

Embodied Carbon Building Codes: Are We Ready?

Nora Wang Esram, American Council for an Energy-Efficient Economy

Ming Hu, University of Maryland

ABSTRACT

The building construction industry accounts for 5% of global energy use and 10% of global greenhouse gas (GHG) emissions. A primary source of these emissions is the manufacture of building construction materials such as steel, cement, and glass. As aggressive building energy codes push new construction toward net-zero-energy and net-zero-carbon operations, we must pursue corresponding efforts to reduce embodied energy and carbon from building construction materials to achieve the building sector's decarbonization goals. Building standards and codes can be an effective policy approach to accelerate the shift to low-embodied-carbon buildings by influencing the general practice in the building industry. However, it is unclear whether we have an adequate knowledge infrastructure to incorporate embodied carbon in national model codes. This paper reviews the current state of the knowledge of existing methods, databases, and tools on embodied carbon. It identifies the knowledge gaps at multiple levels across building materials, components, and whole-building designs. To leapfrog from voluntary standards adopted by market leaders to building codes guiding general practice, we need to build adequate knowledge infrastructure. The current efforts of many have been creating important momentum and providing important pieces of the puzzle, but multi-layer solutions are still needed before we can successfully incorporate embodied carbon metrics or provisions into model codes. Our study provides a basis for governments, academia, industry, and NGOs to collaboratively fill these gaps and move toward standards and practices to fully decarbonize buildings.

Background

In 2019, global GHG emissions from the building sector were nearly 14 gigatons of carbon dioxide (GtCO₂), or 38% of total energy-related GHG emissions, including 28% from building operation and 10% from building construction (United Nations Environment Program 2020). Manufacture of energy-intensive building construction materials such as steel, cement, and glass has the most-severe environmental impact. As aggressive building energy codes push new construction toward net-zero-energy and net-zero-carbon operations, we must pursue corresponding efforts to reduce embodied energy and carbon from building construction materials to achieve building sector decarbonization goals. As buildings become more efficient, embodied carbon will be a greater share of their overall carbon footprint. For example, Chastas et al.'s review (2016) of 90 case studies found that embodied carbon accounted for 26–57% and 74–100% of the total lifecycle carbon emissions of low-energy and near-zero-energy buildings, respectively (Chastas, Theodosiou, and Bikas 2016). Embodied carbon is not “negligible” anymore, and the need for knowledge and standards for embodied carbon becomes more and more urgent.

Moreover, at the intersection of the building and industrial sectors, initiatives to reduce embodied carbon in building materials will create market demand for low-carbon products, thereby improving the business case for manufacturers. Support for sustainable business has

been growing in both developed and developing economies. For example, consumer searches for sustainable goods increased globally by 71% since 2016 and corporations are responding (The Economist 2021). Consumer actions can significantly affect embodied carbon imports, in addition to domestic carbon emissions (Moran et al. 2018). The importance of embodied carbon emissions in building products and materials will continue to grow as consumer preference for lower-carbon products is expected to grow rapidly (Whelan and Kronthal-Sacco 2019). Architects and engineers, who serve as the interface between building owners/developers and manufacturers, play a key role in not only selecting materials and products but also making critical decisions such as building reuse and structural efficiency. To some extent, the architecture and engineering communities can be viewed as consumers or consumer advocates.

The emerging interest in Buy Clean policies in the United States, which require that products and materials that are used for public projects (such as infrastructure improvements) be manufactured in a clean and sustainable manner, provides a unique opportunity to accelerate the reduction of embodied carbon in building materials and buildings systems. The Buy Clean California Act was signed into law in 2017 (Buy Clean California Act 2017), and Colorado passed a similar buy clean bill in 2021 (Colorado General Assembly 2021). Related proposals have been introduced in six additional states as of this writing (Carbon Leadership Forum 2021). There has also been activity at the county and municipal levels where similar policies have been proposed or considered. Still, most existing policy efforts have focused on the materials level (e.g., specifying materials with low embodied carbon, requiring disclosure of environmental impacts). Perspectives on whole-building performance (e.g., selecting alternative materials, reducing waste, trade-offs between embodied carbon and operational carbon emissions) have not yet been defined or integrated into any mandates in the United States, although voluntary activities have been carried out since the 1990s, such as the building lifecycle impact reduction credit in Leadership in Energy and Environmental Design (LEED), the embodied carbon requirements in Living Buildings Challenge certification, and the Life Cycle Assessment (LCA) Practice Guide from Carbon Leadership Forum (Carbon Leadership Forum 2020). We also need complementary approaches that require buy-in from key stakeholders (e.g., manufacturers, builders) to facilitate changes in low-carbon choices and behaviors.

Building Codes to Drive Decarbonization of Buildings, Construction, and Manufacturing

Supporting the development or modification of building standards and codes could be an effective policy approach to accelerate the shift to low-embodied-carbon buildings by influencing general practices in the building industry. Although there have been continuing efforts by environmental advocates and architectural pioneers to promote zero-waste buildings,¹ mainstream building design and construction practices, generally highly regulated by building codes, have remained largely unchanged. Building codes are designed to safeguard public health, safety, and general welfare. In tandem with other codes (e.g., plumbing codes, electrical codes, fire codes, mechanical codes), energy codes have traditionally focused on energy use from

¹ For example, Bill McDonough created the Cradle to Cradle™ design philosophy in 2002, which is inspired by Walter Stahel's vision of a circular economy first published in 1976.

building operations, including the energy used for lighting, heating, cooling, ventilation, appliances, and other equipment, while continuing to meet building function and comfort requirements. Progressive building energy codes and the underlying research on reducing operational energy and its related GHG emissions have stimulated changes of practice in building design and operation. Significant progress has been made to reduce the operational energy of a building during its use phase, largely as a result of energy codes. In general, we have a clear understanding of operational carbon emissions and a solid knowledgebase of carbon reduction strategies for reducing building energy use.

In contrast, strategies to reduce embodied carbon in the subsequent remaining lifecycle stages of a building are less defined and studied. The selection of building materials and systems is largely unregulated beyond minimum health, safety, and performance standards. Energy code requirements come in only after a particular type of construction has been selected. One challenge is that upstream energy use and carbon emissions resulting from the production of building materials and equipment are more difficult to measure and track than building operational energy use and emissions. Relying on the self-assessment and reporting of building products from manufacturers alone cannot provide an accurate assessment of the embodied carbon of a building.

Assessing the embodied carbon of a building has remained challenging for building design teams because a building consists of hundreds or thousands of materials and components, which need specific expertise, trainings, and ready-to-use tools. Building design teams often do not have this broad expertise or tools. For example, two window units from different manufacturers may appear to be identical, have similar costs, and perform to the same standard, but the embodied carbon of the two products may differ greatly. As another example, a 100% recycled-steel beam, produced using renewable energy, may have significantly lower levels of embodied carbon than a virgin-steel beam produced using a coal-fired blast furnace, even though their structural performance is the same (McKinsey & Company 2020). The location of the steel manufacturer not only determines the type of energy source from the local grid, but also plays an important role in the amount of carbon derived from transporting products to the construction site. Furthermore, the complexity of global manufacturing and supply chains makes it even more difficult to measure carbon emissions from material extraction to the assembly of building products and components.

Consumption-based carbon accounting² could unlock new opportunities for climate policy innovation and for climate mitigation (Afionis et al. 2016). Building codes could be an effective vehicle to raise the minimum carbon performance of buildings and reduce overall lifecycle carbon emissions because they provide clear market signals to manufacturers who need to invest in long-term low-carbon technologies, processes, and infrastructure to meet future market demands. Architects and engineers who are responsible for compliance with building codes would also have a great opportunity to reduce embodied carbon through nontraditional design strategies. A major barrier to incorporating embodied carbon provisions into model building codes lies in the complexity of the code-development process, which requires

² Consumption-based accounting accounts for emissions at the point of consumption, attributing all the emissions that occurred during production and distribution. In comparison, production-based carbon accounting measures emissions generated in the place where goods and services are produced.

standardized methodologies at the national level, robust analyses based on adequate data, and thorough evaluations of the readiness and maturity of the required techniques, technologies, and materials. Moreover, a code structure (primarily prescriptive) has been largely unchanged for decades; performance-based options could provide a path forward for considering embodied carbon.

Attempts have been made to develop and support the use of voluntary disclosure initiatives or other voluntary standards. For example, the U.S. General Services Administration's (GSA) Office of Federal High-Performance Green Buildings issued "Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies" in February 2021 (General Services Administration 2020). These recommendations include a material-based approach for all projects and a whole-building lifecycle assessment approach for projects over \$3.095 million. The material-based approach requires "environmental product declarations for 75% of materials used (by cost or weight), and that their emissions fall in the best-performing 80% of global warming potential (GWP)³ among functionally equivalent products as demonstrated by environmental product declarations (EPDs)."⁴ The whole-building approach requires "designing a building in such a way that lifecycle carbon assessments show that the selected design results in a 20% carbon reduction, compared to a baseline building."⁵ With a robust backdrop of community pressure and regulatory threats, well-designed, voluntary initiatives in environmental governance can effectively motivate private firms to act proactively, but such initiatives have only modest effects and are unlikely to substitute for regulations (Coglianese and Nash 2016).

To progress from voluntary standards adopted by industry leaders to building codes guiding general practice, we need to build adequate knowledge infrastructure. Knowledge infrastructure is defined as "robust networks for people, artifacts, and institutions that generates, shares, and maintains specific knowledge about the human and natural worlds" (Edwards 2010). In this case, knowledge infrastructure for embodied carbon includes individuals, organizations, and their generated information and shared norms and practices that are necessary to support the development, evaluation, and implementation of building codes. As the first step, we need to identify the critical missing components that would support such knowledge infrastructure.

³ Global warming potential (GWP) is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time (usually 100 years), relative to the emissions of 1 ton of carbon dioxide (CO₂). The larger the GWP, the more that a given gas warms the Earth compared to CO₂ over that time period. (reference: <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>)

⁴ An Environmental Product Declaration (EPD) is a report that provides information about a product's impact on the environment, such as global warming potential, smog creation, ozone depletion, and water pollution. (reference: <https://www.ul.com/resources/environmental-product-declarations-program>)

⁵ A baseline building has yet to be clearly defined. For example, LEED specifies that "the baseline and proposed buildings must be of comparable size, function, orientation, and operating energy performance as defined in EA Prerequisite Minimum Energy Performance." A baseline building for energy analysis usually follows the building performance rating method in Appendix G of ANSI/ASHRAE/IESNA Standard 90.1, which is not designed to address embodied carbon. (<https://www.usgbc.org/credits/healthcare/v4-draft/mrc1>)

Setting Evaluation Criteria Through the Lens of Building Codes

Codes and standards are often confused as being the same and the terms are frequently incorrectly treated as interchangeable, but they usually have specific meanings for different professionals, and it is worth clarifying their definitions before we discuss our evaluation criteria.

In the context of building design and construction, there are two types of codes: model and adopted. Model codes are a set of rules and suggested practices for building professionals to follow. National model codes are not considered law until they are adopted by local, state, or national governments. Examples of national model codes include the International Building Code (IBC) and International Energy Conservation Code (IECC) developed by the International Code Council (ICC), the Uniform Plumbing Code (UPC) developed by the International Association of Plumbing and Mechanical Officials (IAPMO), the National Electric Code (NEC) developed by the National Fire Protection Association (NFPA), and ANSI/ASHRAE/IESNA 90.1 Standards developed by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE). State building code councils (names vary by state) and jurisdictions adopt national model codes by reference or amend them to form base local codes that set minimum requirements for compliance by professionals and trades (e.g., architects, engineers, contractors) practicing within the state and/or municipality. The adopted codes are enforced by law and have established consequences for non-compliance.

Sometimes model codes are published as standards, such as the ASHRAE Standard 90.1. More often, standards broadly refer to documents that establish performance criteria, testing methodologies, or material specifications. Standards are usually more specific, and a code may reference a standard when requiring a building element to perform to a certain criterion. These standards are developed through an international process overseen by the International Standards Organization (ISO)⁶ that brings together technical and professional organizations from countries around the world to develop, validate, and update these standards, building on a shared knowledge infrastructure. In many cases, the ISO recognizes standards developed in an individual country facilitating harmonization of standards globally promoting international trade. Similarly, the U.S. standards are developed through the process defined by the American National Standards Institute (ANSI). ANSI is the sole U.S. representative and full member of ISO.

Energy codes set the minimum energy performance standards for building components (roof, wall, window, lighting, controls, and heating, cooling, and ventilation systems). The model energy codes in the United States primarily refer to ANSI/ASHRAE/IES Standards 90.1 and the IECC, administered by ASHRAE and ICC, respectively. Some states may even develop and adopt stretch codes (e.g., Massachusetts, Vermont) or reach codes (e.g., Oregon) to provide an alternative compliance path that is more aggressive than the base local codes to allow municipalities to achieve greater levels of energy efficiency (Building Codes Assistance Project 2021)⁷. In contrast, some states (e.g., Kansas, Missouri, Wyoming) have no statewide energy

⁶ For more information on the international standards process see: <https://www.iso.org/about-us.html>

⁷ A stretch energy code is a voluntary appendix to a mandatory statewide minimum energy code that allows municipalities to adopt a uniform beyond-code option to achieve greater levels of energy efficiency. Reach codes are

code, but instead allow local governments to adopt and enforce their own local codes (DOE 2021).

Energy codes are focused on the energy performance of a building and use thermal performance, equipment efficiency, energy use, and energy cost as the primary evaluation criteria. In the past decade, high-performance building codes and standards have emerged to support sustainable development. For example, the ANSI/ASHRAE/USGBC/IES Standard 189.1: Standard for the Design of High-Performance Green Buildings and the International Green Construction Code (IgCC), in the format of model codes, cover many aspects of high-performance, green buildings.⁸ Given the urgency of addressing climate change, a shift from energy to carbon metrics is also emerging. Marin County, California, is the first and so far the only jurisdiction that has adopted an embodied-carbon provision in its building codes (Marin County 2021). Chapter 19.07 of Title 19 in the Marin County Building Code sets maximum embodied carbon limits (ranging from 260 to 675 kg CO₂e/m³) for concrete of various compressive strength levels.⁹ It also allows the total embodied carbon of all concrete mix designs to be calculated and evaluated at the project level. The Marin County code also grants exemptions for circumstances that make it a hardship or infeasible to meet the requirements.

If embodied carbon were to be included in model codes, it would be essential to ensure that we have an adequate knowledge infrastructure to support code development, adoption, and implementation. The knowledge infrastructure should cover the upstream data collection and reporting and the downstream data synthesis and calculation. More specifically, it includes the means, processes, procedures, tools, and capabilities to collect, process, report, transparently communicate, and validate data and warehouse information connected with the function of evaluating embodied carbon across materials and supply chains that handle those materials. It also includes standard methodologies and tools to convert these data and information to knowledge and practices to guide building design and construction. To identify the gaps and eventually establish a robust knowledge infrastructure, we need to answer some key questions:

- Are there adequate, trustworthy product data and publicly accessible databases to enable the calculation of whole-building embodied carbon throughout its lifecycle?

a set of statewide optional construction standards for energy efficiency that exceed the requirements of the state's mandatory codes. (reference: <https://bcapcodes.org/beyond-code-portal/stretch-and-reach-codes/>)

⁸ The latest version of Standard 189-2017 has more-stringent energy provisions than ASHRAE 90.1. It also sets up higher standards for indoor air quality and includes requirements for lifecycle assessment of materials/resources, carbon emissions, electric vehicle charging infrastructure, etc. More than 20 cities and counties across 13 states have adopted Standard 189.1 in part or in whole. In the 2018 edition of IgCC, Standard 189.1 has been wholly incorporated into the IgCC.

⁹ The Marin County building code defines embodied carbon as “the greenhouse gasses emitted in material extraction, transportation, and manufacturing of a material corresponding to life cycle stages A1 (extraction and upstream production), A2 (transportation), and A3 (manufacturing).” Compressive strength of concrete is the primary measure determining how well a given concrete mix can withstand loads. It is measured in psi or MPa. Higher-compressive-strength material is allowed to have higher ordinary Portland cement content and higher embodied carbon.

- Are there established standards to guide measurement, calculation, and assessment of embodied carbon in buildings?
- Are there accessible, high-quality tools to support practitioners that conduct the analysis and make an informed decision on their design solutions?
- Are there transparent, credible processes to govern the database and/or tool development?

Literature Review and Analysis Methodology

To answer the above questions, we conducted an initial literature search and review using the keywords “embodied carbon,” “embodied GHGs,” and “embodied CO₂” through the ScienceDirect website. The search yielded 8,341 relevant books, journals, and papers published between 2010 and 2021 that match our initial search criteria. During our literature review, we focused on three essential components of embodied carbon, which are necessary for any LCA project assessing embodied carbon: calculation method, database of embodied carbon, and calculator (tool) that converts material qualities and properties to embodied carbon (measured in kg CO₂e/m³). After multiple rounds of screening, we identified 28 papers that present new knowledge for developing embodied carbon standards, methodologies, databases, or tools in the United States.

Most of the research papers focused on methods, tools, and case studies, with very few on data collection and database development. To fill this gap, we scanned publications from industry practitioners, nonprofit organizations, and federal agencies through an open internet search, using key words such as “embodied carbon data” and/or “embodied energy data,” in combination with “building” and/or “construction.” We also investigated published documents on lifecycle inventory (LCI) data from the United States and Canada. We identified eight additional publications that contributed to the existing body of knowledge in our targeted topic areas.

To quantify the findings from our literature study, we categorized the topics in each article by knowledge area (i.e., method, data, tool) and assessment level (i.e., material, product, whole building). The product level includes the building components (e.g., windows, doors) and building assemblies (e.g., exterior walls, floors).

Knowledge Matrix

Figure 1 visualizes the distribution of the existing body of knowledge in a matrix pyramid. Shown as a hierarchy, the size of the circles indicates the relative amount of information needed at each level. At the building level, the circles are smaller because information is aggregated. The percentage (shown as the darker shade in each circle) represents the degree of topic coverage in our literature study. We calculated the percentages from the topic counts in the literature review. Some articles covered more than one topic; others included studies across multiple levels. Therefore, the total percentage does not necessarily add up to 100%. Overall, the most detailed knowledge we have for embodied carbon in the building industry (reflected in practice and research) resides at the material and product level (bottom of the diagram). In contrast, the building level (top of the diagram) has the least-developed knowledge. Of the information we discovered in our literature review, about 11% was related to

embodied carbon data, 69% to methodology, and 78% to tools. The least amount effort has been made on “data” across all levels.

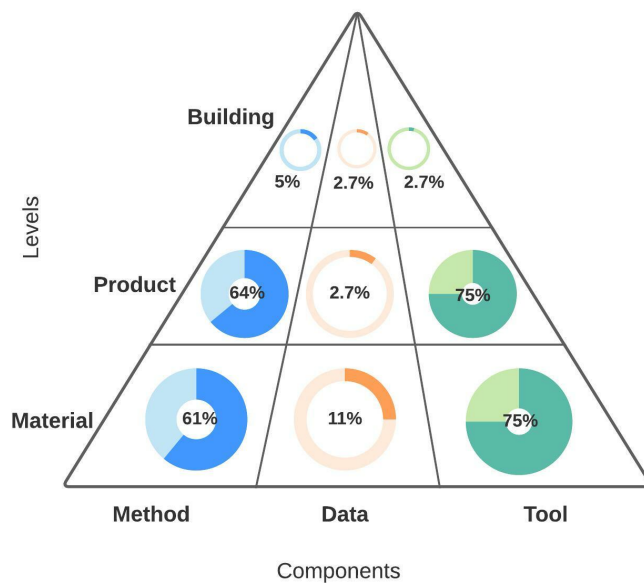


Figure 1. Embodied carbon assessment knowledge matrix

The diagram serves to illustrate rather than provide an exact quantification. Our literature review is not designed to provide an exhaustive review of the existing body of knowledge on embodied carbon in buildings. Instead, it serves as a representative snapshot of the current state of the available information. We acknowledge that our review focuses mainly on peer-reviewed publications. More reports, case studies, and best practice guides on the whole-building level may exist in the building design community. Nonetheless, we believe that a review of the peer-reviewed publications has allowed us to identify the critical gaps to guide future knowledge development. In addition to using publications to understand the current effort in knowledge development, we reviewed 10 databases and seven tools that are used primarily in the United States for building lifecycle assessment. We published the detailed review and comparison separately (Hu and Efram 2021). The overall findings for the literature review and database and tool reviews are discussed in the following section.

Identified Knowledge Gaps and Needed Improvements

International Standards and Regional Implementation Guides

The quantification of embodied carbon is intertwined with the development of LCA. There are well-established international standards to guide LCA methodology development for assessing embodied carbon in the built environment. There are two “gold standards” that serve as internationally binding standards for conducting LCAs: ISO 14040 Environmental management life-cycle assessment principles and framework (ISO 2006) and ISO 14044 Environmental management life-cycle assessment requirements and guideline (ISO 2006). The two standards

combined cover both LCA and LCI studies, with LCI studies closely tied to embodied carbon assessment, but they do not describe LCA evaluation techniques in detail, nor do they specify calculation methodologies for the individual phases of the LCA. This gap was left intentionally to give LCA researchers and practitioners the space to further develop methodologies that fit their particular context, which has led to the development of a variety of LCA methods and tools. For example, the ISO 14020, 14021, 14024, and 14025 standards (as the Environmental Labels Package) establish the general principles to develop and use various types of environmental labels¹⁰ (ANSI 2021). ISO 14027 and 21930 standards provide more specifications.

The ISO standards focus on principles and frameworks of LCA. The EN 15978 (Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method) was developed in Europe to provide specific guidance on whole-building LCA, such as the lifecycle stages to include and data sources to use. There have been discussions on the potential to adopt the European standards in the United States and internationally to support global alignment, but some provisions under the European context may not be directly applicable to buildings in North America and therefore need further exploration.

In the United States, ASTM E2921-16a (Standard Practice for Minimum Criteria for Comparing Whole Building Life-Cycle Assessments for Use with Building Codes, Standards, and Rating Systems) was developed to guide comparative assessments of whole-building designs relative to reference building designs (ASTM International 2021). It is referenced in some new ASHRAE standards (such as ASHRAE 228P Standard Method of Evaluating Zero Net Energy and Zero Net Carbon Building Performance (ASHRAE 2021) and ASHRAE 189-2020 Standard for the Design of High-Performance Green Buildings (ASHRAE 2020)) where LCA is mentioned. The ASTM standard is to support the use of whole-building LCA in building codes, standards, and building rating systems by ensuring that comparative assessments of final whole-building designs relative to reference building designs take account of the relevant building features, lifecycle stages, and related activities in similar fashion for both the reference and final building designs of the same building. It does not specify LCA methodology, nor does it guide LCA implementation. Implementation guides in the United States are needed to ensure “apples-to-apples” comparisons, such as how to choose system boundaries and how to use multiple methods to overcome the challenge of upstream data complexity.

Embodied Carbon Benchmarking at Building Level

Currently, very few activities focus on collecting data on embodied carbon or embodied energy at the whole-building level. Unlike operational energy, which has abundant data collected from a variety of building types, embodied energy or carbon has few benchmarking references for comparison and target setting. For example, the U.S. EPA ENERGY STAR program annually publishes the technical reference for U.S. Energy Use Intensity (measured in Btu/sf²-yr) by Property Type. This helps a design team compare its building energy use with similar

¹⁰ The Environmental Product Declaration (EPD) is a widely used, internationally recognized environmental label. EPD is a report that provides information about a product’s impact on the environment. A variety of LCI databases are used to calculate the environmental impact of products, and the calculations and processes follow the ISO 14040 standard.

properties across the nation (Energy Star Portfolio Manager 2021). There is currently no consensus on how to benchmark the embodied carbon of a building.

The most-comprehensive assessment of embodied energy in buildings was published in 1979, in “Energy Use for Building Construction” (Center for Advanced Computation, University of Illinois at Urbana-Champaign 1976), commissioned by The Advisory Council on Historic Preservation. It aimed to assess the benefits of restoring and rehabilitating existing buildings, so it proposed methods to measure the energy needed to produce, replace, repair, and demolish the building materials. The assessments of building materials were then aggregated to calculate the embodied energy of the whole building (ACHP 1979). Embodied energy can be used as a proxy for embodied carbon, though embodied carbon includes carbon emissions from non-energy sources. The Advisory Council assessment included three embodied energy categories corresponding to different lifecycle stages: embodied energy (A1-B5), demolition energy (C1-C4), and operational energy (B6).

To date, this pioneering effort remains the most thorough evaluation of the embodied energy assessment at the whole-building level by different building types that has been produced in the United States. The building materials in the report were based on construction industry data from 1967. Obviously, there have been significant changes in building products, technologies, and manufacturing processes since then. Steel beams, for example, are now made with continuous casting, avoiding the billet reheating of earlier times. Thus, the base numbers for embodied energy from the 1976 report are likely to be outdated, requiring revision and updates.

The Carbon Leadership Forum conducted an embodied-carbon benchmarking study in 2017 by compiling the upfront embodied-carbon results from 1,191 building LCA studies, including office, education, and single- and multifamily residential buildings. (Carbon Leadership Forum 2021b). Half of the entries are from buildings in Northern America. The study found that the upfront carbon emission is typically less than 1,000 kg CO₂e/m²; 50% of the office buildings in the database have upfront carbon emissions between 200 and 500 kg CO₂e/m². As a reference, Living Building Challenge’s Zero Carbon Certification requires the total embodied carbon emissions of the certified project to be less than 500 kg CO₂e/m². The study provides a good reference for benchmarking embodied carbon in buildings, but the sample size is insufficient to provide statistically significant results.

Creating a quantitative benchmark dataset is the first step to create a meaningful pathway to regulate the embodied-carbon emissions in buildings. Based on such a dataset, methodologies should also be developed to baseline building embodied-carbon emissions. Without a robust baseline calculation, it would be difficult to create a reasonable carbon-reduction target for a building. Although net-zero carbon emissions are the ultimate goal, interim steps and pathways are needed based on the available and affordable building products and technologies of today. ASHRAE 90-75: Energy Conservation in New Building Design was published as the first national energy code in 1975; a newer version of the ASHRAE standard has been published every three years since the 1999 version, gradually increasing building energy-use standards. A similar path is needed for embodied-carbon building codes.

Embodied Carbon and Operational Carbon

The whole-building approach, which considers lifecycle impacts of a building, encourages innovative strategies that use alternative structural systems, building technologies,

and construction techniques and processes. To enable a whole-building approach, we need standards to guide design teams to create baseline cases, compare alternative design approaches, and set carbon-reduction targets. RMI's case studies of three typical construction types for low- and mid-rise commercial buildings in the United States show that upfront embodied carbon (A1-A5) can be reduced by 24–46% with less than a 1% cost premium (RMI 2021). This is largely accomplished through material-level substitution. A whole-building approach can yield even greater savings. As with reducing operational energy use, these early-state design choices have substantial impacts on reducing a building's embodied carbon, as changes and interventions become more costly and constrained in a later project stage. As new buildings become more efficient and the utility grid becomes less carbon intensive, the operational carbon emissions of buildings will decrease. The question is whether reduction of operational carbon emissions is at the cost of increasing embodied carbon. The trade-offs between operational and embodied carbon need to be investigated further to achieve optimal results.

Shadram et al. conducted a study on a hypothetical eight-story multifamily residential building in Stockholm, Sweden, using a multi-objective optimization approach to examine the trade-off between embodied and operational carbon impacts (Shadram et al. 2019). The variables in the study included the window-to-wall ratio and the floor, roof, and wall insulations (i.e., insulation types and thickness) used in the exterior construction elements of the building. The energy simulations showed that the embodied carbons quickly decrease as the operational carbons increase, and that decrease slows down until it plateaus. The authors found optimal solutions that resulted in the lowest lifecycle carbon footprint. One of the solutions has a higher operational carbon impact than the initial design but significantly reduces the embodied carbon impact. It is also worth noting that the study showed that expanded polystyrene is an optimal insulation material for the exterior walls and floors, while cellulose is a better choice for the roof than mineral wool. Petroleum-based products (mostly used for rigid and spray foam insulations such as expanded polystyrene and extruded polystyrene) have higher embodied-carbon footprints than blown-in insulations (e.g., fiberglass, cellulose), if compared at the material level. Although the finding from this case study does not universally apply to all buildings, it highlights the importance of whole-building-level analysis, considering the whole lifecycle of a building.

Gaps in Database Development

Comprehensive embodied-carbon data exist to evaluate all lifecycle stages of buildings in the United States. Some are accessible to users and others are proprietary and therefore less transparent. It is difficult to diagnose why different tools generate different results because some underlying databases are not regularly maintained and documentation of their data sources and methodologies are not easily available. A robust database is the backbone of reliable LCA analyses. Guidelines for data standardization and transparency are needed.

We identified four primary issues pertaining to database quality and the data-collection process across all levels. The first issue relates to data availability for the use and the end-of life stages of a building, since they are both highly dependent on the assessor's assumptions of how a building may be used and maintained. The second issue lies in the pre-use stages of a building. There are limited published data for the stage of transport to site and the state of construction and installation in comparison to the stages of production (including material extraction, transport, and manufacturing). The third issue concerns missing guidelines for supply-chain-specific and

facility-specific data collection and reporting. The fourth issue is the lack of consensus on how to integrate the benefits and loads of reuse, recycling, and recovery potentials into the lifecycle assessments.

Tool Development

A significant effort has been focused on tool development. Most LCA tools focus on product or material levels and are not specifically designed for buildings. Whole-building-level LCA tools that can be embedded in building design software will greatly help design teams incorporate LCA into their design process. As more LCA tools are developed to facilitate designs, guidelines are needed to standardize the procedures for validating and developing embodied-carbon assessment software. This is vital to increase confidence in the use of embodied-carbon assessment tools.

Summary and Recommendations

To move from voluntary standards adopted by industry leaders to building codes guiding general practice, we need to build adequate knowledge infrastructure. Development of codes and standards is a complex process that requires standardized methodologies at the national and international levels, robust economic analyses and modeling, and thorough evaluations of impacts on various stakeholder groups (e.g., manufacturers, building owners and developers, builders, occupants). Current efforts (e.g., voluntary rating systems, buy clean policies, voluntary reporting and disclosure, development of new materials and technologies, early adopters in the marketplace) have been creating important momentum, but multilayered solutions are still needed for successful implementation across complicated supply chains. Our key findings of the major knowledge gaps are summarized below:

- There are well-established international standards to guide the development of methodologies to assess embodied carbon in the built environment, but these standards focus on principles and frameworks. Implementation guides for buildings in North America are needed for issues such as how to choose system boundaries and how to use multiple methods to overcome the challenge of upstream data complexity.
- Existing data are primarily at the material level, and they focus on the manufacturing process. To enable a more-complete lifecycle analysis, data on transportation, construction, and building use are needed. Data collection and reporting guidelines are also needed for supply-chain-specific and facility-specific data to enable more-accurate counting and fair comparisons.
- A great number of tools are available to facilitate embodied carbon analysis; however, their underlying databases could lead to great discrepancies in results. Guidelines for data standardization and transparency are needed.
- In the United States, the largest knowledge gap concerning embodied carbon in buildings exists at the whole-building level. The lack of publicly accessible building-level data and guidelines to establish reference cases are obstacles to reaching consensus on how to baseline or benchmark the lifecycle embodied carbon of a building. Research is needed to create a quantitative benchmark dataset. Methodologies on how to baseline building

embodied-carbon emissions should be developed. Incremental carbon-reduction targets should be determined. The developed methodologies and guidelines should cover the whole lifecycle in addition to material manufacturing and initial building construction.

- The trade-offs between operational carbon (from building energy use) and embodied carbon should be considered in whole-building embodied-carbon evaluations. The lack of information on product durability may also introduce conflicts between resilience and embodied carbon. Material and product durability is relevant not only to embodied carbon, but also to resilience planning, which is another critical approach to combat climate change. These critical components must be addressed.

Tools, methods, and standards of LCA at building (global scale, ISO) have been established for embodied-carbon assessment in built environments. The past five years have seen embodied carbon and LCA become a standard feature of commercial and governmental green building systems at global scale, particularly in Europe. While this field is relatively new, best practices have started to emerge and can be adopted in the United States to expedite the promotion of embodied-carbon reduction from buildings. In contrast to and lagging behind the EU, the United States has no adopted guidelines of whole lifecycle assessment at the building level. And the development of the U.S. LCI database is not picking up speed. With more-robust U.S. LCI data and U.S. standards, it is possible that an embodied-carbon building baseline and benchmark can be established. Leadership and technical support from U.S. federal agencies and federally funded research and development centers are needed.

Our study provides a basis for governments, academia, industry, and other entities to collaboratively fill the identified gaps. As the first step to build the knowledge infrastructure, we recommend that federal agencies (e.g., Department of Energy, Environmental Protection Agency, National Institute of Standards and Technology), model code-writing organizations (e.g., ASHRAE, the International Code Council), local code officials, and other research institutes and advocacy groups collaboratively develop a roadmap to guide the long-term trajectory of building code development and adoption. This roadmap should also include inputs from the industry (i.e., material and product manufacturers) and serve as an interface to align building decarbonization with industrial decarbonization.

Embodied-carbon standards cannot be driven solely by the building communities. Guidelines and standards on embodied-carbon data collection and reporting need manufacturers' inputs and support. Government also has an important educational and technical assistance role in developing the business cases for manufacturers' investment in the manufacturing and compliance capacity for delivering low-carbon products. In addition, government has a role in integrating building decarbonization efforts with industrial supply chains to connect the knowledge infrastructure of the two sectors to reduce embodied carbon in constructed buildings.

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