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Primer

Embodied carbon emissions of buildings and how to tame them

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SUMMARY

Building construction and operations are pivotal in climate mitigation efforts. While emissions from building operations can be easily reduced through renewable energy adoption and improved energy efficiency, the so-called "embodied" greenhouse gas (GHG) emissions, also called "embodied carbon," associated with building material production and processing are expected to rise due the global construction demand. Thus, a comprehensive understanding of the embodied emissions throughout the building life cycle is crucial to identify mitigation opportunities and implement effective measures. This primer introduces the topic of life cycle embodied carbon emissions in buildings, explains the notion of temporal and spatial embodied carbon, sheds light on current regulations and strategies to reduce embodied carbon emissions throughout the building life cycle, and eventually highlights the importance of accounting for life cycle sustainability beyond a mere focus on carbon emissions.

INTRODUCTION

Since the beginning of human history, the act of "building" and the resulting "buildings" have been of utmost importance. What historically began as a strategy for sheltering from the harsh elements has quickly become an integral part of human civilization. Today, a growing majority of the human population lives in urbanized regions where people are always either in a building or moving between buildings. Buildings, and the large variety of functions they are designed to host, are no less than essential to the sustenance of modern human life.

The significance of buildings for the well-being of people is paralleled only by the magnitude of environmental impacts associated with their production and construction, operation, maintenance, replacement, and demolition. Indeed, greenhouse gas (GHG) emissions released throughout the so-called building life cycle are the single greatest contributor to total global anthropogenic GHG emissions, with building construction and operation alone responsible for almost 40% of global energy-related emissions—one fourth of which can be attributed to the manufacture of building construction materials such as steel, cement, bricks, and glass.

Historically, the vast majority (more than 80%) of emissions within the building life cycle have been related to buildings' operation, specifically the significant (fossil-fuel-derived) energy demands for the maintenance of thermal comfort. However, the introduction of newer, more energy-efficient buildings has helped to reduce operational carbon emissions to less than 50% of whole life carbon (WLC) emissions. As energy-efficient buildings become the norm, renewable energy sources increase, and buildings' operational emissions start to approach "net zero," emissions hotspots are transferring to other parts of the building life cycle, namely material manufacturing (e.g., production for cement and steel), maintenance and replacement (e.g., maintenance or replacement of flooring), and end of life (e.g., incineration of construction waste). These embodied emissions are also on the rise due to an increase in demand for material to support advanced energy efficiency, such as material in technical building systems (e.g., heat pumps, solar cells, or batteries), multi-pane windows, and insulation materials. Furthermore, material demand and embodied carbon emissions per capita are growing due to trends of oversized buildings and at times over-dimensioned or inefficient building structures.

Reducing embodied emissions is fast becoming the major challenge for effective climate change mitigation in the built environment. It is thus of particular importance to have a comprehensive understanding of the embodied emissions throughout a building's life cycle. Whole-building life cycle assessment (LCA) has quickly become the most accepted method to determine buildings' carbon footprint and wider environmental performance and is currently being employed in regulatory frameworks around the world. By systematically considering the resources consumed and the emissions and waste generated throughout all stages of the life cycle of a product, process, or system, LCAs allow the identification of potential hotspots in varied supply chains and enable fairer comparisons and decision-making based on environmental performance.

The proper application of LCA, however, presently requires expert knowledge and a vast amount of data and tools capable of comprehensible calculations and valid comparisons. Furthermore, a building's life cycle encompasses a multitude of economic sectors, making them a field of action rather than a single sector. Consequently, to identify, estimate, and control life cycle carbon emissions of buildings, one needs to consider an

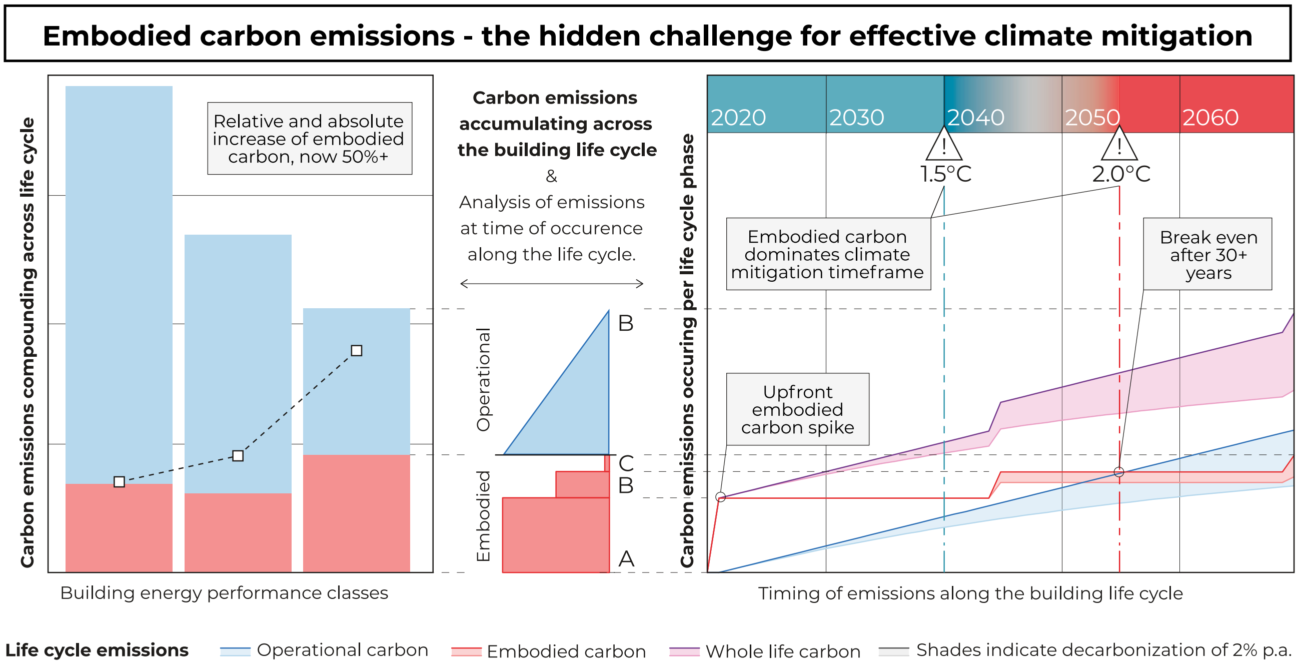

Figure 1. Embodied and operational emissions profile across the building life cycle

Life cycle stages relevant for embodied carbon of buildings and temporal profile of embodied and operational emissions across the building life cycle. Note the distinct nature and different temporal dynamics of operational carbon emissions, which occur continuously over the life cycle, and embodied emissions, which occur in spikes, at particular times and mostly "upfront," for material production and construction processes. Reproduced with permission from Röck et al. (2020).

abundance of activities and their peculiarities, which together contribute to the complex environmental performance of the built environment. Moreover, climate change is increasingly perceived as a wicked problem, meaning that it involves socio--political dimensions that hinder the proposal and implementation of straightforward technical solutions. And when all requirements are assured to allow a careful and comprehensive life cycle modeling, the remaining challenge lies in identifying the best combination of embodied carbon reduction and removal strategies throughout the wide temporal and spatial boundaries of our built environment.

Here, in this primer, we unpack each of these important aspects by explaining the different types of building embodied carbon emissions via the lens of temporal and spatial dimensions. We then explain the current regulations and strategies in mitigating these embodied emissions throughout the building life cycle and eventually reflect upon the need to account for a broader sustainability footprint to support the pathway toward and the implementation of net-zero whole life carbon buildings.

EMBODIED CARBON: SPATIAL AND TEMPORAL DIMENSIONS

Temporal distribution of whole life carbon emissions

Operational carbon emissions mostly stem from energy use. Often, operational carbon emissions are considered to occur continuously during each year the building is in use. When modeling and assessing operational carbon emissions, it is therefore common practice to "annualize" emissions over the full life cycle. The common annualization of carbon emissions is expressed by the still-standard use of a reference of kilogram CO_2 equivalents per square meter (or square foot) building floor area and per year: kgCO_2e/m^2/a.

However, in contrast to the continuous emission of operational carbon, embodied carbon emissions occur in bursts, or "spikes," at specific times (Figure 1). The largest of those spikes occurs "upfront," for initial building material production and processing as well as the transport and construction process itself. Furthermore, in the face of a changing climate and related changes in seasons and weather patterns, the heating and cooling loads of buildings can change, resulting in interannual variations of carbon emissions. In addition, the decarbonization of energy systems and material-related processes is progressing. Therefore, the calculation of embodied and operational emissions without considering the actual timing of emissions can result in under- or over-estimation. Hence, to more precisely account for the temporality of operational and especially embodied carbon, one should use a reference unit that does not annualize emissions but rather expresses emissions according to the physical reality, based on the life cycle stage, the year, or more specific point in time at which they occur. The new reference unit should thus be kilogram of CO_2 equivalents per m^2 floor area—kgCO_2e/m^2. Here, the spatial resolution of LCA studies and results may vary, and emissions can be expressed, for example, per life cycle stage, per year, or, in future assessments, potentially at an even higher resolution of per month or per day.

Another important temporal aspect relates to the forecasting of future emissions. Presently, prospective LCA modeling relies on the selection of plausible scenarios for activities occurring during the future life cycle of buildings such as the service life

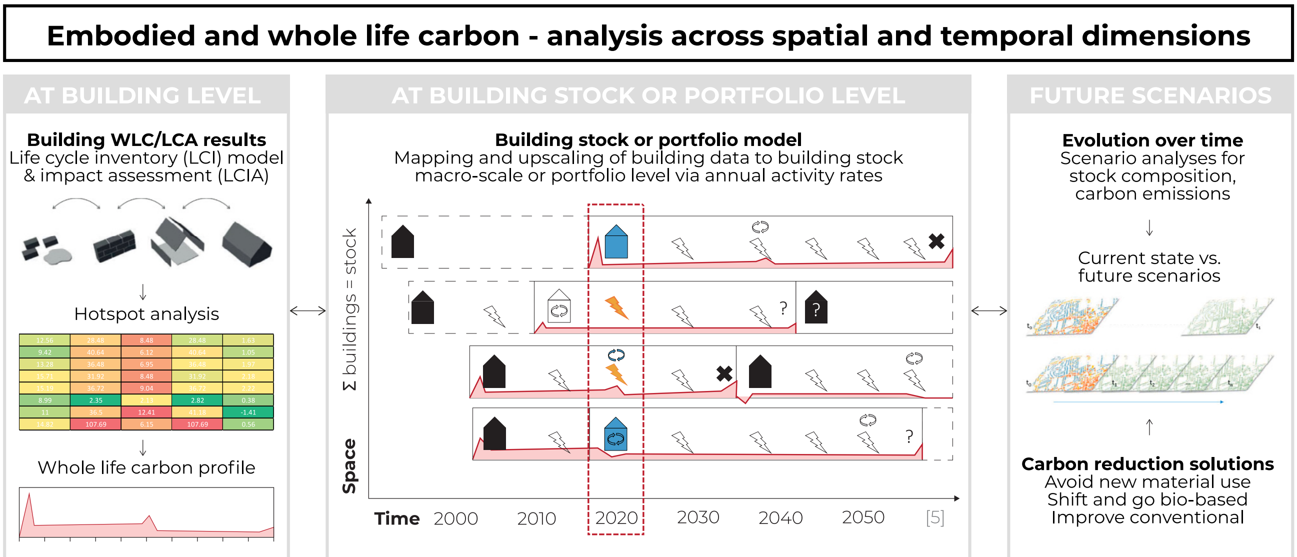

Figure 2. Spatial and temporal hotspots at building and building stock levels

Illustration of hierarchical LCA modeling and analysis of spatial and temporal hotspots of embodied carbon flows at building level (A); the use of building-level LCA/WLC data for macro-level building stock analysis through mapping and upscaling based on annual activity rates (new construction, renovation, demolition, etc.) (B); and the projection of building stock evolution over time for assessing scenarios of stock development and low-carbon strategy uptake (C). Reproduced with permission from Röck (2023), building on Habert et al. (2023), Trigaux et al. (2021), and Mastrucci et al. (2017).

of building components, development of future energy mixes, and future emission intensity of construction products, as well as, increasingly, the effects of climate change (e.g., on the changes of energy use and associated emissions for thermal regulation). However, the landscape is constantly changing. For example, both the growing demand for less carbon-intensive bio-based building materials and the proliferation of mineral-intensive renewable energy systems will each impact long-term carbon emissions through changes in land use. From a methodological perspective, prospective LCA modeling must therefore take into account the newly emerging dynamics if we are to adequately and accurately forecast and correctly interpret the temporal embodied carbon emissions associated with construction materials and buildings over the longer term.

Spatial allocation of whole life carbon emissions

To understand the spatial dimension of embodied carbon emissions, it is important to first distinguish such emissions at the micro level and the macro level.

The spatial micro level of embodied carbon refers to embodied carbon within buildings, elements (e.g., floors, walls, roofs), and materials, as shown in Figure 2. At the micro level, embodied carbon emissions can be best understood based on the modeling of the material inventories, i.e., the compilation of the quantity of different construction materials embedded in the building, which are the basis for modeling the embodied carbon of buildings. When calculating micro-level embodied carbon, the selection of building elements to be included is an important consideration, as this is essential in determining the related system boundaries (i.e., boundaries for which component of a building should be accounted for when calculating the embodied carbon emissions). LCA studies applying the so-called "element method" use a hierarchical approach to define building elements based on their composition in terms of individual functional layers and respective construction materials used. These element definitions can hence be used to model embodied carbon emissions for a complete building. To accurately calculate the micro-level spatial embodied emissions, especially to identify emission hotspots, it is recommended that element-based modeling be conducted and that all levels of information be maintained without aggregation: keeping a high-resolution, non-aggregated inventory can enable the analysis of both resource use as well as embodied carbon of individual materials within every building element.

The spatial macro level of embodied carbon refers to embodied carbon emissions beyond individual buildings but across building portfolios (e.g., a group of buildings managed or owned by the same entity) or building stocks (e.g., the sum of all buildings in a city, at regional, national, or transnational level). The macro-level spatial dimension of buildings and building stocks includes aspects of spatial needs, meaning the requirements to offer spaces for housing and infrastructure of growing populations. In this context, external migration between countries, as well as internal migration from rural to urban regions, is an important but poorly understood driver of new construction in urban areas. Besides new construction activities required to fulfil the needs of growing populations, the macro-level perspective on embodied carbon of a building stocks and portfolios furthermore includes demolition and retrofit activities, particularly energy retrofits for improving inefficient existing buildings to reduce their operational carbon emissions. Considering the large and aging existing building stocks of developed economies like Europe or North America, effective embodied carbon investments for energy retrofitting are crucial to reduce the whole life carbon emissions of the building stock and for achieving decarbonization of the building sector at large.

STATUS AND TRENDS IN WHOLE LIFE CARBON REGULATION

To date, building regulation mostly focuses on reducing building safety risks and, in a growing number of countries, has started to consider the need for improved energy efficiency during building operation. Yet, embodied carbon—or a whole life carbon perspective—is rarely addressed in building regulation. However, very recently, there has been a noticeable proliferation in the adoption of whole life carbon regulations. For example, in Europe, several countries have already regulated or are about to regulate life cycle carbon declarations, with a few of them—including France, the Netherlands, and the Nordic countries—also introducing upper limits for life cycle building carbon emissions. In the UK, a strong push has been initiated by the London municipality to make all buildings net zero by 2050 and to ensure all new buildings are net zero in operational emissions and have reduced embodied carbon emissions by 40% by 2030. In the next few years, the requirement to measure whole life carbon under the European Union's EU Sustainable Finance Taxonomy for sustainable activities and the proposed revisions of the Energy Efficiency and Energy Performance of Buildings (EPBD) Directives are expected to further push the trend toward developing whole life carbon standards and benchmarks. In North America, however, policy measures targeting embodied carbon have mostly been driven by strong state- and city-level action (i.e., city of Vancouver and state of California). The first proposals for mandatory nationwide regulations targeting embodied carbon have only recently occurred in Canada. Similar trends can also be observed in the Asia-Pacific region, where efforts are gaining momentum to advance the Asia Low Carbon Buildings Transition (ALCBT). In the Global South, more and more countries in Asia and Africa are making progress in the development of the methods, databases, tools, and computational infrastructures required to measure whole life carbon emissions of buildings, to guide effective decarbonization measures in the building and construction sector. At the global level, a new Global Building Data Initiative (GBDI) that teams up with the UN Environment Program is currently under construction. This joint effort aims to support capacity building, data generation, and benchmarking for reducing resource use and embodied carbon emissions.

Nevertheless, whether these regulations will enable effective life cycle decarbonization in each individual building remains unclear. For instance, the assessment scope of building life cycle emissions can differ across regulations. Some regulations only account for upfront embodied carbon, whereas others follow a more holistic approach and cover a more complete life cycle. The inclusion of types of buildings can also differ across regulations, such that some focus on particular building types (e.g., single-family houses, or offices only), whereas others focus on building size (e.g., the EU taxonomy currently only applies to buildings >5,000 m^2). In addition, most of the benchmark carbon emission values and targets introduced or proposed thus far are set through bottom-up measurements based on analyses of existing buildings or archetype LCAs. These benchmarks are not based on the global carbon budgets and the Paris Agreement, which can easily cause misaligned decarbonization outcomes. All these remaining gaps are important next steps for both the research and policy communities to ensure effective and equitable net-zero transitions of global buildings.

STRATEGIES FOR CARBON REDUCTION AND REMOVAL POTENTIALS

Design steps and stakeholder perspectives

Reducing embodied carbon as much as possible requires particular attention by all stakeholders in the value chain, starting from the very beginning of the building design and decarbonization decision-making process.

Various opportunities to reduce embodied carbon exist for every step of the design process, but emissions reduction potential can decrease as projects progress (Figure 3). Implementing embodied carbon reduction strategies therefore requires a level of coordinated effort across numerous stakeholders beyond standard practice. The vertical axis of Figure 3 presents a building's design process that can be broken down into common design steps—such as strategic definition, preliminary studies, concept design, and detailed design. The horizontal information identifies the main questions and strategies that should be addressed to encourage a consistent process of using life cycle thinking and LCA tools during the design process to systematically reduce and optimize building life cycle embodied carbon.

Embodied carbon reduction and removal

There is a range of solutions to reduce embodied carbon footprints that can be broadly categorized into solutions focused on sufficiency in building demand ("avoid"), on material efficiency through smart building design or improved means of material production ("improve"), and on shifting to alternative, low-carbon material solutions ("shift"). Moreover, there are process strategies that are aimed at supporting architects and other major stakeholders in realizing the required emissions reductions, including the use of tools for measuring and tracking impacts ("measure") and collaboration to identify the right priorities and targets ("collaborate"). Figure 3 shows some examples of these types of strategies and their integration into the design process.

"Avoid" strategies aim at reducing demand for material production for new construction. Potential to reduce demand for materials can already be encouraged by architects from the very first step in the process through investigating the reuse and renovation of an existing building currently unused or inefficiently used instead of building anew. Additionally, demand can be reduced by optimizing the use of space in buildings to meet the required use profile and program, as well as fulfill similar aesthetic, functional, and energy performance. From a Global North perspective, it is particularly important to consider "sufficiency" strategies in near-term spatial planning and building design. This includes making best use of existing buildings in both rural and urban areas and making sure to prioritize redensification of rural and urban centers as well as the use of vacant buildings over new construction, wherever feasible.

"Shift" strategies include substituting lower-carbon and carbon-sequestering construction materials for conventional ones.

Phase	Design steps	Core objectives	Roles	Strategies & processes to reduce embodied carbon
EARLY DESIGN	0 Strategic definition	Requirements & target-setting, review project risks & alternatives, site appraisal, client's brief	C, D	**Question and clarify the programe and building need** Is a new building really needed? What are alternatives? Can an existing building be transformed/retrofitted instead? **Identify the embodied carbon baseline scenario** What is the building programe, which uses and areas are needed? What is the reference embodied/WLC carbon value to improve upon?
EARLY DESIGN	1 Preliminary studies	Feasibility studies, architectural competition, call for design proposals	C, D	**Build less: Reduce building size and resuse elements, materials** Can the functions/user requirement be satisfied with less built area? Which salvaged elements, products or material are available for reuse? **Set an embodied and whole life carbon budget from benchmarks** Use embodied carbon benchmarks of similar building projects to define a baseline for embodied and whole life carbon emissions early on
EARLY DESIGN	2 Concept design	Concepts, sketches, design proposals	C, D, S	**Opimise the building typology and shape (shape factor/form factor)** Can the building program and uses be fullfillfed with a compact shape be applied to reduce material use and structural requirements? **Perform an initial whole building LCA to identify hotspots to improve** Which are the most contributing building elements and materials? What are alternative solution to reduce embodied carbon emissions?
DETAILED DESIGN	3 Developed design	Design specification, building permit application	C, D, S, B	**Optimise the design of key building systems (structure, envelope)** Can we reduce material quantities? What are trade-offs in embodied and operational carbon, upfront embodied carbon and durability? **Specify low carbon materials, consider like-for-life substition** Can we achieve similar technical, functional, energy performance and better embodied carbon performance with alternative materials?
DETAILED DESIGN	4 Technical design	Detailed technical design, procurement of products and services	C, D, S, B	**Optimise the design of technical services (MEP/HVAC) and finishings** Can we reduce complexity of the MEP/HVAC systems and systems using low carbon refrigerants? Can we minimize finishes where not necessary and select carbon storing or otherwise lower carbon alternatives? Particularly for frequently changed fitouts. **Ask manufacturers for environmental product declarations (EPDs)** Verified EPDs are industry standard for disclosing environmental performance information, require EPDs for informed product selection.
DETAILED DESIGN	5 Manufacturing & construction	(Pre-)Fabrication of construction products and components, construction and supervision	C, D, B, T	**Establish guidance and targets to reduce construction waste** How do we ensure minimal waste of materials and energy off/on site? **Evaluate and document all material and energy flows** How material/energy-efficient is the production and construction, how much is wasted and how can we reduce waste?
DETAILED DESIGN	6 Handover & commissioning	As-built documentation, building hand over, commissioning and testing	C, D, S, B, T	**Document the as-built whole life carbon of the building** Update the LCA model and results as needed. **Sharing is caring: Publish the WLC/LCA data for open benchmarking** Improve collaboration, transparency and accountability by contributing the WLC/LCA results to open benchmarking initiatives.
USE PHASE	7 Operation & management	Facilities and asset management, maintenance, renovation, fit-outs	C, D, B, T	**Choose to improve carbon performance when replacing products** When products reach end-of-life, can we replace them with low carbon alternatives of similar technical, functional, aesthetic performance? **Establish carbon reduction targets for future renovation and fit-outs** How can we optimize maintenance to reduce replacement needs? Where necessary, how can we enable future replacement with low carbon alternatives?
USE PHASE	8 End-of-use, reuse & recyce	Decommissioning, deconstruction, reuse, recycling	C, D, S	**Determine the potential to reuse or recycle the building or parts of it** Which building parts, elements, or materials can be reuse/recyclced/upcycled/downcycled? How can we increase the circularity potential with targeted deconstruction strategies?

Strategies & processes

- **Avoid** material use, build (with) less, reuse, recycle
- **Shift** to bio-based materials and regenerative solutions
- **Improve** non-renewable materials and processes
- **Measure** materials use and carbon emissions, WLC/LCA
- **Collaborate** to break silos via shared targets and priorities

Roles & responsibilities

- **C** Clients (developers, funders)
- **D** Design professionals (architects & engineers)
- **S** Sustainability professionals (WLC/LCA consultants/staff)
- **B** BIM/VDC professionals (managers, modellers)
- **T** Contractors, builders (pre-/fabrication, installation)

Figure 3. Milestones and opportunities for reducing embodied carbon across the building design process

Decision support table illustrating milestones and opportunities in different design steps for reducing embodied and whole life carbon. The recommendations indicate the primary strategies (avoid, shift, improve) and primary roles (clients, design professionals, sustainability professionals, BIM/VDC professionals (BIM: building information modeling; VDC: virtual design and construction), contractors) responsible for specifications and processes to consider. Based on IEA EBC Annex 72, Frischknecht et al. (2023), Passer et al. (2023), and Embodied Carbon Toolkit for Architects.

Typically, low-carbon materials include low-carbon concrete with alternative blends, steel produced with electric furnaces, timber from sustainably harvested forests, and other bio-based materials. There is increasing evidence of the strong potential of reducing embodied carbon and enabling temporal carbon storage through the use of fast-growing bio-based materials, such as bamboo for lightweight structure and straw or hemp for insulation or finishings. Straw is of particular interest since it is available in large amounts as an agricultural waste product, the use of which offers many benefits (e.g., facilitates agricultural waste upcycling and helps to improve resource circularity).

"Improve" strategies applied to the building design from concept to detailed technical levels require architects and engineers to coordinate to optimize the building form and structural system, prioritize material efficiency, e.g., through use of lightweight-based construction methods instead of massive construction, and apply designs for easy-to-disassemble approaches. These strategies reduce the material resource use and, as a consequence, embodied carbon. "Improve" strategies also relate to product manufacturers, as improvement measures can be applied to material production processes through, e.g., a zero-emission production process by the use of renewable energy and carbon capture technologies.

The crux of scaling decarbonization strategies

An aspect particularly relevant in context of strategies for carbon reduction and removal is the difference between a strategy's impact at the building level and its applicability at scale.

There are various strategies available and promising for reducing embodied carbon at the building level. While especially, the "avoid" strategies, such as avoiding material use through well-designed building organization and improved structural efficiency, can be implemented at scale in principle, other strategies, particularly those relating to the "shift" and "improve" approaches, face technical and at times financial constraints.

As an example, the use of timber construction is a promising strategy for reducing embodied carbon at the building project level. However, the potential of scaling sustainable forestry and thereby increasing the supply of sustainably forested timber is limited more than many like to admit. A viable strategy to support the wide application of bio-based construction is to combine lightweight timber structures with other bio-based construction materials, such as bamboo, straw, or hemp, which offer faster regrowth cycles and have fewer limitations on material availability. Similarly, not all strategies for low-carbon concrete are scalable to the extent that they would be able to meet demand. This can be due to limited availability of the substituting materials in general or in the region. In the short term, a particularly promising and scalable approach for concrete seems to be the use of limestone calcined clay cement, which results in up to 40% less carbon emissions than regular concrete.

BEYOND CARBON: LIFE CYCLE SUSTAINABILITY ASSESSMENT

Environmental indicators beyond carbon emissions

Beyond carbon emissions, the production and processing of building materials can generate a wide array of impacts on the so-called "planetary boundaries," a concept in Earth system science that defines the safe limits within which humanity can operate to maintain a hospitable planet. The nine planetary boundaries relate to aspects such as change in biosphere integrity (e.g., biodiversity loss); novel entities (e.g., environmental pollution); biogeochemical flows (fertilizer use and nutrients); stratospheric ozone depletion (e.g., use of air conditioning); freshwater withdrawal (e.g., irrigation); atmospheric aerosol loading (e.g., burning fossil fuels); ocean acidification (e.g., increased carbon emissions); land-system change (e.g., deforestation); and—most famously—climate change. Building-related activities, be they construction or mining/planting materials for buildings, can pose direct and indirect threats to nearly all planetary boundaries. In particular, biodiversity and land use change are directly affected by ecosystems displacement due to land development and by increasing sprawl and harming natural habitats. Moreover, solutions to decrease buildings contribution to climate change must be assessed from the perspective of further planetary boundaries to avoid environmental trade-offs. The environmental issues brought forth by building construction and operation are linked to modern society's failure to decouple the value of construction from the overall consumption of resources in a world of growing population and ever-growing spatial needs.

A radical transformation of the building and construction sector and joint efforts from key stakeholders throughout the building value chain is paramount if we are to stay within a "safe operating space" on planet Earth.

Non-environmental indicators, social aspects, and cost

In addition to the broader environmental impacts, there are non-environmental, social-related aspects that the building and construction sector must also consider. A vital non-environmental indicator, also a key factor in decarbonization decision-making, is financial cost. In practice, whether a low-carbon building approach will be opted depends on the extent to which it will be cost competitive when compared with conventional building approaches. What usually determines the overall cost of low-carbon construction is material availability and material safety perceptions (e.g., fire risk concerns for timber-framed buildings that may increase insurance premiums), as well as standardization of the whole life carbon assessment process through regulation. If the market eventually attaches higher prices for new low-carbon buildings, the goal of just transitioning and building for everyone will be untenable since these buildings will most likely only be accessible to a wealthy few. Aside from cost and its social implications, another potential barrier to low-carbon buildings may be related to aesthetic preferences and overall building culture. Lower life cycle carbon emissions are often associated with buildings that adopt a compact shape with clear and identifiable technical or geometric requirements, which may not be desirable. A simple but useful proposal from proponents of optimized low-carbon buildings is to make the buildings "boxy but beautiful"—this, again, requires cross-disciplinary efforts, particularly collaborations between architects and designers, engineers, and contractors as well as the support of clients and appropriate regulatory frameworks.

Conclusion

Buildings are at the center of global decarbonization, but the effective decarbonization of the buildings throughout life cycle is not an easy task. While we can celebrate the many achievements made in decarbonizing emissions at the building operational level, the complex and bulk embodied emissions, with their temporal and spatial dynamics at the micro and macro level, require cross-disciplinary collaborations to design and deploy effective decarbonization measures and strategies via "avoid," "shift," and "improve" approaches. At the same time, the broader sustainability impacts associated with buildings and construction, including but not limited to implications on planetary boundaries and financial and cultural barriers, all require particular attention to enable the safe and just development of sustainable buildings for all.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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