Embodied carbon emissions in buildings: explanations, interpretations, recommendations

BRIEFING NOTE

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ABSTRACT

What is embodied carbon and why is it a significant challenge for clients and designers in the real estate and construction sector? It is the sum of greenhouse gas (GHG) emissions that arise in the life cycle of a building during manufacture and construction (upfront), maintenance and replacement of building components (recurrent), as well as dismantling and waste processing (end of life). Currently, the relative and absolute share of embodied carbon in the life cycle of a single building is growing and becoming a dominant factor in the case of energy-efficient buildings. For example, for new buildings, it can represent more than 50% of life-cycle carbon. Against this background, embodied carbon is becoming an object of assessment not just in research but also in design and decision-making. It also becomes a key action to reduce GHG emissions. Embodied carbon assessment and reduction are being increasingly mandated in national regulations. Clients and designers (as key actors in the supply chain) can harness new knowledge and tools to reduce embodied carbon as part of a strategy to reduce overall GHG emissions. Appropriate methods, data, benchmarks and tools are being further developed and operationalised to support the processes for specifying and designing low carbon buildings. An overview is presented of the state of knowledge and current developments. Constructive recommendations are provided for actions that clients and designers can take.

KEY FINDINGS

- From the perspective of a single building's life cycle, the proportion of embodied carbon is around 50% on average for new energy-efficient buildings. From a macro-economic perspective, approximately 10% of global energy-related CO_2 emissions are attributable to the embodied emissions of buildings.
- Designers can influence and assess embodied carbon according to related design targets in the client's brief and/or legal requirements.
- A trade-off between operational and embodied carbon is typical, but possibilities exist to optimise both sides.

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- Embodied carbon can be reduced by selecting low carbon construction products and/or reused building components.
- Further possibilities are the revitalisation of existing buildings, the extension of their service life, the minimisation of useable areas (sufficiency), as well as the optimisation of buildings and their components.
- With good design, it is possible to construct low embodied carbon buildings with little or no additional costs, and even generate economic benefits.

1. PROBLEM DEFINITION

The consequences of global warming have created an imperative to significantly reduce greenhouse gas (GHG) emissions. For buildings, this means considering not only the operational emissions but also the embodied emissions. This entails the development of legal requirements as well as changes in building design and construction practices. Embodied carbon is becoming a topic of growing importance, especially because its absolute and relative share in the life cycle of buildings is currently increasing. Questions arise for all those involved in policymaking, the real estate and construction industries, as well as design who may now be dealing with this topic for the first time.

The specific questions addressed in this briefing note are:

- What does the term ‘embodied carbon’ mean? How is it interpreted?
- Which system boundaries should be considered in an assessment?
- Why is reducing embodied carbon important?
- How can embodied carbon be assessed and influenced when designing new construction and refurbishment projects? Are there appropriate methods and user-friendly tools available?
- How can embodied carbon be reduced by decisions of clients and designers?

2. BACKGROUND

There is a long track record to reduce the demand for construction materials, as well as for the raw materials and energy required to produce them. A century ago an interest in the minimum amount of coal required to manufacture products arose, while 50 years ago the ‘energy crisis’ shifted the emphasis on crude oil. Over the last decade, the recognition of a growing ‘climate crisis’ broadened the embodied energy concept to embodied carbon. Authoritative scientific reports (such as the United Nations’ Intergovernmental Panel on Climate Change—IPCC) have highlighted why embodied carbon requires urgent action.

Building regulations have been focused on building operational energy demand (and the associated emissions). However, GHGs are caused and emitted at every stage of a building’s life cycle. From a macro-economic perspective, today approximately 10% of total global anthropogenic GHG emissions result from the manufacture of building construction materials such as steel, cement and glass (UNEP 2021). To meet the stated societal goals of radically reducing GHG emissions, it is necessary to assess and reduce the building-related embodied part (the embodied GHG emissions are called ‘embodied carbon’ here in line with common terminology). This task can be assisted by using harmonised assessment methods, the improvement of data quality for construction products, and the deployment of user-friendly design and assessment tools.

3. CURRENT STATUS

Today, several developments are driving the consideration of embodied carbon (Figure 1). Several formal standards provide the basic principles for assessing life cycle GHG emissions of buildings and construction products at both the European (European Committee for Standardization (CEN), *e.g.* EN 15978 and EN 15804; CEN 2011, 2019) and international (International Organization for Standardization (ISO), *e.g.* ISO 21929 and ISO 21930; ISO 2011, 2017) levels. Based on these standards, several organisations such as The Royal Institute of British Architects (RIBA), The Royal Institution of Chartered Surveyors (RICS) and the World Green Building Council (WGBC) have implemented methods, guidelines and tools to assist their members. International research projects such as the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC) Annex 72 are underpinning the development of methods, guidelines and tools to ensure they are robust and fit for purpose, and to create the basis for a next generation of guidelines, standards and legal requirements.

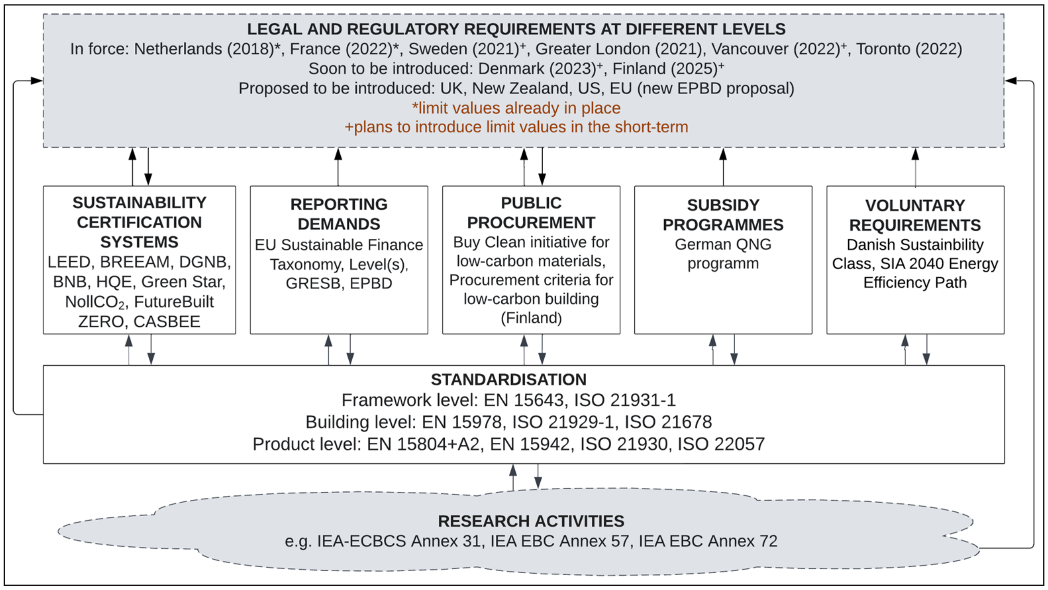

Figure 1: Examples of developments regarding embodied carbon.

Source: Authors.

In the policy and market realms, there is a trend to establish whole-life carbon (WLC) as a criterion in building sustainability assessment systems. The reduction of embodied carbon is becoming a requirement in green public procurement, as well as a prerequisite for the allocation of subsidies. Building developers and buyers are increasingly being informed about the carbon footprint of buildings (*e.g.* EU Taxonomy and the current draft of the Energy Performance of Buildings Directive (EPBD) in Europe). Several countries (Figure 1) have now set mandatory requirements to report life cycle-based environmental performance assessment results of buildings, including embodied carbon, and some have even introduced or will soon introduce binding embodied carbon or WLC limits (*e.g.* France, Denmark and Sweden). In some countries, local authorities take the lead and demand such assessments (*e.g.* Greater London Authority (GLA), City of Vancouver).

4. KEY CONSIDERATIONS

4.1 TERMINOLOGY

What is meant by the term 'embodied carbon'? This is not the carbon physically contained in the building. Rather, it is the allocation of GHG emissions that arise in the production of construction products of all kinds, their transport to and from the building site, the processes of building construction, maintenance, replacement and deconstruction, as well as the end of life of building components and the building. There are initial/upfront, recurrent and end-of-life-related emissions.

GHG emissions include not only CO_2 but also other gases with a global warming effect. CO_2 emissions dominate GHG emissions with 75% of the global average and in some countries up to 90%. These are typically reported by converting them into kg CO_2 equivalents to express their global warming potential.

Concerning the physical carbon content in a building, the indicator 'biogenic carbon content' was recently introduced in European standards to describe it (kg C).

The quantification of embodied carbon of building products is often achieved using the life cycle assessment (LCA) methodology. LCA is the systematic analysis of the energy and material flows and the resulting effects on the environment, including the climate. The case of determining the embodied carbon of a building as part of a WLC assessment is an applied LCA. It is usually sufficient to link product quantities with life cycle-based environmental data for products and services determined using LCA—although variation can occur between similar products due to different primary energy sources or manufacturing processes. The result is also referred to as a building-related carbon footprint, where embodied carbon is seen as a partial carbon footprint.

4.2 IMPORTANCE

The development of more stringent operational performance requirements has increased the importance of embodied carbon from buildings. Often, high-efficiency buildings require more materials and technical equipment which increase the embodied part of the carbon footprint. However, high operational energy performance does not necessarily have to result from high embodied carbon. An analysis of hundreds of global LCA case studies of both residential and office buildings (Figure 2) demonstrates the possibility of designing buildings with low embodied carbon that comply with ambitious building energy-efficiency regulations (Röck *et al.* 2020). To put it differently, the optimisation of both embodied and operational emissions is technically feasible and necessary to achieve net zero emissions over the life cycle.

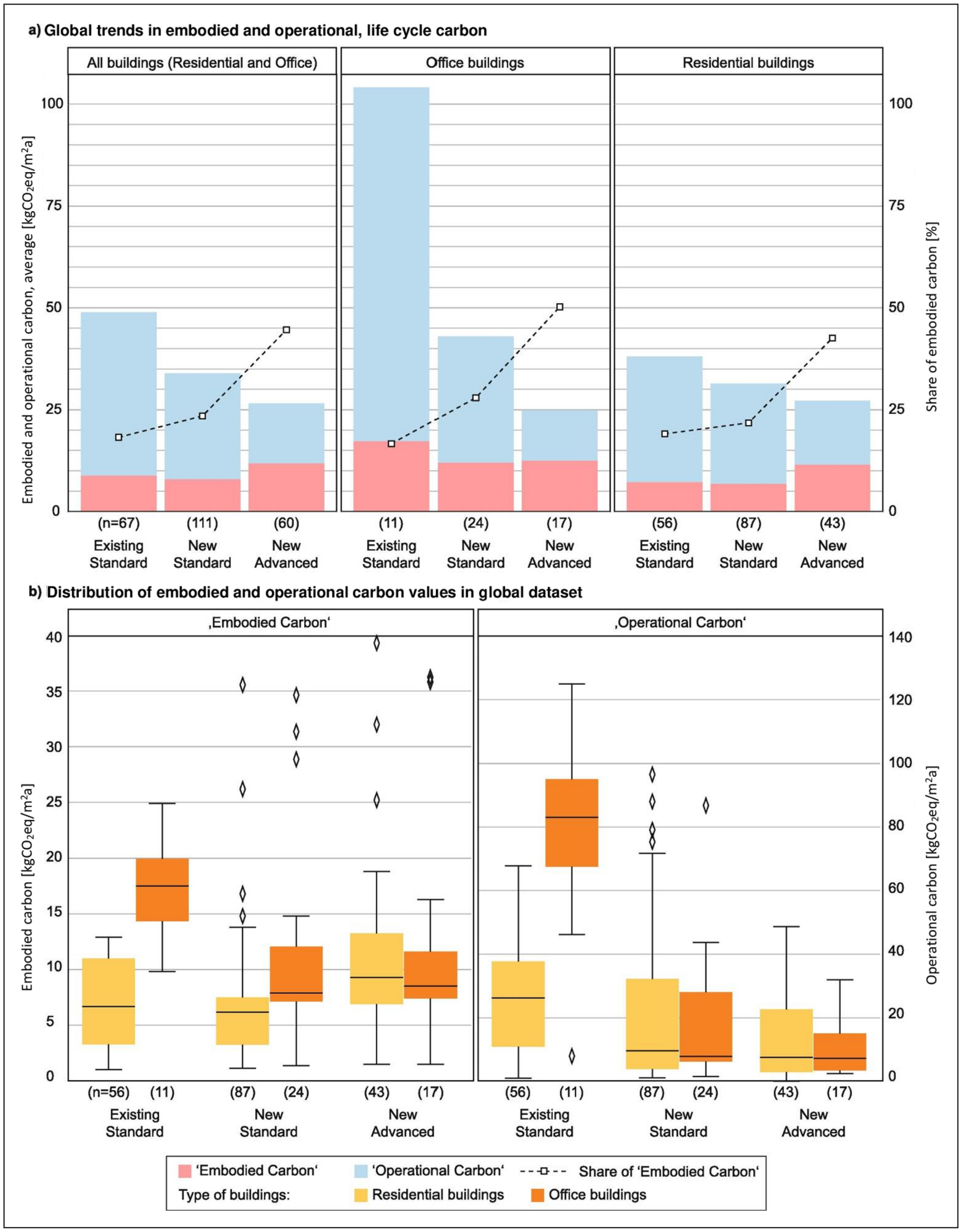

Figure 2: (a) Global trends in life-cycle greenhouse gas (GHG) emissions (sometimes also called whole-life carbon—WLC) showing an increasing proportion of embodied GHG emissions (called embodied carbon) (dotted line) ranging from 20% to 50% of overall GHG emissions for new standards and advanced standards; and **(b)** distribution of GHG emissions for residential and office buildings by energy performance class showing that within a class there is considerable scope for optimisation of the embodied part.

Source: Röck *et al.* (2020).

4.3 SYSTEM BOUNDARIES

The life cycle of a building has several stages and a framework exists to define each stage (Figure 3). Each stage requires a calculation of embodied carbon. The range of values for embodied carbon found in the literature is often due to the methodological choices behind their calculation. The interpretation of these values depends heavily on the defined object of assessment, *i.e.* what building components are included in the building model and what life cycle stages are included or omitted in the life cycle model. In combination with communication of an assessment result, it must be made explicit what scope of assessment and which system boundaries were applied.

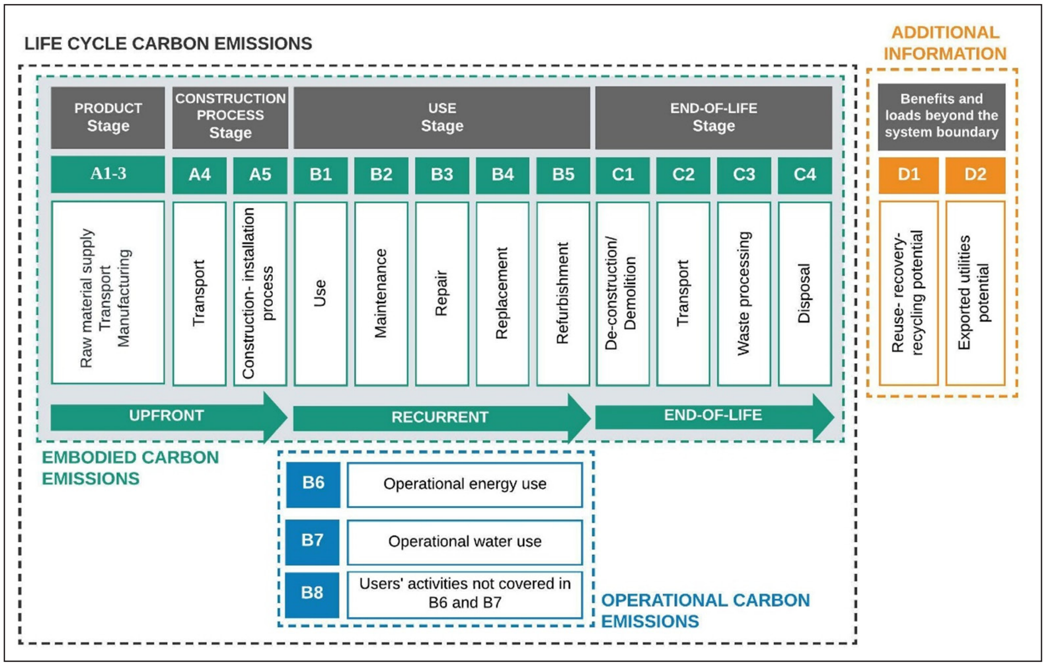

Figure 3: Life-cycle model and names of modules, highlighting the embodied part.

Source: Based on Standard EN 15643 (CEN 2022).

Carbon footprint assessments differ significantly in these two scopes. Regarding the building model, the variation with the most critical effect is the inclusion/exclusion of building services such as heating, ventilation and air-conditioning (HVAC) systems. These could account for nearly 40% of embodied carbon of technology-intensive buildings (Hoxha *et al.* 2021). In the past, the focus was on the structure so the technical systems were neglected due to limited data availability. However, this has changed and today the aim is to have an as complete building model as possible.

In future, a more intense focus on emissions released before the building operation begins (often called upfront carbon emissions) is expected as they are responsible for more than 60% of the total embodied carbon and are immediately consuming the remaining global carbon budget (Röck *et al.* 2022). However, the inclusion/exclusion of the impacts associated with the replacements of building components during use stage can have a considerable effect (Birgisdottir *et al.* 2017). It is important to stress that post-handover results strongly depend on assumptions about the service life of building components (Goulouti *et al.* 2020) and end-of-life processes, among others.

4.4 AVAILABILITY OF DATA AND TOOLS

The design team faces many design and material choices. Quality assured data for construction products and processes are vital for evaluating the carbon implications of these choices. Reliable data exist for construction products and construction processes based on published LCAs, as part of quality-proofed environmental product declaration (EPD), in quality-verified databases, integrated in quality-verified assessment tools or from other sources. These require regular updating to provide temporal and geographical validity. For example, the energy mix used in the manufacturing of a large proportion of products as well as the efficiency of the manufacturing processes themselves change over time (Alig *et al.* 2020). In the long run, data taking into account the results of the decarbonisation processes in the sense of forecasts for 2030, 2040 and 2050 are needed to model future replacement.

Building assessment tools are currently being developed worldwide that are easy for designers to use even without knowledge of the details of an LCA (Melton 2019; Marsh *et al*. 2018). A procedure for identifying the right tool according to specific designers' or users' needs is proposed by Di Bari *et al*. (2022).

5. CONCLUSIONS

Embodied carbon is an important part of the carbon footprint of buildings. Their relative, and in most cases also the absolute, contribution is increasing. For buildings with no or net zero GHG emissions in operation, the share of the embodied part is 100%.

A prerequisite for the assessment of embodied carbon for buildings is the availability of corresponding data for construction products. Assessment method, data and benchmarks and/or target values must form a package.

The reduction of embodied carbon makes a significant contribution to reducing the building-related share of global GHG emissions. For this, operational energy efficiency standards need to be augmented with specific target values for embodied carbon and/or WLC. Related policy and regulation are already being developed in some countries. The introduction of regulation will reduce uncertainties, define system boundaries, and make both the assessment process and reporting more transparent.

The assessment and reduction of embodied carbon is a design task. Targets should already be formulated in the client's brief or integrated into voluntary/legal requirements. The system boundaries need to be communicated transparently and should be based on international or European formal standards.

6. RECOMMENDED ACTIONS FOR CLIENTS AND DESIGNERS

Clients have a responsibility for decisions throughout the initiation, design and implementation of a building project. Clients may be individuals, institutional and public organisations or commercial project developers. Standard EN 15643 (CEN 2022) recommends formulating requirements not only for the functional and technical performance in the client's brief but also for environmental performance. In this context, the aim to reduce embodied carbon can also be addressed. However, it is first necessary for the client to make full use of the possibilities to act, given as examples in Table 1.

Table 1: Non-exhaustive list of recommended actions for clients.

AVOID CONSTRUCTION	REDUCE CONSTRUCTION
• Organisational instead of structural solutions (new working practices, home offices, *etc.*) • Densification of organisational processes in existing building areas • Avoidance of non-essential spaces (*e.g.* cellars and underground garages)	• Reuse/refurbish/repurpose existing buildings • Extension of existing buildings • Use of already developed land

A sufficiency strategy and space optimisation can avoid building anew. The willingness to forgo a new building can be allayed if the functional and technical requirements can be met by an existing one. Clients can already receive support from design professionals and consultants with these tasks. Another client task is to provide designers with adequate time and money to compare and assess design solutions and to actively commission them to do so. For many clients, the benefit of lower embodied carbon is already obvious. This can lead to better results in sustainability assessments, marketing, valuation and financing as well as insurance conditions. The associated cost needs to be examined more closely. Despite the wide range, there are examples of only minor additional costs for low embodied carbon buildings (Jungclaus *et al*. 2021).

Clients/investors and their associations (amongst others) should:

- make specifications for limiting embodied carbon as part of the environmental performance targets in the clients' brief
- ask banks for special financing conditions, *e.g.* see EU Sustainable Finance Taxonomy
- request 'as built' embodied carbon values and actively communicate them to third parties: customers, tenants and valuation professionals
- undertake cost–benefit analyses in relation to the design option for low embodied carbon

Options for designers to influence embodied environmental impacts, including embodied carbon, are listed in Table 2.

Table 2: Non-exhaustive list of recommended actions for designers.

DESIGN DECISIONS	MATERIAL CHOICES
• Choice of construction and structural system • Choice of storeys and spans • Use of form factor or surface-to-volume ratio as a metric • Building and component optimisation • Optimisation of ancillary/public spaces • Design for durability • Design for dematerialisation • Design for flexibility and adaptability • Design for ease of maintenance and repair • Design for deconstruction and recyclability	• Reuse of building components • Use of products that demonstrate lower embodied carbon through data from environmental product declarations (EPDs) or other reliable sources • Use of local products (reduced transport distances)

These possibilities fall within the efficiency and consistency (regenerative) strategy. It is important to determine, assess and influence embodied carbon during design. Designers and their associations (amongst others) should:

- design (for associations) and undertake (for individuals) further training on calculating, assessing and reducing embodied carbon
- include the task of calculating, assessing and reducing embodied carbon in the scope of professional services and fee regulations
- develop user-friendly design tools that integrate embodied carbon considerations and can be used at early design phases such as element catalogues or suitable software, or specifically ask about them
- start own initiatives, which call for the introduction of binding reporting and reduction requirements for embodied carbon

Since upfront emissions are an important part of embodied carbon and immediately consume parts of the remaining global budget for greenhouse gas (GHG) emissions, it is particularly important not to delay efforts to reduce them in both new building and refurbishment projects in a coordinated action of clients and designers but also policymakers and the construction product industry.

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COMPETING INTERESTS

The authors have no competing interests to declare.

FURTHER READING

De Wolf, C., Pomponi, F., & **Moncaster, A.** (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, 140, 68–80. DOI: https://doi.org/10.1016/j.enbuild.2017.01.075
Evaluates the current construction industry practice in relation to embodied carbon emissions (ECE) measurement of buildings. Particularly, it analyses incentives in the available building codes, standards and benchmarks, as well as the existing methodologies, tools and datasets.

Häkkinen, T., Kuittinen, M., Ruuska, A., & **Jung, N.** (2015). Reducing embodied carbon during the design process of buildings. *Journal of Building Engineering*, 4, 1–13. DOI: https://doi.org/10.1016/j.jobe.2015.06.005
Evaluates how current methods can be systematically integrated into different phases of the design of low embodied carbon buildings. Particularly, it uses the Royal Institute of British Architects (RIBA) stages of design, and for each stage it identifies the objectives, typical deliverables and milestones necessary for ensuring embodied carbon efficiency.

LETI. (2020). *LETI embodied carbon primer: Supplementary guidance to the Climate Emergency Design Guide.* https://www.leti.uk/ecp
Offers guidance to designers, including architects, engineers, interior designers and urban designers, interested in exploring embodied carbon in more detail and design buildings that deliver ambitious embodied carbon reductions.

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Rasmussen, F. N., Wiberg, A. H., & **Potting, J.** (2018). Design and construction strategies for reducing embodied impacts from buildings—Case study analysis. *Energy and Buildings*, 166, 35–47. DOI: https://doi.org/10.1016/j.enbuild.2018.01.033
Analyses a large number of case studies collected under the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC) Annex 57 as well as additional scientific literature to identify design strategies and their quantitative potentials to reduce embodied energy and greenhouse gas (GHG) emissions from both new and refurbished buildings. These strategies can be considered by the stakeholders with the capacity to influence the outcome of individual building projects.

Mohebbi, G., Bahadori-Jahromi, A., Ferri, M., & **Mylona, A.** (2021). The role of embodied carbon databases in the accuracy of life cycle assessment (LCA) calculations for the embodied carbon of buildings. *Sustainability*, 13(14), 7988. DOI: https://doi.org/10.3390/su13147988
Demonstrates the importance of establishing accurate baselines for ECE, as the results can vary drastically based on the chosen database. Particularly, based on a case study, it shows that using a more detailed database compared with a more general one could result in a more than 30% reduction of ECE, while using more detailed data from a single database can reduce it even further.

Minunno, R., O'Grady, T., Morrison, G. M., & **Gruner, R. L.** (2021). Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments. *Renewable and Sustainable Energy Reviews*, 143, 110935. DOI: https://doi.org/10.1016/j.rser.2021.110935
Creates a benchmark for ECE of buildings and develops a procedural guideline that assists practitioners in decreasing the environmental impact of buildings, looking at strategies focusing on both single construction materials (*i.e.* concrete, reinforcement bars, structural steel, timber, tiles, insulation and plaster) and entire buildings (*i.e.* three building types: concrete, timber and steel).

Pomponi, F., De Wolf, C., & **Moncaster, A.** (Eds.). (2018). *Embodied carbon in buildings: Measurement, management and mitigation*. Springer.

Provides a comprehensive guide to ECE calculation and reduction, with a particular focus on understanding uncertainty. Also includes examples of approaches used by industry professionals, and specific routes to ECE reduction.

RIBA. (2021). *RIBA 2030 Climate Challenge Version 2*. The Royal Institute of British Architects (RIBA). https://www.architecture.com/about/policy/climate-action/2030-climate-challenge
Provides targets and a checklist of actions to encourage built-environment practitioners to take action now and to collaboratively shift in the profession towards outcome-orientated design approaches.

Sturgis, S. (2019). *Targeting zero: Whole life and embodied carbon strategies for design professionals*. Routledge.
Explains a practical approach to carbon emission reductions through the construction and use of buildings based on the experience of the consultancy Sturgis Carbon Profiling (Scp) and the selection of a wide range of building projects.

ULI. (2019). *Embodied carbon in building materials for real estate*. Urban Land Institute (ULI). https://knowledge.uli.org/-/media/files/research-reports/2019/greenprint-embodied-carbon-report-final.pdf?rev=4e5811159ba745dd9676d34fdc2b39d2&hash=EE529444275289229F3071FB940D4FD8
Provides a simple pathway for a developer to reduce ECE in construction and explains how this can also lead to financial savings in addition to mitigating the impacts of climate change.

WBCSD. (2019). *Decarbonizing construction: Guidance for investors and developers to reduce embodied carbon*. World Business Council for Sustainable Development (WBCSD). https://www.wbcsd.org/Programs/Cities-and-Mobility/Sustainable-Cities/Transforming-the-Built-Environment/Decarbonization/Resources/Decarbonizing-construction-Guidance-for-investors-and-developers-to-reduce-embodied-carbon
Targets developers and investors and provides over 50 ECE reduction policies and best practices that can be adopted by them for their building projects.

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