligation to calculate the life-cycle global warming potential and to include this in the EPC for new buildings above 2000m2 from 2027 and for all new buildings from 2030. However, only disclosure is provided for in the proposal, without any reference levels, as is the case with energy efficiency classes for operational emissions. [9]

Increasing the ambition for embodied carbon in these instruments, by applying limits for embodied carbon, would require reference values or even mandatory limit values that express the ambition required for, as well as the practical feasibility of, decarbonisation.

At **national level**, several EU Member States have also adopted or proposed regulations on embodied carbon levels. Several countries have introduced requirements to carry out LCAs for new buildings and to document the results. This is the case in Denmark, France, the Netherlands and Sweden.

Denmark and France have also adopted limit values for whole life carbon emissions that represent reference values for new buildings. In Denmark, the whole life carbon limit is based on the bottom-up approach of 12 kgCO2e/m2 per year. The legal requirements are supplemented with a voluntary CO2 class of 8 kgCO2e/m2/year. The limit value will apply for all new buildings greater than 1000 m2 from 2023 and is expected to be lowered every second year resulting in a new value in 2025, 2027 and 2029 [10]. In France, the building Regulation sets whole-life carbon thresholds for houses and apartments, which will be valid from 2022. These thresholds take into account both operational and embodied carbon [11]. For upfront embodied emissions, the requirements provide that new buildings will emit at least 30% less in 2030, compared to 2013 by gradually tightening the reduction requirements of 15% in 2024, 25% in 2025 and 30-40% in 2027 [20]. Similar instruments are being developed in Sweden and Finland.

In total, however, **only a few countries are implementing embodied carbon benchmarks or limit values into building regulations,** and these are not necessarily aligned with the ambition of the Paris Agreement, that the EU and all its Member States have committed to. The difference between the current approaches and the Paris-aligned benchmarks is explained in the following section.

Other local or public initiatives

Several other initiatives have introduced requirements for embodied carbon at local level for public buildings moving from voluntary sustainability assessments to mandatory requirements [14]. Not all of them are aligned with the climate goals which the countries have committed to, while some have been aligned with the climate targets.

As one example, Germany introduced the Sustainable Building Assessment System (BNB) in 2013 [15] as a requirement for new public buildings. With this assessment system, a holistic evaluation of the whole-life cycle of public buildings is achieved [16]. The BNB defines a bottom-up based reference value of 9.4 kgCO2e/m2NFA/year for whole-life carbon emissions, thus aligning with the DGNB certification system benchmark. Recently, new bottom-up based reference values for the German DGNB system were determined, resulting in a reference value of 8.7 kgCO2e/m2NFA/year [17]. This could also potentially become an updated benchmark for BNB.

An example for a local initiative is the Swiss Federal Office of Energy which, in compliance with their vision for a 2000-Watt Society, has developed an energy efficiency path for the city of Zurich, where one of many objectives is to establish a sustainable basis for the building stock. The aim of the efficiency path is to reduce GHG emissions to 1 ton CO2e/capita and achieve 'climate neutrality by 2050' [18]. Based on the 2000-Watt Society, the Swiss Society of Engineers and Architects has produced the SIA 2040 report, in which the limit value value of 11 kg CO2e/m2/year is proposed for public buildings [19].

Summary

In summary, the overview of existing sustainability initiatives for buildings indicates the growing awareness for reducing embodied and whole-life carbon, but only few have defined benchmarks or limit values for this type of emissions. Where reference values exist, these have been defined in a bottom-up approach based on good practices from current new building construction projects.

A performance framework that accelerates the decarbonisation of the construction sector in line with science-based, Paris-aligned, carbon budgets would enable increased ambition in the certification systems, reporting frameworks and regulations.

4. What should a performance framework for embodied carbon look like?

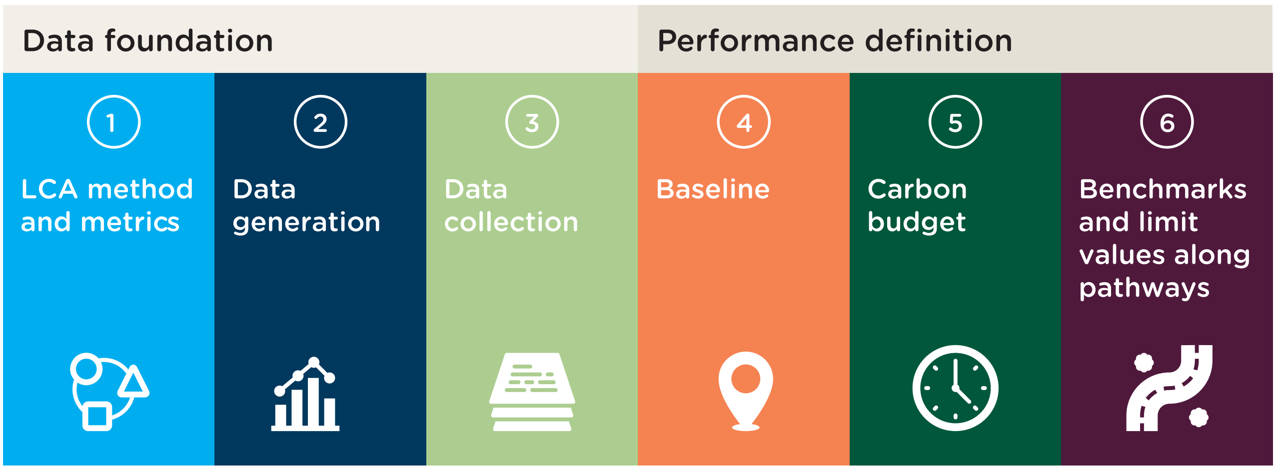
The previous chapters have highlighted the need for embodied carbon benchmarks as an enabler for the transition of the construction sector towards a climate-neutral society by bridging the embodied carbon performance gap between reality and necessity. This is needed to support both national policies and several important European initiatives such as Level(s), EPBD and EU Taxonomy.

The goal of an embodied carbon performance framework must be to efficiently lower the carbon emissions from buildings. However, the report so far, which has also been informed by the other three reports produced by this project on: data availability, baseline and budgets, shows that the development of a performance framework has to build on a robust data base and also reflect sufficient ambition to bridge the gap between the baseline and the available budget.

In this respect, the two benchmarking approaches should supplement each other. **A bottom-up component building on baseline data and an agreed industry pathway has to gradually align with the top-down component of the carbon budget.** Bringing together these two components will enable efficient reference and limit values.

The concept for the efficient benchmarking system is built on six elements, as shown in Figure 8. The first three elements constitute the foundation which ensures that an evidence base is available for defining the benchmarks, while the three further elements represent the performance framework which must be established based on the foundation and on additional calculations and consultations. Establishing the benchmarks, as proposed below, is very ambitious, but they are efficient in combining the feasible with the necessary. Each element is presented in detail below.

Figure 8: Overview of the proposed performance system



4.1 The data foundation

As mentioned above, a data foundation constitutes a crucial element for the performance framework and, therefore, has to be the initial focus. It provides the robust evidence base in the benchmark setting process, and also the structure for measuring whether future buildings comply with the reference values.

1. LCA method and metrics

As a first step, it is crucial that a standardised calculation method for life cycle assessments is formulated. Currently, as can be seen in the overview of certification schemes, national methodologies are common. Building on this basis, national LCA methods for buildings, that can calculate and document whole-life carbon emissions, are the most efficient solution and should be developed or agreed upon more widely. This can be considered the first right step in developing a methodology. The key parameters, on which the methodology must provide standardisation, are as follows:

- ISO standards and EN standards to define the overall method
- Environmental data on building products and materials and technical systems
- A fixed reference study period
- Service life of construction products, materials, processes and systems
- Life cycle modules included
- Building elements included
- All environmental impact categories considered and their respective units
- An agreed method for allocating emissions from reused or recycled materials
- An agreed method for estimating quantities for the building
- An agreed method for handling biogenic carbon

The existing schemes and experiences in similar countries can be used as highly relevant starting points.

The EU must take a role in this process as well, by defining the requirements for these LCA methods, for example based on the relevant ISO standards[3] and EN standards[4]. The Level(s) framework has the potential to greatly influence a harmonised data framework and establish a common language for assessing the environmental impacts from buildings. This is a key focus of Level(s) indicator 1.2 and is also stressed by the World Business Council for Sustainable Development (WBCSD) in SBT4forbuildings[5]. Combining these existing approaches creates a good starting point and will support harmonisation across national borders in the future.

In order to conduct standardised life cycle assessments of buildings, a **database containing environmental data** on construction products, materials, systems and processes is necessary, based on environmental product declarations that follow the EN standard.

The **metrics**, on which the resulting whole-life carbon emissions should be reported, should also be standardised. As described in the previous reports for this project, by quantifying emissions per square metre (based on the definition in the national building regulations), and also per capita (at least for residential and office buildings), each convey relevant information on the decarbonisation contribution and carbon efficiency of a building. These metrics can be normalised to values per annum with the suggested reference study period, as this facilitates comparison with operational carbon in the aim of minimising the whole-life emissions from a building.

3. ISO 14040 Environmental management – Life cycle assessment – Principles and framework and ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines
4. EN15978:2012 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method and EN15804+A1:2012 or EN15804:2012+A2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products
5. SBT4buildings A framework for carbon emissions management along the building and construction value chain by WGCSD: https://www.wbcsd.org/contentwbc/download/6321/91663/1

The focus of this step of the data foundation is not on harmonised LCA methods across Member States, but rather on supporting the development of Member States' LCA competencies to enable reference values. However, if Member States develop LCA methods based on Level(s), for example, harmonisation can eventually be achieved.

2. Data generation on embodied carbon and contextual factors

In the second step, the LCA data needed to calculate embodied carbon baselines should be generated in accordance with the method defined in the first step. To this end, a legal obligation or other form of incentive for using the method should be created. In order to fully use the data and assess its representativeness, it is also highly necessary that extended reporting requirements are also included in this data generation. In addition to the levels of embodied carbon and operational carbon[6], other highly relevant contextual data points include:

- Building typology
- Year of commissioning
- Number of floors above and below ground
- Gross and heated floor area
- Energy performance class
- Energy consumption and energy supply
- Included life cycle modules in the LCA
- Included building elements in the LCA
- Materials used for the building frame and envelope
- Total weight of the building
- Climatic zone
- Planned number of occupants

The data generation process is crucial in the initial phases to reach a sample size of buildings that is sufficiently large and representative in order to enable an assessment of the baseline across building types. In the following section, the continued data generation on cases remains highly important in order to maintain an up-to-date status of the changing embodied carbon levels in construction projects as the benchmarks evolve. In addition, the points listed above will support building design professionals in the construction sector with identifying the reduction potential in their buildings, which will enable a broader understanding of which design parameters should be changed to achieve significant reductions in carbon emissions.

3. Data collection in a database and a software tool

The third element of the foundation is a central data collection of results from the LCAs on new construction projects, including the extended documentation requirements. This data should be compiled in an accessible database on embodied carbon as part of whole-life carbon that summarises, in an anonymised and aggregate form, the national data collected in accordance with steps 1) and 2). The database should be accessible by building designers to view and export data. However, the data should not be editable so as to ensure correctness and reliability. As the data will have been collected in accordance with the LCA method from step 1), new buildings can be compared to the current status in the database.

6. Additionally, it is highly recommended that data on environmental impacts other than the global warming potential, that are quantified in an LCA, such as water consumption, eutrophication, etc. are collected to enable future benchmarks to be set for these impacts as well.

In order to facilitate the expansion of the database, a software tool can be developed. The tool can calculate the whole-life carbon emissions from buildings aligned with the national methods and directly input the information into the database. A tool such as this would strongly support the updating of benchmarks in the future, as will be outlined in the following steps of the performance framework. Also, the software tool can ensure that all LCAs are based on the same prerequisites, thus resulting in a minimal number of mistakes in terms of the points listed in step 1).

4.2 The performance definition

While the foundation is a necessary basis for being able to define benchmarks or limit values, the performance definition sets the reference values for the decarbonisation of new construction.

4. Baseline

In the fourth step, the data collected in the first three steps feeds into a baseline of the current level of embodied carbon. A similar exercise has been performed as part of this project for five EU Member States in report #2 “Setting the baseline”. This represents the bottom-up starting point of decarbonisation efforts, and thus the pathways that will be defined. An overall baseline and specifications for building types should be envisaged.

As mentioned above, the baseline should state the embodied carbon per square metre and per capita, and it should be updated regularly based on cases being added to the database.

5. Carbon budget

In the fifth step, a carbon budget for embodied carbon in buildings must be calculated to understand the remaining emissions in order to limit global warming to 1.5°C, as specified in the Paris Agreement. Currently, a widely recognised global budget or national sectoral budgets are not available for embodied emissions, which is why efforts for calculating this budget will have to be made at a national level. In line with the baseline metrics, a budget should also be calculated per square metre and per capita.

Fundamental elements for the budget calculation method will have to be agreed on to set a budget which is consistent with the overall global one, or comparable national ones. For instance, principles for allocating emissions are a key element of the budget calculation and can influence the detailed results significantly. Therefore, the use of these principles and the models used for calculation must be aligned and agreed on in a wide consultation. As the budget essentially makes normative statements on future emissions, the involvement of various stakeholders is key for the robustness and acceptance of the results.

Spreading the budget over the years defines top-down, budget-based targets for embodied emission reductions that will form the basis for the Paris-aligned decarbonisation pathway in the sixth step. Report #3 “Defining budget-based targets” provides a concept for budget and target calculation for Denmark and Finland.

As with the baseline, the budget needs to be updated regularly to take into consideration developments in climate science, global emission levels and overshoot (or, less likely, overperformance) which may have taken place since the last budget calculation.

6. Benchmarks and limit values along two pathways

As the sixth and final step, benchmarks or limit values have to be set along pathways that align the baseline and the budget. To account for the difference between reality and climate necessity, two pathways should be developed:

- One the one hand, a Paris-Aligned Pathway (PAP) based on the carbon budget distribution. This pathway can be calculated based on step 5) and steer the decarbonisation process in a way so that the required levels of embodied emissions are reached as quickly as possible.

- On the other hand, a Cost-Efficient Pathway (CEP) should be defined based on the baseline and the carbon budget figures in a wide consultation with the building industry along the entire value chain and including non-profit actors. The World Business Council for Sustainable Development's Building System Carbon Framework provides a structured map of the sector and the relevant actors. This pathway constitutes a realistic, but ambitious, scenario of embodied emission reduction based on available and economically-feasible reduction solutions[7], which the sector can commit to, while also considering social and technological parameters.

The combination of the two pathways brings together the bottom-up and the top-down perspectives into a comprehensive benchmarking system for embodied carbon. The commitment to the CEP should represent limit values per square metre and per capita in the process to decrease emissions below the carbon budget. Ideally, it can be supported with legislation to create mandatory limits that tighten over time. The PAP initially represents voluntary reference values as benchmarks at building level. Respecting these values would allow a building to be referred to as 'Paris-aligned'. Legislation could foresee classes of buildings based on their embodied carbon levels. In this case, staying within the PAP could be acknowledged as class A.

Similarly, in addition to the updated calculations of the current baseline and the carbon budget, the pathways also have to be updated regularly based on those two elements. This underlines the importance of a dynamic data collection system and central database.

7. For example, circular economy actions are compiled and described in the "The decarbonization benefits of sectoral circular economy actions" report. https://ramboll.com/media/environ/decarbonisation-benefits-of-sectoral-circular-economy-actions

4.3 The complete performance framework

The elements of the performance framework and its key features are summarised in Table 5.

Table 5: Proposal for an efficient performance framework that enables aligned bottom-up and top-down reference values to be achieved.

Performance system for embodied carbon	
Data foundation	

LCA method and metrics	• Nationally standardised LCA methods following the ISO and EN standards:
	  • ISO 14040 **Environmental management – Life cycle assessment – Principles and framework** and
	  • ISO 14044 **Environmental management – Life cycle assessment – Requirements and guidelines**
	  • EN15978:2012 **Sustainability of construction works- Assessment of environmental performance of buildings – Calculation method** for the building level
	  • EN15804+A1:2012 or EN15804:2012+A2:2019 **Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products** for the building product level
	• Environmental data of construction products, materials, processes and systems based on the EN standards. Data should be both industry-specific and product-specific and applicable (representative) to the country.
	• Clearly defined parameters for the LCA calculations (including life-cycle scope, building elements, service life of buildings, handling of biogenic carbon and reused and recycled materials.)
	• Reporting metrics (per m2 and per capita)
	• Includes extended documentation requirements, e.g. supported by the Level(s) framework or Digital Building Logbooks

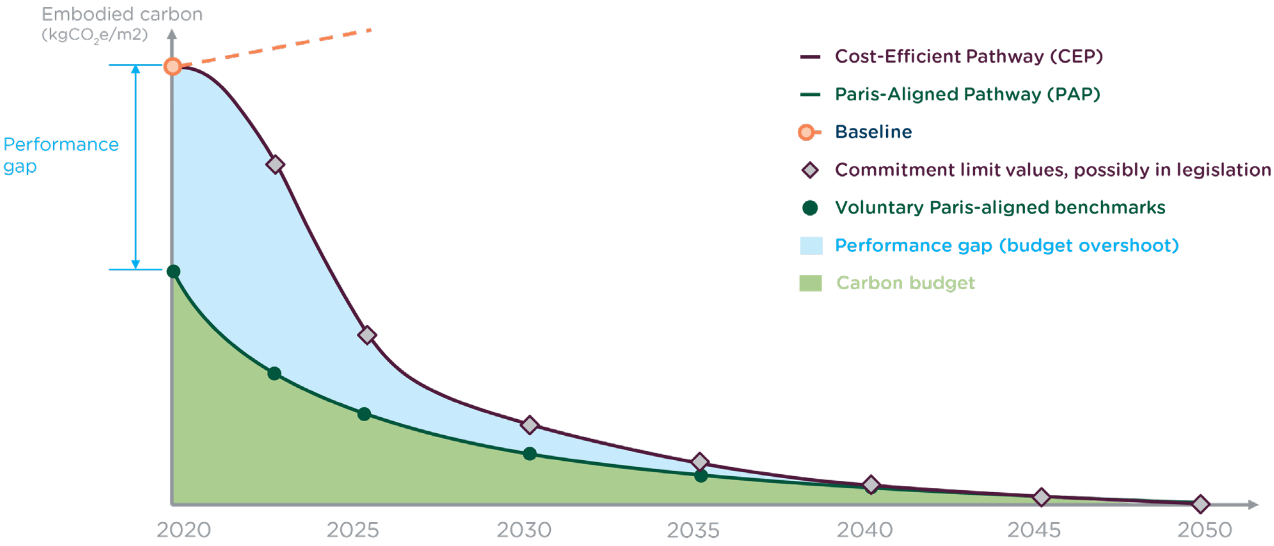
Data generation	• Obligation or strong incentives to conduct LCAs for new buildings • Based on extended documentation requirements of contextual factors • Obtain a representative sample of new buildings for developing the baseline
Data collection in databases and software tool	• Centralised collection of LCA data for new buildings • Central database for calculating and comparing future buildings • Supported by a software tool for LCA calculations and data input • Aligned with national LCA method • Open data available to stakeholders
Performance framework	
Baseline	• Baseline/reference value of status quo building practice • Calculated based on data collected in steps 1-3 • Expressed in embodied carbon levels per square metre and per capita • Updated regularly based on data for new buildings
Carbon budget	• Paris-aligned emission levels for embodied carbon • Calculated based on downscaled global budgets • Expressed in embodied carbon budgets per square metre and per capita • Representing target values for decarbonisation that should be reached as soon as possible • Updated regularly based on revisions of the global carbon budget and sectoral overshoot

Benchmarks and limit values along pathways	• Two sets of reference values along two pathways:
	  • Voluntary benchmark values in a Paris-Aligned Pathway (PAP) in accordance with the carbon budget pathway
	  • Limit values in a Cost-Efficient Pathway (CEP) in accordance with a shared commitment by the industry after consultation

By assembling the elements described in the three steps of the performance definition, a performance framework in the form of Figure 9 will be created. This figure represents the embodied carbon baseline, budget and pathways per square metre as one of the two metrics, as this is more widely applicable to building types. However, these reference values should be supplemented with per capita calculations for specific building types wherever, and as soon as, possible.

The graph highlights again the performance gap between the baseline and the carbon budget for embodied carbon. The purple line of the CEP bridges the gap to the PAP. However, a budget overshoot is inevitable as long as the CEP levels are higher than those of the PAP.

Figure 9: Embodied carbon performance framework



The following chapter will outline possible measures to minimise the embodied carbon performance gap and budget overshoot.

5. How can the embodied carbon performance gap be minimised?

Considering the urgency of reducing global GHG emissions to mitigate climate change, the embodied carbon performance gap must be minimised. The CEP represents the first step towards decarbonisation that summarises the potential for innovation and the potential for reducing embodied carbon per square metre. This relates to advances in low carbon production methods for construction materials or the substitution of traditional materials with low carbon alternatives.

However, the reduction of embodied emissions per square metre needs to take place rapidly and additional efforts and measures will be necessary to minimise the gap. The following section outlines and discusses the relevance of three key additional actions:

- Urgent action is needed, as delayed action results in additional overshoot
- Reducing new construction activity as a means to increase the available budget per square metre
- Carbon removal from biogenic building materials with capturing and removing the end-of-life emissions in the near future being a last resort to balance the budget.

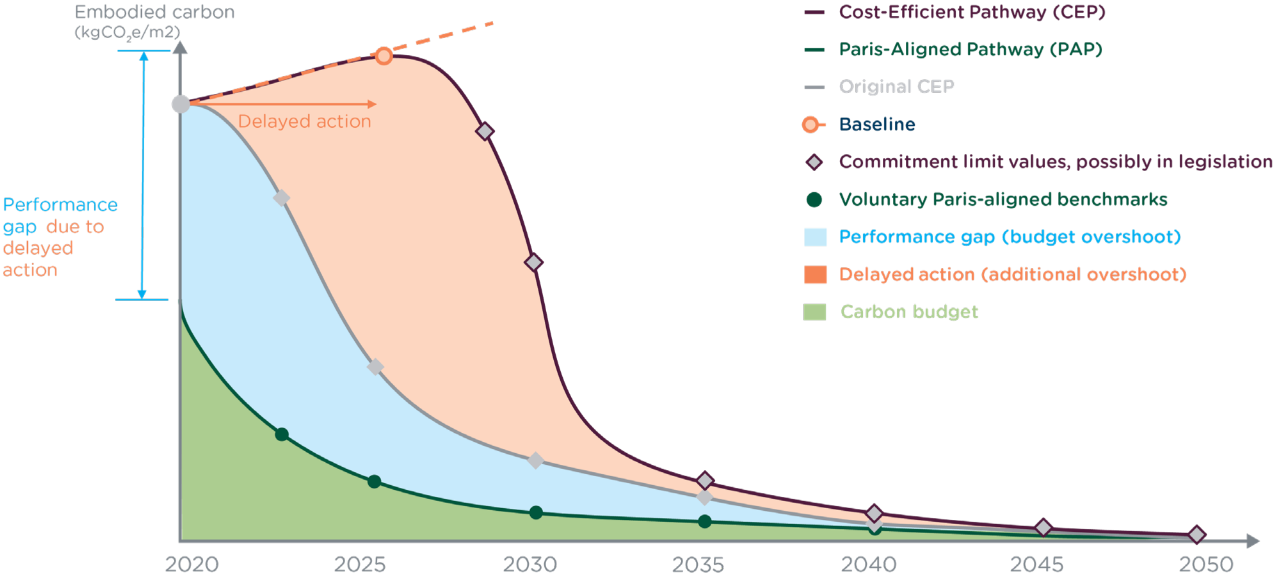
None of these actions can be expected to substantially reduce or even close the performance gap in isolation. Rather, a combination is needed, and the specific potential of each measure needs to be assessed, as they may vary between countries, building types and other contexts.

5.1 Urgent action is needed

Research on embodied carbon has identified an increasing trend both in absolute emissions and in the relative share of building emissions [19]. Therefore, the baseline of embodied emissions per square metre is expected to increase further if no specific commitment to a reduction is made. This means that any delay in taking action and committing to a CEP will result in the gap to the PAP becoming wider and the budget overshoot more significant. **The greater the overshoot in the near future also means that the available carbon budget depletes more quickly, meaning that a comprehensive reduction of embodied carbon has to take place even quicker.**

Figure 10 shows an example illustration of the consequence of delayed action on developing the performance framework: as the later and higher baseline results in additional overshoot, this in turn reduces the budget.

Figure 10: Effects of delayed action on developing an embodied carbon performance framework



Existing feasible and cost-effective strategies for reducing embodied and whole life cycle carbon emissions should be promoted and employed. This includes **optimised space and material use depending on the building type and purpose, selecting low carbon materials, as well as the use of recycled building materials**. A starting point for the uptake of strategies to reduce embodied carbon could be producing reports that present the potential of different solutions[8]. The sooner a reduction in the CEP is initiated, the more limited the embodied carbon performance gap and the lower the budget overshoot will be.

5.2 Reducing construction activity increases the budget available per square metre

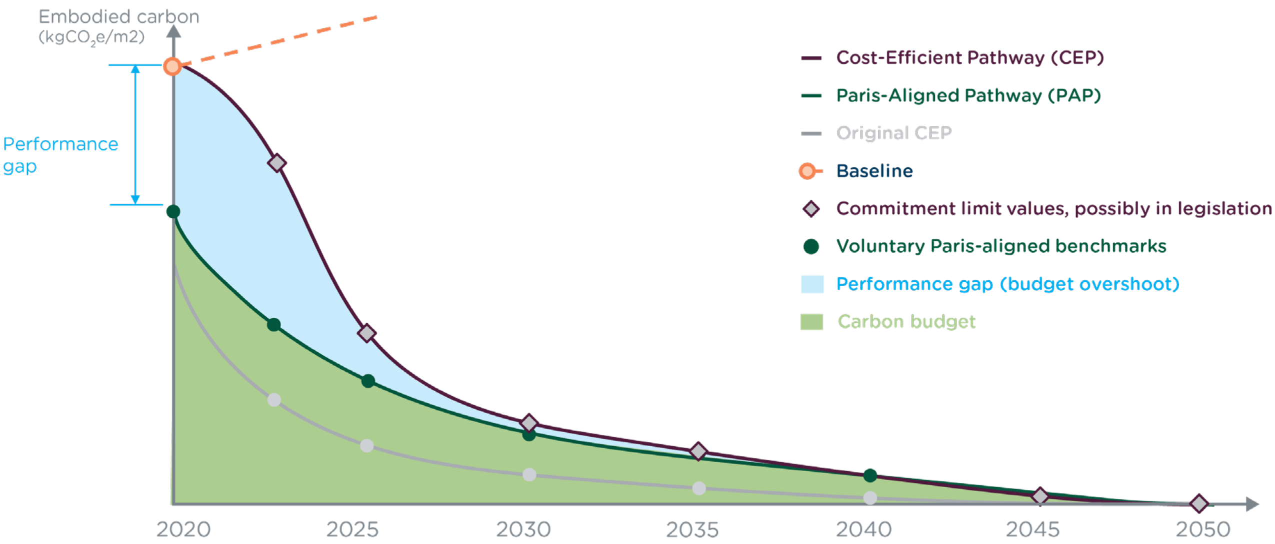
A reference value of embodied emissions per square metre can be influenced by the number of square metres built. As the carbon budget and relative pathway are based on past construction trends (see report #3 Defining budget-based targets"), a change to this trend also changes the available carbon budget for each unit.

An increase in new construction activity would mean that less budget can be attributed for each square metre, but inversely, a reduction of construction activity increases the carbon budget per m2 and therefore helps to align the two pathways.

Figure 11 illustrates the exemplary effect of a reduced construction activity with fewer square metres built. **As a result, alignment between the two pathways is possible earlier than in the original scenario, and the overshoot is substantially lower.** Mapping the embodied carbon per capita and aligning the respective pathway with the carbon budget, will be important in ensuring that a total reduction is achieved.

It should be noted that, in line with the focus and scope of this study, this scenario only relates to new buildings. In the case of older constructions, renovation plays an even greater role than in the current discussions, as it reduces the need for new buildings. Renovation also involves embodied carbon emissions, but at a lower amount as core building parts, such as the structure and frame, can be retained.

Figure 11: Effects of reduced construction activity on a performance framework



8. For example:
Malmqvist et al. (2018). Design and construction strategies for reducing embodied impacts from buildings – Case study analysis
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5.3 Carbon removals may help balance the carbon budget

Carbon removals refer to activities that remove GHGs from the atmosphere. Using biogenic construction materials that naturally capture CO2 and other GHGs means removing and capturing the emissions for the duration of the building's existence or until the said materials are replaced. This can be achieved by using plant-based products such as wood. However, it should be underlined that in a whole life cycle perspective, the captured and stored CO2 in the materials will eventually be emitted back into the atmosphere corresponding to the end-of-life carbon. The storing of the emissions can be elongated if the construction products are not demolished and disposed of. Potentially, emissions at the end-of-life stage could be captured and removed for even longer.

Carbon removals are one way to balance the embodied emissions that occur in the budget overshoot at the beginning. The need for negative emissions at a global scale is documented in most global emission scenarios (for example in IPCC reports and IEA scenarios). In the EU as well, initiatives are underway to structure, certify and thus promote promising carbon removal techniques. The underlying scenarios for the carbon budget calculation in report #3 "Defining budget-base targets" of this study also consider negative global emissions from 2073 onwards [21].

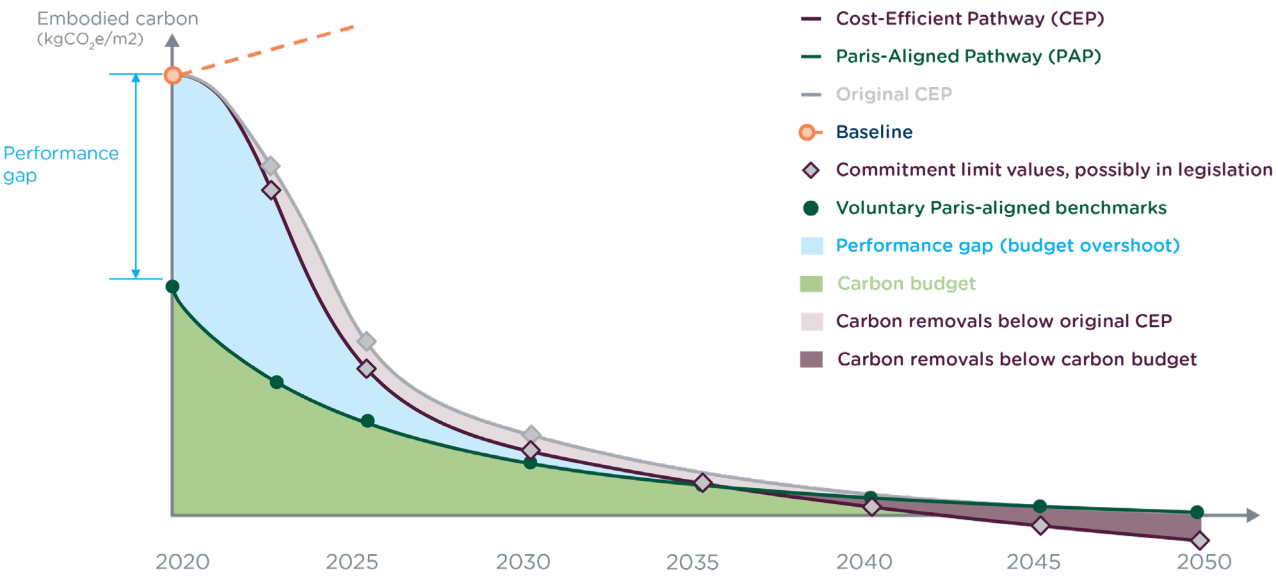
However, there are **important limitations to removing carbon as part of** achieving climate action. Firstly, the amount of carbon removed in the future is uncertain, in particular as technological removal solutions are not yet available at a significant or commercial scale. Secondly, the storage duration in a building is also uncertain, as early demolition may release the captured GHGs back into the atmosphere. These two reasons result in a risk in relation to relying on future negative emissions to balance short-term overshoots. As a third limitation, the emissions will have had their greenhouse effect over the period between their release and the removal. Thus, global warming may have continued, and a direct balancing may not be appropriate.

Nonetheless, the contribution of carbon removals through biogenic materials and end-of-life carbon capture – as one measure in combination – can be a relevant factor in mitigating the performance gap of embodied carbon.

The sum of emissions is assumed to be negative in the CAP after 2073. Therefore, an excess in the global emission scenario could lower the budget overshoot. It is stressed that using biogenic materials and preparing for further carbon removal needs to start without any delay and must reach a negative sum prior to 2073 in order to balance the overshoot from the earlier years.

Figure 12 illustrates the possible effect of carbon removals with an earlier start, in the 2040s. As the illustration shows, expanding negative emissions at a speed comparable to previous emission reduction rates only balances small shares of the initial overshoot.

Figure 12: Effects of carbon removals on a performance framework



6. Conclusions and recommendations

A performance framework is urgently needed to close the embodied carbon performance gap between the baseline of current embodied emissions and the available carbon budget for these emissions. To achieve this, both bottom-up and top-down considerations need to be reflected in the reference or limit values. However, data availability is a crucial challenge in this context, as standardised LCA data for buildings is needed to calculate a baseline, budget and to inform the definition of decarbonisation pathways.

Therefore, the proposed performance framework builds on a **foundation** that aims at making the necessary data accessible and usable, in order to then be able to define a **performance framework** in which benchmark values are set as milestones for the future.

This performance framework requires broad efforts at national level, involving policymakers, existing certification schemes, the building industry value chain and academia, as summarised in Table 6. **The role of the EU** is, however, also important in enabling cross-national comparison through general standards and supporting and harmonising national efforts with initiatives, for example the Level(s) framework. Moreover, an EU-level g system as a framework, guidance and reference for national advances is highly relevant.

Table 6: Call to action on combined effort for establishing a performance framework

Call for action	Who?	What?
Foundation		
LCA method and metrics	Policy makers Researchers Product manufacturers Building designers Certification bodies Non-profit organisations	• Develop a robust national LCA method and develop environmental product declarations applicable to the country both industry-specific and product-specific • Create basis for harmonising national methods
	Policy makers	• Implement LCA method in national building regulations or otherwise promote the use of the method
	Building designers Real-estate investors	• Adopt whole life cycle thinking and the national method and integrate in everyday practice
Data generation	Policy makers	• Create obligations or other strong incentives to use the LCA method developed in step 1
	Researchers Product manufacturers Certification bodies Building designers Non-profit organisations	• Use the method to monitor embodied carbon and publish reports regularly
Data collection in databases and software tool	Researchers Certification bodies Building designers Non-profit organisations	• Initiate and maintain national data collection for LCA data
	Policy makers Certification bodies	• Develop a software tool for LCA calculation, data collection and analysis • Create open-source database for LCA data
	Building designers Real-estate investors	• Use data and tool to assess and compare projects

Performance framework		
Baseline	Policy makers Researchers	• Determine the baseline based on the current building practice compiled in the database • Monitor progress and regularly update the baseline
Carbon budget	Policy makers Researchers Building industry NGOs	• Define carbon budget based on data and support from the industry, researchers and certification bodies
	Policy makers	• Publish carbon budget in a policy document
Benchmarks and limit values along pathways	Policy makers Researchers Building industry NGOs	• Agree on and commit to a Cost-Efficient Pathway
	Policy makers	• Define Paris-Aligned Pathway based on carbon budget distribution over time and Cost-Efficient Pathway based on sector agreement • Set reference values for limit values and voluntary benchmarks at intervals of 3-5 years • Monitor progress and regularly update the pathways and reference values
	Certification bodies	• Align with voluntary benchmarks, go beyond limit values

Out of the steps needed to develop the proposed performance framework, **defining a harmonised data collection method** is the first priority, where collaboration is needed to align the potential existing practices used by public institutions, the different certification schemes, research methodologies and information on material production fed into an LCA calculation method, that is efficient and robust on all of a building's life cycle stages. Promoting the resulting method and requiring its application by policymakers would provide highly relevant support to ensuring fast and widespread uptake.

As a result, **data could be generated and collected** by researchers, building designers, investors or shared via the certification bodies. This collective work would help create the database required within the shortest possible time, while maximising the data collection efficiency and representativeness.

The **calculation of the carbon budget** will be needed on the same scale as the LCA method. Again, a combined effort of academia, policymakers, industry and certifiers is needed to obtain the necessary data points. A broad coalition of credible institutions across the building industry is needed to form the basis of the calculation. An agreement on principles at the global or EU level is considered to be very useful to ensure a harmonised and consistent approach at national level, and in organisations and municipalities. Ultimately, policy documents should define a carbon budget for embodied emissions, for example as part of a whole life carbon emission roadmap for buildings.

As mentioned, **defining the Cost-Efficient Pathway** requires an agreed commitment by the sector and should, therefore, be based on a wide consultation. This should be managed by a credible and well-accepted institution in the national sustainable buildings landscape, either from public policy institutions or from independent bodies.

Establishing this performance framework will be an important step towards reducing embodied carbon in maximum alignment with global climate objectives and would provide a framework for further actions and measures in the sector.

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