KNOWLEDGE INFRASTRUCTURE: THE CRITICAL PATH TO ADVANCE EMBODIED CARBON BUILDING CODES

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Executive Summary

KEY FINDINGS

- 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 Northern America are needed for issues such as how to choose system boundaries and how to utilize multiple methods to overcome the challenge of upstream data complexity.
- Existing data are primarily at the material level and focus on the manufacturing process. To enable a more complete life-cycle 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 of guidelines to establish reference cases are obstacles to reaching consensus on how to baseline or benchmark the life-cycle embodied carbon of a building. Better data and consensus are both needed.
- 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. These are all critical components that must be addressed.
- Development of guidelines and standards on whole-life embodied carbon data collection and reporting will require participation from manufacturers, construction companies, and building owners. Developing and enhancing their capability to collect and report data should be considered when demanding more data from these stakeholders.
- Developing business cases for manufacturers and integrating building decarbonization with industrial decarbonization are essential steps to build the knowledge infrastructure needed to reduce embodied carbon in buildings.

In 2019, the global greenhouse gas (GHG) emissions from the building sector were nearly 14 gigatons of carbon dioxide ($GtCO_2$), or 38% of the total energy-related GHG emissions, including 28% from building operation and 10% from building construction (United Nations Environment Programme 2020). The building construction industry (including commercial, residential, and industrial buildings) accounts for 5% of global energy use and 10% of global GHG emissions. A primary source of these emissions is the manufacture of building construction materials such as steel, cement, and glass. As modern building codes move new construction toward net-zero-energy and net-zero-carbon operations, corresponding efforts to reduce embodied energy and carbon from building construction materials must be pursued to achieve the building sector's decarbonization goals.

The emerging interest in Buy Clean policies in the United States provides a unique opportunity to accelerate the reduction of embodied carbon in building materials and buildings systems. The consumer preference for lower carbon products, driven by awareness, policies, or incentives, is expected to grow rapidly, creating market demand for these products that will provide additional justification and impetus for their manufacture (EIU 2021; Whelan and Kronthal-Sacco 2019). Increased manufacturing capacity may lead to a further increase in procurement policies for low-embodied-carbon products.

Most of the current efforts have focused on develping material-level policies and specifications. These are critical steps to reduce embodied carbon in buildings, but they are inadequate to tackle the full spectrum of building decabonization (e.g., the trade-offs between embodied carbon, operational carbon, and building durability; considerations of manufacturing location, means of transporation, and construction method) and may limit other solutions such as innovative designs and adaptive reuse. Therefore, whole-building life-cycle assessment is essential to truly reducing embodied carbon in buildings.

Building life-cycle assessment (LCA) has gained more attention in recent years, but is not growing fast enough to enable wider adoption. Building standards and codes can be an effective policy approach to accelerate the shift to low-embodied-carbon buildings by influencing general practice in the building industry. Still, it is unclear whether we have an adequate knowledge infrastructure to incorporate whole-life embodied carbon in national model codes or even in construction specification by building owners wanting to be market leaders. On the other hand, development of codes and policies provides an expedited path for building the knowledge base. This study provides a comprehensive review of the current state of existing methods, databases, and tools for embodied carbon viewed through the lens of building codes. It aims to identify the existing and missing components that are critical for initiating, developing, and advancing regulation of embodied carbon in building codes.

If life-cycle embodied carbon is to be included in model codes, it is essential to ensure that we have an adequate knowledge infrastructure to support code development, adoption, and implementation. We acknowledge that code development is a continuous and progressive process as more knowledge is developed and more information is accumulated over time. Therefore, the inadequate knowledge base we have today does not necessarily mean that we should not start introducing embodied carbon provisions into building codes. A global view of what we know today and what we need to know in the future will help pave a path leading to holistic building codes that integrate the whole-building life cycle of embodied carbon with other important aspects, such as energy use, health, safety, and resilience.

Ultimately, the knowledge infrastructure to support such holistic codes should cover upstream data collection and reporting and downstream data synthetization and calculation. More specifically, it should include 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 the supply chains that handle those materials. It also includes standard methodologies and tools to convert such data and information into knowledge and practices to guide building design and construction. To identify the existing gaps and eventually establish a robust knowledge infrastructure, the key questions to be answered are:

- Are there adequate, trustworthy product data and publicly assessable databases to enable the calculation of whole-building embodied carbon throughout its life cycle?
- Are there established standards to guide measurement, calculation, and assessment of embodied carbon in buildings?
- Are there accessible, quality tools to support the practitioners conducting the analysis and make an informed decision on their design solutions?
- Are there transparent, credible processes to govern the database and/or the tool development?

The development of embodied carbon assessment is intertwined with the development of life-cycle assessment methodologies for materials and buildings, as embodied carbon is most often considered as a part of the whole carbon life cycle associated with a building project. LCA is a method to assess the environmental impacts of a product or service throughout its entire life cycle (Müller et al. 2020). When LCA is applied in the building and construction sector, four different levels of assessments (depending on chosen scopes, system boundaries, and functional units) may be conducted: at the level of the building material, the building product (including building components, systems, and assemblies), the whole building, or the industry level,[1] but all four often use the same database of inputs. LCAs are most often conducted at the material and the whole-building levels. It is essential for a project team to discuss the goal and scope of the LCA at the beginning of a project, then make the decision on what level of LCA is appropriate for the project.

We scanned the literature in the past 10 years (2010–2021) with a focus on the United States, screened over 5,000 published articles, and reviewed 44 articles in extensive detail to identify the current state of knowledge for existing methods, databases, and tools on embodied

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[1] Industry level in LCA refers to industrial practice.

carbon in buildings. We identified the knowledge gaps at multiple levels across building materials, components, and whole-building designs. Our findings are summarized below:

- **Standards and Methodologies:** There are well-established international standards to guide LCA methodology development for assessing embodied carbon in buildings, but the ISO standards focus on principles and frameworks. Methodology guidance is needed to ensure consistent comparisons, such as how to define scope, choose system boundaries, design a function unit, and utilize multiple methods to overcome the challenge of upstream data complexity.
- **Data:** Comprehensive embodied carbon data exist to evaluate all life-cycle 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. Data collection and reporting guidelines are also needed for supply-chain-specific and facility-specific data and for transport and construction data, which are currently missing in many databases. A robust database is the backbone of reliable LCA analyses. Guidelines for data standardization and transparency are needed.
- **Tools:** A significant effort has been focused on tool development. Most LCA tools are focused on product or material levels and not specifically designed for buildings. Whole-building-level LCA tools that can be embedded in building design software will help design teams incorporate LCA into their design process, yet there is no standard on tool development to ensure comparable inputs and outputs.

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 within 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 revolves around the lack of consensus on how to integrate the benefits and loads of reuse, recycling, and recovery potentials into the life-cycle assessments.

The largest knowledge gap exists at the whole-building level. No consensus exists on how to baseline or benchmark the embodied carbon of a building due to the lack of building-level data. 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 life-cycle stage beyond initial building construction. Trade-offs between operational carbon and embodied carbon and between material/product durability and its environmental impacts should be addressed.

Whole-building LCAs have been mostly conducted without an associated life-cycle-cost analysis (LCCA). LCCA is an economic method of project evaluation in which all costs accumulated from all life stages of a building are considered as potentially important to the decision. LCCA provides significantly better assessment of the long-term cost effectiveness of the overall investment and considers building maintenance and future renovation costs, in contrast to alternative economic methods, which only focus on the initial costs of development and construction. Economic impact and technology maturity (such as alternative materials, equipment, systems, and techniques) are critical considerations during the building code development process. Architects and engineers can specify or select low-carbon materials and products only when they are economically viable and their performance (energy, structural, durability, etc.) is comparable to other alternatives.

Embodied carbon standards cannot be driven solely by the building communities. Guidelines and standards on embodied carbon data collection and reporting need manufacturers' participation. 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.

To leapfrog from voluntary standards adopted by industry leaders to building codes guiding general practice, we need to build adequate knowledge infrastructure. Current efforts (e.g., voluntary rating systems, buy-clean policies, voluntary reporting and disclosure, development of new materials and technologies, and early adopters in the marketplace) have been creating important momentum, but the multilayered solutions for successful implementations across complicated supply chains still needs additional rigor, testing, and response to a dizzying array of products.

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 the federal agencies (e.g., Department of Energy, Environmental Protection Agency, National Institute of Standards and Technology), model code-writing organizations (e.g., ASHRAE and 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.

The roadmap should include what we know today that is sufficient to start the development of embodied carbon codes and standards at the building level, what we need to develop immediately to facilitate standard adoption and implementation, which part of the codes and standards can be mandatory and which part should start as voluntary, and what knowledge we can build over time to strengthen and continue advancing the embodied carbon building codes. The roadmap should also evaluate the importance level of the identified knowledge gaps and the challenges and strategies to address them collaboratively.

In sum, tools, methods, and standards of LCA (global scale, International Organization for Standardization [ISO]) have been established to assess embodied carbon in the built environment. The past five years (from 2021) have seen embodied carbon and LCA become standard features of commercial as well as governmental green building systems at global scale, particularly in Europe. While this trend is relatively recent, best practices have started to emerge and can be adopted in the United States to expedite the movement toward reducing embodied carbon in buildings. Unlike in the European Union, in the United States, there is no adopted guideline of whole life-cycle assessment at the building level. And the development of a U.S. LCI database is moving slowly. With more robust U.S. LCI data and U.S. standards, benchmarks for embodied carbon in buildings can be established. There are two actions U.S. federal agencies can take immediately: (a) develop applicable U.S. standards based on ISO standards referencing European National (EN) standards and (b) fund the collection and organization of LCI data. The federal agencies and the federally funded research and development centers should take the lead to develop whole-building LCA baselining methods and establish the embodied carbon reduction targets given embodied carbon's impact on operational carbon.

Background

In 2019, GHG emissions from the building sector were nearly 14 gigatons of carbon dioxide ($GtCO_2$), or 38% of the total energy-related GHG emissions, including 28% from building operation and 10% from building construction. Today, the building construction industry (including commercial, residential, and industrial buildings) accounts for 5% of global energy use and 10% of global GHG emissions (United Nations Environment Programme 2020). 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,[2] corresponding efforts to reduce embodied energy and carbon from building construction materials must be pursued to achieve building sector decarbonization goals. As buildings become more and more efficient, embodied carbon will be a greater and 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 life-cycle carbon emissions of low-energy and near-zero-energy buildings, respectively (Chastas, Theodosiou, and Bikas 2016). Embodied carbon is not "negatable" anymore, hence 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 decrease embodied carbon[3] 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 (EIU 2021). Consumer actions can significantly affect embodied carbon imports, in addition to domestic carbon emissions (Moran et al. 2018). The importance of embodied 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, as the interface between buildings 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 consumers' 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

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[2] Building operation accounted for 30% of global energy use and 29% of global greenhouse gas emissions in 2019.

[3] The scope of embodied carbon is defined in the Definitions and Terminologies section. Embodied carbon and embodied emissions are used interchangeably in this report.

improvements) are 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 (California Legislature 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.[4] 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 life-cycle impact reduction credit in Leadership in Energy and Environmental Design (LEED) (USGBC 2021), the embodied carbon requirements in Living Buildings Challenge certification (International Living Future Institute 2021), and the LCA Practice Guide from Carbon Leadership Forum (Simonen et al. 2019). In addition, complementary approaches that require buy-in from key stakeholders (e.g., manufacturers, builders) to facilitate changes in low-carbon choices and behaviors are needed.

BUILDING CODES TO DRIVE DECARBONIZATION OF BUILDINGS, CONSTRUCTION, AND MANUFACTURING

Supporting the development or modification of building standards and codes is 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,[5] 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 building operations—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 greenhouse gas emissions have stimulated changes of practice in building design and operation. Significant progress (figure 1) has been made to reduce the operational energy of a building during its use phase, largely as a

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[4] The Carbon Leadership Forum has been tracking the embodied carbon policies in the U.S. Carbon Leadership Forum, 2021. https://carbonleadershipforum.org

[5] 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.

result of energy codes. In general, we have a clear understanding of operational carbon emissions and a solid knowledge base of carbon reduction strategies for reducing building energy use.

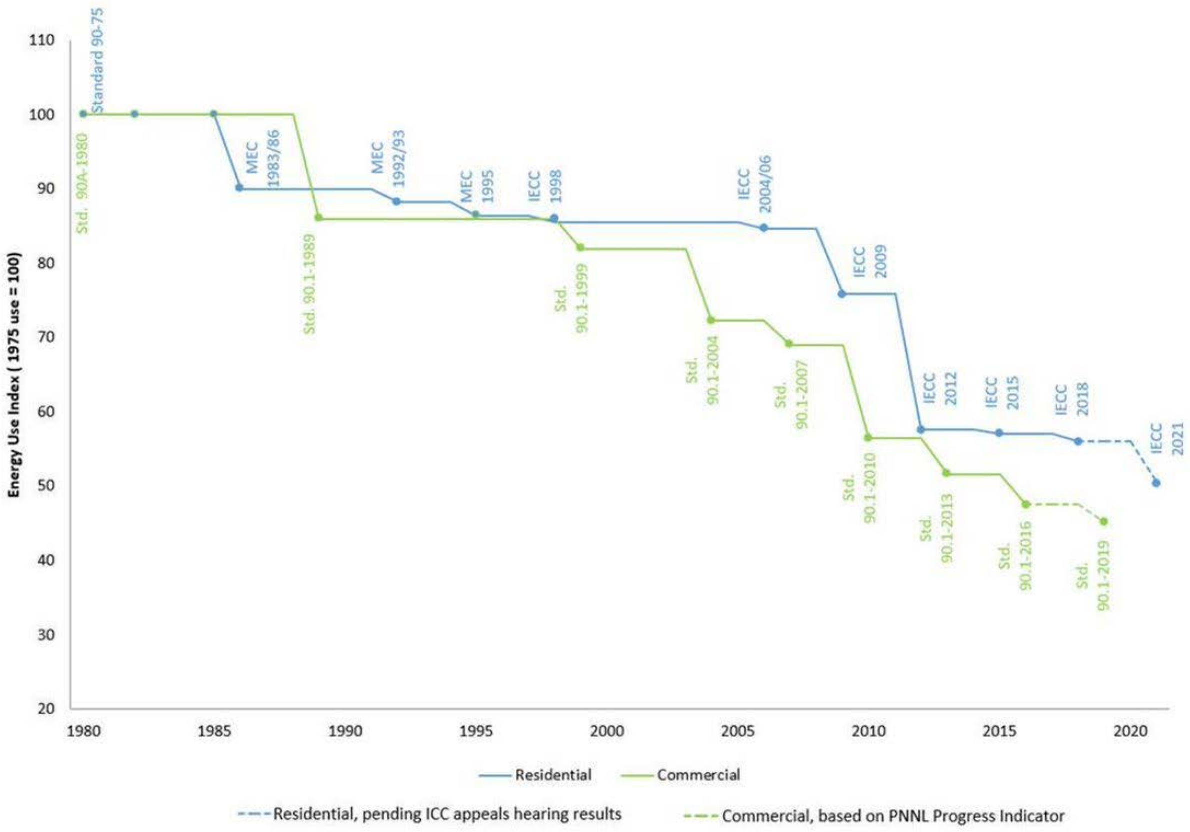

Figure 1. Relative energy use under model building energy codes 1980–2020. Source: ACEEE based on analysis from Pacific Northwest National Laboratory.

In contrast, strategies to reduce embodied carbon in the subsequent remaining life-cycle 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. 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 these 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; however, the embodied carbon of the two products may vary drastically. 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 (Cameron 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 accounting[6] 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 life-cycle 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 lead 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 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.

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 (GSA 2021). These recommendations include a material-based approach for all projects and a whole-building life-cycle assessment approach for larger 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)[7] among functionally equivalent products

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[6] 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.

[7] The 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 (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. (www.epa.gov/ghgemissions/understanding-global-warming-potentials)

as demonstrated by environmental product declarations (EPDs)."[8] The whole-building approach requires "designing a building in such a way that life-cycle carbon assessments show that the selected design results in a 20% carbon reduction, compared to a baseline building."[9] 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; however, such initiatives have only modest effects and are unlikely to substitute for regulations (Coglianese and Nash 2016).

To leapfrog 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 very first step, we need to identify the critical missing components that would support such knowledge infrastructure.

SETTING EVALUATION CRITERIA THROUGH THE LENS OF BUILDING CODES

Codes and standards are often incorrectly used interchangeably and confused as being the same, 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),

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[8] An Environmental Product Declaration (EPD) is a report that provides information about a product's impact upon the environment, such as global warming potential, smog creation, ozone depletion, and water pollution. (www.ul.com/resources/environmental-product-declarations-program)

[9] 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).

and ANSI/ASHRAE/IESNA 90.1 Standards developed by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE). State building code councils (the name varies 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 (architects, engineers, contractors, etc.) practicing within the state and/or municipality. The adopted codes are enforced by law and have established consequences for noncompliance.

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, material specifications, and so on. 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 Organization for Standardization (ISO)[10] that brings together technical and professional organizations from countries around the world to develop, validate, and update these standards, building upon a shared knowledge infrastructure. In many cases, the ISO will recognize standards developed in an individual country facilitating harmonization of standards globally promoting international trade.

Energy codes set the minimum energy performance standards for building components (roof, wall, window, lighting, and heating, cooling, and ventilation systems). The energy model 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 and 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). In contrast, some states (such as Kansas, Missouri, and Wyoming) have no state-wide energy 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, and energy use 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-

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[10] For more information on the international standards process, see: www.iso.org/about-us.html.

performance, green buildings.[11] Given the urgency of addressing climate change, a shift from energy to carbon metrics is also emerging. Marin County in California is the first and the only jurisdiction that has adopted an embodied carbon provision in its building codes (Marin County, California 2021). Chapter 19.07 of Title 19 in the Marin County Building Code sets maximum embodied carbon limits (ranging from 260 to 675 kg CO_2e/m^3) for concrete of various compressive strength levels.[12] 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 synthetization 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 existing gaps and eventually establish a robust knowledge infrastructure, the key questions to be answered are:

- Are there adequate, trustworthy product data and publicly assessable databases to enable the calculation of whole-building embodied carbon throughout its life cycle?
- Are there established standards to guide measurement, calculation, and assessment of embodied carbon in buildings?
- Are there accessible, quality tools to support practitioners that conduct the analysis and make an informed decision on their design solutions?

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[11] 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 life-cycle assessment of materials/resources, carbon emissions, electric vehicle charging infrastructure, and so on. 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.

[12] 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 is allowed to have higher ordinary Portland cement content and higher embodied carbon.

- Are there transparent, credible processes to govern the database and/or the tool development?

To answer these questions, we developed and used five criteria to review the existing body of knowledge on embodied carbon. They are *accessibility, completeness, quality assurance, standardization,* and *transparency.* Knowledge infrastructure is a framework used to organize content: we cannot make good use of our existing knowledge without a robust infrastructure. Complete and robust knowledge is essential to provide the building blocks for this infrastructure.

Definitions and Terminologies

LIFE-CYCLE ASSESSMENT

The development of embodied carbon is intertwined with the development of life-cycle assessment (LCA) methodologies for materials and buildings, since embodied carbon is a part of the whole life-cycle carbon associated with a building project.[13] LCA is a method to assess the environmental impacts of a product or service throughout its entire life cycle (Müller et al. 2020). Each LCA is composed of four stages: goal and scope definition (in this stage, the intent of LCA is defined), inventory analysis, impact assessment, and interpretation. The LCA method was standardized in the 1990s by the International Organization for Standardization (ISO) in ISO 14040 and 14044; the most widely used version is from 2006 and is still updated and extended regularly (Müller et al. 2020). Along with ISO 14040 and 14044, ISO 21930 (ANSI 2017b) and ISO 21931 (ANSI 2019) are often used together to support the application to the construction industry at product and building levels (Lowres and Hobbs 2017).

Through each life stage of a building's life cycle (from cradle to grave), the building impacts the ecosystem by consuming raw materials and producing carbon and pollutants. LCA is a quantitative way to describe these interactions and the related environmental and human health impacts. Examples include global warming potential (GWP), ozone depletion potential (ODP), eutrophication potential (EP), acidification potential (AP), and smog formation potential (SFP).

Embodied carbon quantification is derived from the GWP output, which measures a multitude of greenhouse emissions (such as methane, nitrous oxide, chlorofluorocarbons) in CO_2 equivalence. When LCA is applied in the building and construction sector, four different levels of assessments (depending on chosen scopes, system boundaries, and functional units) may be conducted at the: building material level (e.g., concrete), building product level

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[13] Embodied carbon can be dealt with in a variety of ways with the end goal toward understanding whole-building LCA. Whole-building LCA is critical because it allows for optimizing design choices based on carbon.

(including building components, systems, and assemblies), whole-building level, or industry level (see figure 2), but all four often use the same database of inputs. Among the four levels, the industry-level LCA is less known to practitioners and researchers in built environments. The industry level of LCA is often conducted in the industry ecology field, which is the study of material and energy flows through industrial systems. It regards the industry process as a closed loop system (similar to a natural ecosystem) where the waste of one product become the raw ingredients to others (Kibert, Sendzimir, and Guy 2000). One good example is substituting the fly ash byproduct from coal burning practices for cement in concrete production. It is most common to conduct LCAs in the built environment at the product and the whole-building levels.

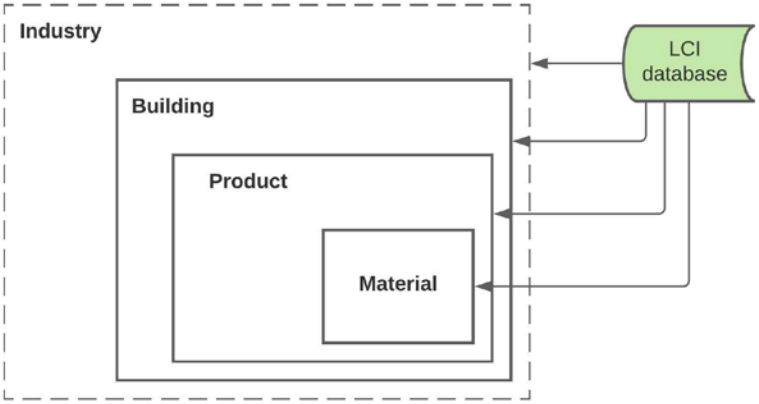

Figure 2. Level of life-cycle assessment

LIFE-CYCLE EMBODIED CARBON

The term embodied carbon is sometimes used without a clear definition, which may result in incomplete calculations or weak comparisons. Figure 3 illustrates different types of embodied carbon that are often referred to and discussed in the building sector and their relation to the entire life cycle of a building. Definition of the goal and scope, the life-cycle inventory analysis, and the interpretation are based on the ISO 14044 standard (ANSI 2006). This study focuses on a cradle-to-grave scope for embodied carbon LCAs (A through C). As shown in figure 3, stage A encompasses the product and construction phases and includes A1–A5. Substages A1–A3 are commonly included in a “cradle-to-gate” scope (or upfront carbon) and substages A1–A4 are typically included in a “cradle-to-site” scope by researchers and practitioners, which will lead to different results for the overall embodied carbon assessment for the same building due to differing system boundaries. For ease of reference, we designate the cradle-to-gate scope as embodied carbon one (C2Gt), cradle-to-site as embodied carbon two (C2St), cradle-to-grave as embodied carbon three (C2Gv), and cradle-to-cradle as embodied carbon four (C2C).

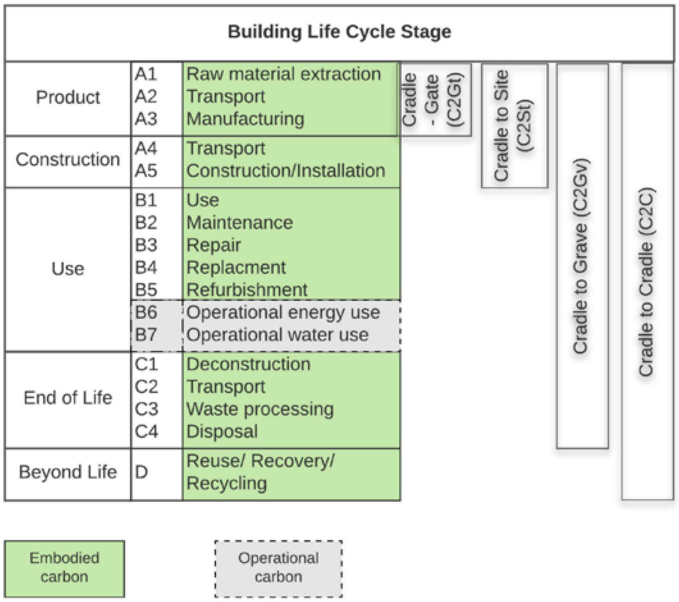

Figure 3. embodied carbon definition and life-cycle stages (adapted from Pomponi and Moncaster 2016)

Any building's carbon emissions include two broad categories of emissions: life-cycle embodied carbon and operational carbon. Life-cycle embodied carbon is the cradle-to-grave carbon associated with constructing and maintaining a building during all phases of production, onsite construction, operation (except utilities in B6 and B7), and final demolition and disposal. Operational carbon (B6) is composed of the carbon emissions generated from the use of energy to condition and power a building. Figure 4 shows a building stock analysis of the ratio of operational carbon and embodied carbon in Denver, Colorado over 40 years (City and County of Denver 2021). As building codes head to net-zero energy and we consider decarbonization of heating through electrification, the operational carbon becomes a smaller percentage of the overall emissions from a building. In the example of Denver, the embodied carbon emissions are estimated to make up 27% of all emissions from buildings built in 2030 compared to annual operational emissions for all buildings in 2030. If Denver were to achieve its goal of all buildings to be net-zero energy by 2040, 100% of emissions will be from embodied carbon.

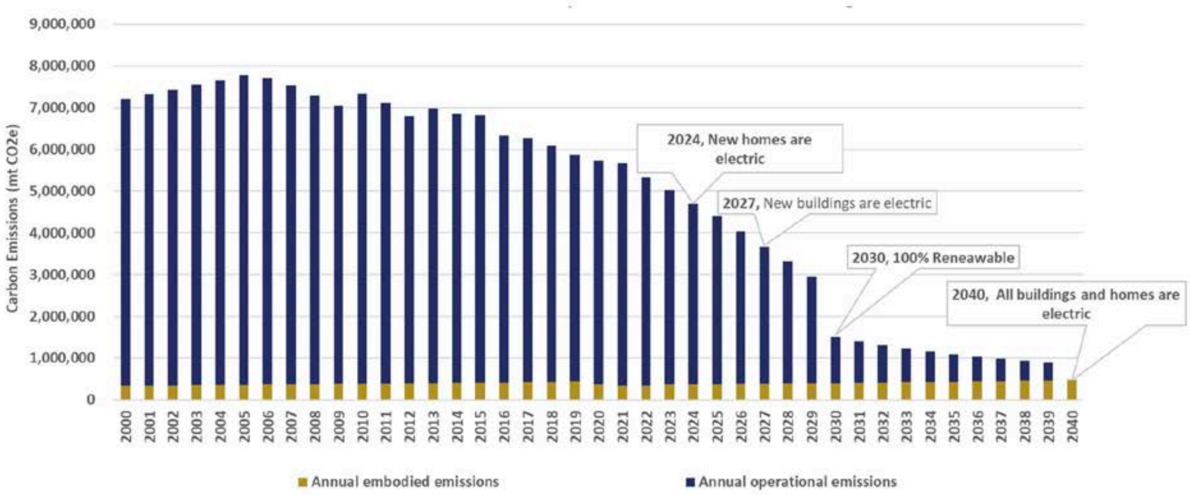

Figure 4. Embodied carbon and operational emissions for all buildings by year. Source: City and County of Denver 2021.

Life-cycle embodied carbon consists of three primary categories: upfront embodied carbon, recurring embodied carbon, and end-of-life embodied carbon. Upfront embodied carbon (UEC) is the carbon emitted on-site and off-site before a building is in operation, from construction, on-site prefabrication, transportation, and other related activities, such as site preparation. UEC spans life-cycle stages A1–A5. It accounts for a significant portion of the total life-cycle carbon and can be reduced by decreasing the building's area, using fewer energy-intensive materials, and optimizing other design strategies (e.g., the use of lightweight instead of heavy structure systems).

Recurring embodied carbon (REC) is the carbon emitted during the use stage and is associated with repair, replacement, refurbishment, and maintenance of the building. REC spans life-cycle stages B1–B5. End-of life embodied carbon (EEC) is the carbon emitted during the demolition, deconstruction, transport of deconstructed building assemblies, waste processing, and material disposal. EEC spans life-cycle stages C1–C4. EEC is a type of embodied carbon that today is mainly neglected in tracking and counting mechanisms, in practice, although the international standards include EEC in the whole-building LCA. IEC and EEC occur once over a building's lifetime, and REC is influenced and modified by multiple factors (i.e., climatic condition of building site, use condition, and maintenance frequency).

The life-cycle embodied carbon (LCEC) can be calculated using Equation A:

$$LCEC_b = UEC_b + \sum_{c=i}^{c=n}(REC_i)\ x\ BT_c\ x\ L_c + EEC_b \qquad \text{Equation A}$$

where $LCEC_b$ *is the cradle-to-grave life-cycle embodied carbon of a building,* IEC_b *is initial embodied carbon,* REC_i *is recurring carbon of a building product or material (maintenance and repair).* BT_c *is the building type factor; certain building types need more frequent* *maintenance and repair than others, such as those with swimming pools.* L_c *is the location (climatic) condition.* EEC_b *is the end-of-life embodied carbon.*

LIFE-CYCLE COST ASSESSMENT

Life-cycle cost assessment (LCCA) is an economic method of project evaluation in which all costs accumulated from all life stages of a building (as described in the previous section and shown in figure 3) are considered to be potentially important to the decision. LCCA provides significantly better assessment of the long-term cost effectiveness of the overall investment and considers building maintenance and future renovation, in contrast to alternative economic methods that only focus on the initial costs of development and construction. Furthermore, LCCA helps compare and identify which building retrofit strategies are economically justified from the building owners' perspective based on energy consumption reduction and other cost measures. In current practice, LCCA is not conducted in parallel with LCA, although it could be an important and valuable tool when considering the economic impacts of regulating embodied carbon. Incorporating embodied carbon in building codes requires not only the calculation and reduction of greenhouse gas emissions, but also the associated economic issues, such as affordability. LCCA would also factor into policy development, such as green mortgages.

Literature Scan Methodology

We conducted an initial literature search and review using the keywords "embodied carbon," "embodied GHGs," and "embodied CO_2" 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. As illustrated in figure 5, interest in embodied carbon in the building industry has grown exponentially since 2010. We decided to focus on the literature in the past 10 years, from 2010–2021, and excluded publications from less-related fields such as chemical engineering (273); earth and planetary science (259); agricultural and biological science (504); social science (1,196); economics, econometrics, and finance (455); and business, management, and accounting (448). Additionally, articles from encyclopedias, short communications, conference abstracts, discussions, mini reviews, and other uncategorized types were also excluded. Thus, we narrowed our search results to 5,329 relevant papers in the more directly related fields of energy, environmental science, engineering, and materials science.

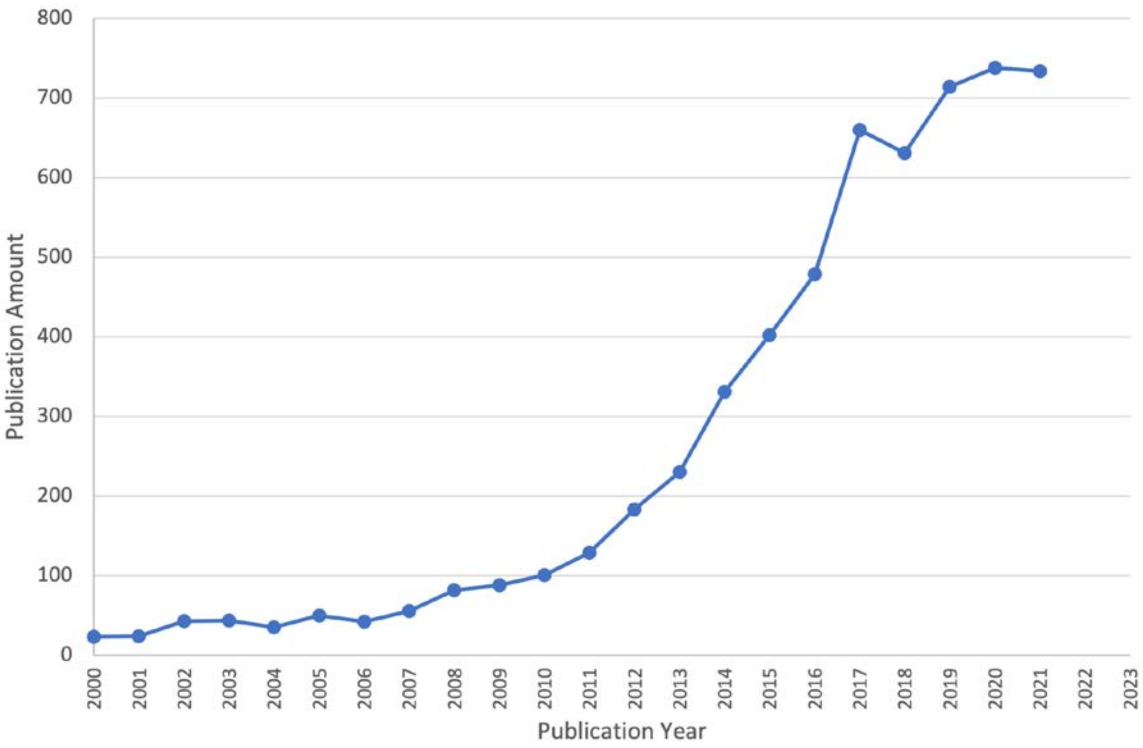

Figure 5. Literature scan results: number of published articles on embodied carbon

Subsequently, we reviewed the titles of the 5,329 articles in a second selection round, and selected publications based on whether they took a global approach or had a U.S. focus. For example, if a publication was titled as an embodied carbon study in Australia, then it was excluded from further study. Such filtering further eliminated irrelevant topics and resulted in a smaller subset of 40 articles.

Most of the eliminated articles focused on specific technical developments but did not offer new knowledge for developing embodied carbon standards, methodologies, databases, or tools. One example is a paper entitled "Comprehensive investigation of embodied carbon emissions, costs, design parameters, and serviceability in optimum green construction of two-way slabs in buildings." While the title of the article appeared applicable, the body of the article was not relevant to developing new knowledge on standards, methodologies, databases, or tools. We also excluded articles that presented case studies outside of the United States and Canada because the life-cycle assessment of embodied carbon is sensitive to and influenced by its geographic system boundary. We will further discuss system boundary selections later in this paper.

The third round of the literature selection process involved reading the abstracts of the 40 articles to determine whether the publication provided information on one or more of the following: embodied carbon data, calculation tools, or embodied carbon code requirements and regulations. In the end, we identified 28 papers for in-depth review and analysis.

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 CO_2e/m^3). Most of the research papers were 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, not-for-profit 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 life-cycle inventory (LCI) data from the United States and Canada, since LCI data serve as the primary inputs for conducting the inventory analysis in LCA studies and high-quality data that are consistent, accurate, and relevant allow for robust and meaningful results (NREL 2012). Our search resulted in eight more publications from the U.S. Department of Energy, the American Institute of Architects, and industry and academic collaborative entities (such as the Carbon Leadership Forum). The literature scan methodology is shown in figure 6. In total, we reviewed 44 articles in extensive detail to identify the current state of the knowledge of existing methods, databases, and tools on embodied carbon in buildings. In addition, the knowledge gaps were analyzed and quantified by summarizing the topics found in each article. Findings are presented in the following sections.

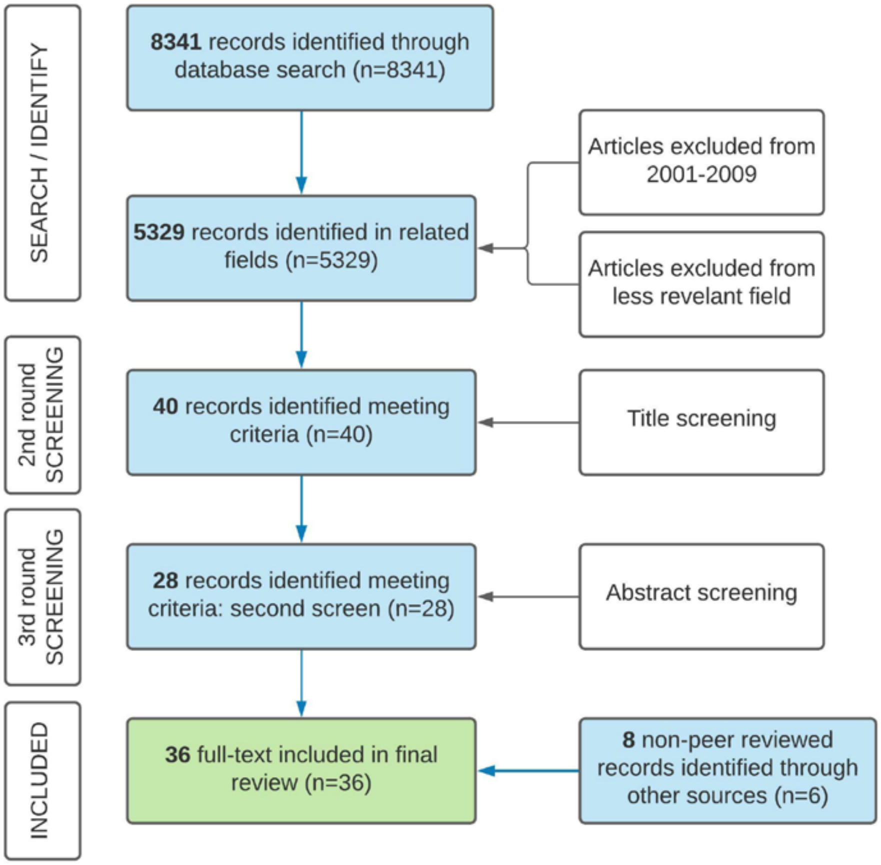

Figure 6. Review process

Review of Existing Standards, Methods, Data, and Tools

STANDARDS AND METHODS

STANDARDS FOR LCA

The quantification of embodied carbon is intertwined with the development of LCA. 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). All LCAs should comply with these standards and follow the guidelines and steps laid out in them. The ISO 14040 and ISO 14044 standards together describe LCA principles, frameworks, requirements, and procedures, including definition of the goal and scope of LCA, the LCI analysis phase, the life-cycle impact assessment (LCIA) phase, the life-cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. The two standards combined cover both LCA and LCI studies, with

LCI studies closely tied to embodied carbon assessment, but do not describe LCA evaluation techniques in detail, nor do they specify calculation methodologies for the individual phases of the LCA. This gap was intentionally left to allow LCA researchers and practitioners the space to further develop methodologies that fit their particular context, which in turn has led to the development of a variety of LCA methods and tools.

Some other important international standards related to LCA and embodied carbon and applicable to the United States and Canada include

- *ISO 14020 Environmental labels and declarations - general principles*
- *ISO 14021 Environmental labels and declarations - Type II environment declarations*
- *ISO 14024 Environmental labels and declarations - Type I environment labeling principles and procedures*
- *ISO 14025 Environmental labels and declarations - Type III environment declarations - Principles and procedures*
- *ISO 14027 Environmental labels and declarations – Development of product category rules*[14]
- *ISO 21930 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products*

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 labels (ANSI 2021). ISO 14027 and 21930 standards provide more specifications. The Environmental Product Declaration (EPD) is a widely used and internationally recognized environmental label. EPD is a report that provides information about a product's impact upon the environment. EPD reports are generally available from the International EPD System database, especially in Europe (The International EPD System 2021b).[15] The typical report summarizing a product's environmental information is normally fewer than 50 pages (EPD International 2021b). A variety of LCI databases are used to calculate the environmental impact of products, and the calculations and processes follow the ISO 14040 standard.

After the development of ISO standards, in 2004 the European Commission mandated the European Committee for Standardization (CEN) to develop a set of horizontal standards that enables the sustainability assessment of construction work. The developed standards include EN 15804 (CSN 2019) and EN 15978 (BSI 2012), developed together based on the same life-

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[14] Type I includes third-party verified labels based on criteria set by a third party. Type II includes self-declarations of product information made by manufacturers or retailers. Type III includes quantified product information based on LCA and verified by a third party.

[15] The EC3 Tool aims to fill the gap in the United States.

stage modular concept. EN 15804 communicates the product category rules (PCR) that define the minimal requirements for Type III environmental declarations particular to building products. The purpose of EN 15804 is to enable a consistent LCA of different building product types based on ISO 14040/44 (Achenbach, Wenker, and Rüter 2018). EN 15978 regulates the LCA at the building level. According to this standard, information on the environmental performance of the product stage (cradle to gate) of a building is to be derived from EPDs or other LCA datasets that are in the line with EN 15804. Therefore, using EN 15978 and EN 15804, practitioners can conduct different forms of LCA, such as the assessment of the product stage or of a whole life-cycle stage on building level. Because of the modularity and flexibility, this set of EN standards (including EN 16309 for the social performance and EN 16627 for the economic performance of buildings) can be adopted by different EU member states as a comprehensive guide to conduct sustainable building performance assessment at all life-cycle stages and from environmental, social, and economic perspectives.

Overall, there are three commonly used, recognized and agreed-upon LCA methods, which we describe in the following sections.

ECONOMIC INPUT-OUTPUT METHOD

The economic input-output (I-O) method is a widely adopted strategy for LCA. It was developed by economist Wassily Leontief in the 1930s for the U.S. economy, earning him the Nobel Prize in Economics in 1973. This method includes an economic input–output table and a set of equations to use in a model (Leontief 1986). The model represents the various inputs required to produce a unit of output in each economic sector based on surveyed census data of purchases and sales in the sector (e.g., the single-family-home sector). By assembling a table describing all the major economic sectors, Leontief was able to trace all the economic purchases needed to produce outputs in each sector from the very beginning when raw materials are extracted. The I-O model was popular in the mid-20th century for high-level economic planning purposes, and later it was adopted as an LCA method. As illustrated in figure 7, by appending data on energy, environmental, and other flows to the input-output table, non-economic impacts, such as carbon emissions, can be predicted.

The I-O method has a complete system boundary (Crawford 2011). As illustrated in figure 7, the system boundary shows which processes are in the calculation and which are not; therefore, the I-O method can potentially overcome the major drawback of the process analysis method (discussed in the next section). This method has some limitations as well. The I–O analysis is generally viewed as a "black box" providing users with little understanding of the values being assumed in the model for each process (Crawford 2008). In addition, even though the I-O method may produce a relatively accurate assessment of the overall embodied carbon, a perfect I-O model may not produce valid results for a particular material or product, because it is based on many inherent assumptions that were originally developed for national economic assessment (Ochoa, Hendrickson, and Matthews 2002; Crawford 2008). For this reason, the I-O method should be used as a screening tool or a scoping tool to evaluate the alternatives when detailed data are missing from the process-based method (DOE 2021). This screening tool can be used to make high-level selections and provide information to decision makers.

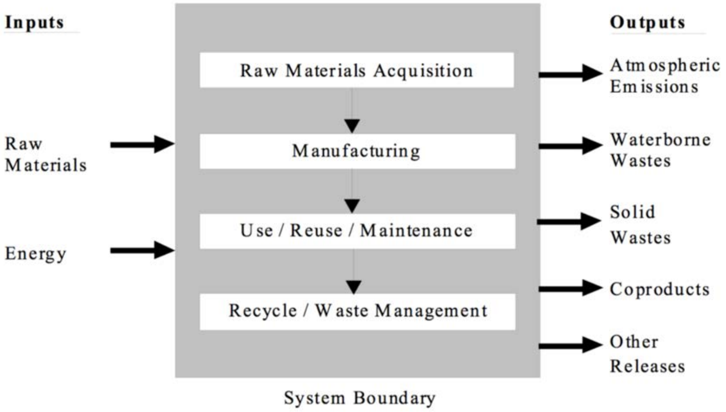

Figure 7. Overview of Input-Output method. Source: EPA 2006.

PROCESS METHOD

As opposed to the I-O method, which is a top-down approach, the process-based method is a bottom-up approach. Data are derived from the knowledge of industrial processes within the life cycle of a product (a product can be a building component, e.g., windows, or building material, e.g., cement), and the logistic flows connecting them (Leontief 1986). This method may result in the most incomplete outcomes because of the complexity of the upstream requirements for goods and services (Lave et al. 1995). The magnitude of this knowledge gap varies with the type of product or process being assessed and the granularity of the study; the inaccuracy of the assessment may be as high as 50% or more of the actual results (Treloar 1998).

Figure 8 demonstrates one example of a process-based model. The system boundary for this example encompasses only three unit processes: mining coal, transporting it by rail, and burning it at a power plant, but the refinery process that produces diesel fuel (an input for rail), is considered to be outside of the studied system boundary, even though the effects of using diesel as a fuel are included. In comparison, the I-O method would include the diesel refinery process and more (Leontief 1986). The process LCA method tends toward establishing tight system boundaries, which limits the scope of the project and thus the time and effort needed to collect information on the inputs and outputs. While this is useful in developing a manageable LCA project, defining such narrowed boundaries for the analysis automatically limits the results and creates an underestimate of the life-cycle impacts. Furthermore, the other main issue with process-based LCA methods concerns circularity effects. Since several precursor products are used in the manufacture of a final product, an LCA of all contributing materials and processes is required before completing the LCA of any material or process (GDI 2016).

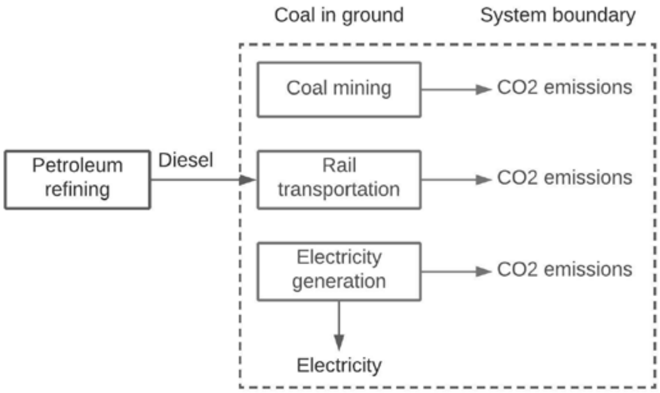

Figure 8. Product system diagram for coal-fired electricity example

The connection between the economic I-O and process-based methods is that we can regard each sector of the I-O model as a process. In each process, the "inputs" are the economic inputs (as purchased) from all the other sectors, and the "output" is the product of the sector.

HYBRID METHOD

An emerging method is a hybrid of the two methods above. It has been a main development area in LCA methodology in the past decade, attempting to combine the advantages of both methods and minimize their limitations. Generally, a hybrid method can be I-O based or process based and may combine the process data and the I-O data in different ways (Ward et al. 2017). Researchers have proposed promising hybrid methods that are specifically tailored toward the building and construction industry. A literature review of hybrid life-cycle inventory methods found 97 peer-reviewed publications referencing the use of a hybrid LCI between 2010 to 2015 (Crawford et al. 2017). Mostly recently, Yu et al. (2020) proposed a hybrid method focused on embodied emissions in the built environment, which can potentially be used as a value engineering tool. A summary of the three methods is presented in table 1.

Table 1. LCA methods

Method	Advantages	Limitations	Suitable applications
Economic I-O method	With a complete system boundary	A black box with little information on model assumptions. May not provide valid result for a particular material or product	A screening or scoping tool for high-level decisions
Process method	More-specific data derived from the industrial processes within the life cycle of a product and the logistic flows connecting them enable more detailed and comprehensive analyses.	May result in incomplete outcomes because of the complexity of the data requirements for upstream goods and services. Narrowed boundaries may create an underestimate of the life-cycle impacts. Circularity effect when precursor products are used in a final product.	Analysis of a specific product or process
Hybrid method	Combining the advantages of above two methods and minimizing their limitations.	Less established and to be explored and further developed.	Analysis of a specific product or process

In sum, there are adequate international standards to guide methodology development for assessing embodied carbon in buildings, but the accuracy of results depends on the data fed into models and the definition of the system boundary; both need to be further investigated and standardized to ensure consistent analyses and comparisons.

DATA AND DATABASES

DATA SOURCES

There are different types of LCA data available, which influences how embodied carbon estimates are assessed and derived. The LCA data result from the method used for assessment; therefore, the data, the methodology, and their application should be linked. Standards for assessing LCI data follow the ISO standards mentioned above. Assessing data quality requirements is one of the steps under scope definition during the first stage of any LCA as stipulated in the ISO standards. Data may come from a primary or secondary source.

A primary source of data comes directly from an entity that collects the data and/or analyzes it to evaluate the environmental performance or impact of a product or service. The product can be materials (e.g., cement, steel) or their aggregations and assemblies (e.g., concrete ready-mix, steel "I" beams). A primary data source is generally a definitive and more reliable source of information because of its traceability and specificity to the product or process being assessed and therefore is preferable if it is available. A known example of a primary data source is an Environmental Product Declaration (EPD), which also allows the use of secondary data sources.

An EPD (mostly referred to Type III EPD in the context of building embodied carbon) is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products (EPD International 2021c). The International EPD System has its roots in the Nordic European Union (EU) nations where the first and leading global EPD program was developed and operated in accordance with the ISO 14025, TS/14027, 14040 standards. For the building and construction sector, manufacturer EPDs also comply with the ISO 21930 and EN 15804 standards (EPD International 2021a).

An alternative to a primary data source is a secondary data source. Broadly defined, secondary data come from citing a primary LCI database and/or literature sources (i.e., results in the published literature). The advantages of using secondary data sources include flexibility and the existence of multilevel data, which allows data to be collected and presented at the material level, product level, and/or building level. At the same time, such data sources may use information in ways that are inconsistent with the intent of the primary source and introduce potential biases. Hence, secondary databases vary in quality. The free databases tend to be less reliable because of the lack of funding for frequent updates and expansion of data sources, but they help make LCA more accessible to a broader audience.

One example is the Bath Inventory of Carbon and Energy (ICE) database created by the University of Bath, which consists of over 400 datasets, and whose main data sources include published academic research, industry statistics, government publications, and references from other primary LCI databases (Greenhouse Gas Protocol 2021a). In the United States, the Federal LCA Commons was formed in 2012 to coordinate LCA development and application across 12 federal agencies and national laboratories. The Commons developed an open-source repository and publication workflow for federally funded and federally produced LCA data.

CURRENT DATABASES

OpenLCA Nexus (openLCA Nexus 2021) is by far the most comprehensive website providing information on LCI datasets globally. It was created in 2012 for OpenLCA, which is an open-source LCA software. OpenLCA Nexus includes 25 datasets, mainly developed for European countries. Using the Nexus website, users can search for individual datasets, based on customized search criteria such as country, price, sector, etc. Some of the datasets include LCI data of U.S. origin.

To create a reliable and relatively accurate embodied carbon assessment, LCI databases need to be regionally sensitive, taking into consideration local manufacturing technology, fuel sources, transportation, and recycled content differences for products produced in various regions. For example, Emami et al. used regional databases (that represent the studied location) from Simapro and GaBI to study two residential buildings in Finland. For the whole-building assessment, the resulting discrepancy is estimated to be around 15%, which subsequently leads to different design solutions/directions for the studied cases (Emami et al. 2019). Another research effort compared the life-cycle impact of passive-house-compliant small residential buildings in Italy using the AH-LCA evaluation tool v1.6 and EPDs. This led to differences/discrepancies in all LCA environmental impact categories of up to 10% for global warming potential, 20% for acidification potential and eutrophication potential, and 40–50% for renewable primary energy (Palumbo 2021). In both cases, the discrepancy cannot be simply attributed to specific product data in the databases. The data sources are unknown or unspecified in the studies. Due to the imprecision of LCI, these "huge" differences are not uncommon in LCA. Differences of this magnitude have the potential to mislead design choices and project investments if embodied carbon were to be introduced to building standards or codes. A national protocol to guide database development, application, and result verification and comparison is critical but currently missing.

In this study, we focus on databases that are relevant to the United States and Canada. Table 2 lists nine commonly used and known databases that include regional data samples from the United States and Canada, and consequently their regional characteristics. Using the five criteria that we defined in the Background section of this paper, we evaluated the *accessibility, completeness, quality assurance, standardization,* and *transparency* of each database based on the following questions (note that answers to the underlined questions are not included the table due to the lack of information):

- Is the database free to use? Who is paying for data collection and maintenance? *(accessibility)*
- Can the database be viewed and used directly (a standalone database)? Can the database be embedded in other tools? *(accessibility)*
- How many datasets does the database consist of? *(completeness)*
- What countries or regions are covered by the database? *(completeness)*
- Is the database based on a primary or secondary data source? Are the original data third-party verified? *(quality assurance)*
- What life-cycle stages are covered in the database? Are data collected with standard methods? *(standardization)*
- Is there published documentation of its data sources and how the database is maintained? *(transparency)*

Overall, comprehensive embodied carbon data to evaluate all life-cycle stages of buildings in the United States exist and are available to users. Four out of the nine reviewed databases use primary data sources; seven are free for users or tool developers. Some databases, such as ecoinvent, are very comprehensive, containing data on hundreds if not thousands of unique processes. Each process comprises hundreds of input or output flows (see figure 8 for an example of input/output flow(s)). Others, such as the NIST database, have only aggregate-level data, rather than processes and flows for materials and products, partially due to proprietary data concerns. Therefore, the user can only get information for generic products from the NIST database, such as generic brick, generic stucco, and so on.

Table 2. Database characteristics

Database	Cost of use	Stand-alone versus embedded	No. of datasets	Region	Data source	Life-cycle stage
ecoinvent [a]	EUR 3,800 (USD 4,482)	Standalone, Embedded	18,000+	Global, Europe focus	Secondary [b]	A1–A3, A1–A5, A1–C4
U.S. National Renewable Energy Laboratory (NREL) LCI Database [c]	Free (companies or agencies pay to publish data)	Standalone	600+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
USDA LCA Digital Commons	Free (manufactures and agencies pay to publish data)	Standalone	300+	U.S. focus	Primary	A1–A3, A1–A5, A1–C4
NIST BEES database [d]	Free	Standalone, Embedded	Unknown	U.S. focus	Secondary	A1–A3, A1–C4
Quartz [e]	Free	Standalone	102 products	U.S. focus	Secondary (no lingered maintained)	
GaBi database	USD 3,000	Standalone, Embedded	15,000+	Global, Europe focus	Primary and Secondary	A1–A3, A1–A5, A1–C4
Athena database	Free	Standalone	200,000+ (building and construction materials specific)	U.S. and Canada focus	Secondary	A1–A5, A1–C4
Carnegie Mellon database [f]	Free	Standalone	3,500+	U.S., Canada, Germany, Spain, China	Secondary	A1–A3, A1–A5
Environmental Product Declaration (EPD) library	Free	Standalone	149 products [g]	Global	Primary	Vary
Embodied Carbon in Construction Calculator (EC3)	Free	Standalone	47,000+	Global, with a U.S. focus	Primary	A1–A3 (as of 2021)

Sources: [a] Wernet et al. 2016. [b] ecoinvent 2021. [c] NREL 2021. [d] Curran et al. 2002. [e] Quartz 2015. [f] Greenhouse Gas Protocol 2021b. [g] Greenhouse Gas Protocol 2021c.

Data standardization and transparency need to be improved. Not all databases are regularly maintained, nor do they consistently include documentation of their data sources and methodologies. Not all databases make data sources and collecting processes visible and transparent to general users. This information is often embedded in some reference reports that can take significant effort for users to discover. For example, with respect to the transparency of the data used in the Building for Environment and Sustainability (BEES) database, NIST noted:

> Reliable, transparent U.S. LCI data are, at present, only available from commercial tools. BEES does not publish fully transparent data because none are publicly available and NIST does not intend to compete with private sector tools by placing these data in the public domain.... Users seeking full transparency are free to purchase DEAM™ for complete documentation on its upstream data sources and calculation procedures. NIST seeks to provide a public service by making available at no charge LCI data that are transparent in an aggregated sense....

TOOLS

In this section, we review tools that are available and more popular among building practitioners in the United States. Using the same five criteria that we previously defined, we evaluated the *accessibility, completeness, quality assurance, standardization,* and *transparency* of each tool based on the following questions (note that answers to the underlined questions are not included the table due to the lack of information):

- Is the tool free to use? Who is paying for tool development and maintenance? (*accessibility)*
- Can the tool be used directly (a standalone tool) or embedded in other tools? (*accessibility)*
- What database does it use? (*completeness)*
- What level of assessment can the tool provide? (*completeness)*
- What life-cycle stages can the tool calculate? (*completeness)*
- What calculation method does the tool use? Is it a standardized method? *(standardization)*
- Is there a procedure to compare or verify the calculated results? (*quality assurance)*
- Is there published documentation on how the tool is developed and maintained? *(transparency)*

Table 3 compares six tools with respect to their provider, method, and database used, and the type of embodied carbon (EC) assessment that can be performed. The table also provides information on the cost and format of each tool. Each tool is discussed in detail in subsequent sections. Athena and Tally provide whole-building assessments and are mostly used by building designers and professional consultants. The other tools provide assessments at the material and/or the product level. GaBi and SimaPro are the most well-known LCA tools, with the latter being mostly used for research purpose in academia, but neither is U.S. focused. BEES is the only tool that uses the Economic I-O method and provides both LCA and LCC assessments.

Table 3. Current tools applicable to the U.S. EC assessment

Tool	Provider	Cost of use	Stand-alone versus embedded	Database used	Focus level	Life-cycle stage	Methodology
Athena	Athena Sustainable Material Institute	Free	Standalone	GaBi database	*Whole building*	A1-A3, A1-C4	Process LCA
GaBi	Thinkstep; Building Transparency (as of 2021)	No price information provided	Standalone	GaBi database	*Material*	A1-A3, A1-C4	Process LCA
Tally	Building Transparency, KT Innovations, thinkstep, and Autodesk	USD 695/year; free for non-commercial educational and research use	Plug-in	GaBi database	*Whole building*	A1–C4	Process LCA
Simapro	Pre Sustainability consultants	No price information provided	Standalone	ecoinvent, Japan database, NREL LCI	*Material*	A1–A3	Process LCA
BEES	NIST	Free	Standalone	NREL LCI	*Material, Product*	A1–A3	Economic I-O
EC3	Building Transparency	Free	Standalone	EPD data	*Material*	A1–A3	Process LCA
One Click LCA	One Click LCA	No price information provided	Plug-in; Standalone	Varies	*Whole building*	A1–C4	Process LCA

The tools' transparency and quality assurance need to be improved: Overall, there is no standard testing procedure to compare or benchmark the results from the tool. For example, ASHRAE Standard 140 (Standard Method of Test for Building Energy Simulation Computer Programs) creates standardized and citable test procedures for validating, diagnosing, and improving the generation of building energy modeling software (ANSI 2017a). This is critical to increase confidence in the use of building energy modeling. An equivalent standard does not exist for embodied carbon tools. Moreover, the result accuracy from a tool is partially determined by its underlying database, which could be developed by another entity. For example, SimaPro v.8 notes that the extensive ecoinvent background reports can be accessed via the SimaPro help menu or the ecoinvent website (Goedkoop et al. 2016a).

ATHENA

The North American governments began to develop LCI data in the 1990s, as part of their effort to develop LCA (Fava, Baer, and Cooper 2011). The data for the building industry have been the pilot data developed in Canada by Environment and Climate Change Canada in 1991. In the mid-1990s, the Canadian "Athena Project" made these data available in spreadsheets, and in 2002 the data were converted and integrated into an LCA tool, now called the Athena Impact Estimator for Buildings (IE for Buildings) (Cooper et al. 2012). Later, the Athena Sustainable Materials Institute (ASMI) was established as a nonprofit research collaborative that continues to upgrade, manage, and develop a suite of tools and LCI data.

Athena is free for users. It uses the GaBi database, which is built from the ground up using actual mill or engineering process models and is not reliant on trade or government data sources (Athena Sustainable Materials Institute 2021). So far, IE for Buildings is still one of the most suitable calculation tools for researchers and practitioners to assess the embodied carbon of whole buildings in the United States, because of its North American data.

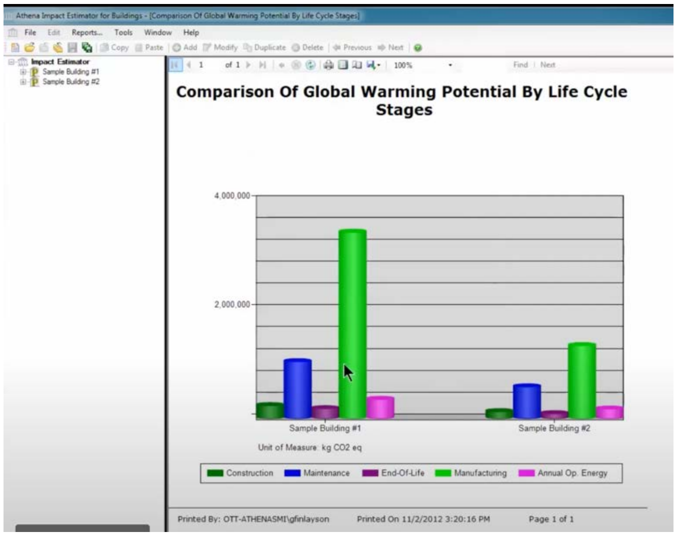

Figure 9. Athena example screenshot

GABI

GaBi (which stands for "Ganzheitliche Bilanz" meaning "holistic balance" in German) was developed by PE Product Engineering GmBH and IKP in Germany. Created in the mid 1990s, it has been used in over 19 countries and has been widely used in many industries, especially in Germany (Olagunju and Olanrewaju 2020).[16] GaBi allows users to customize the database,

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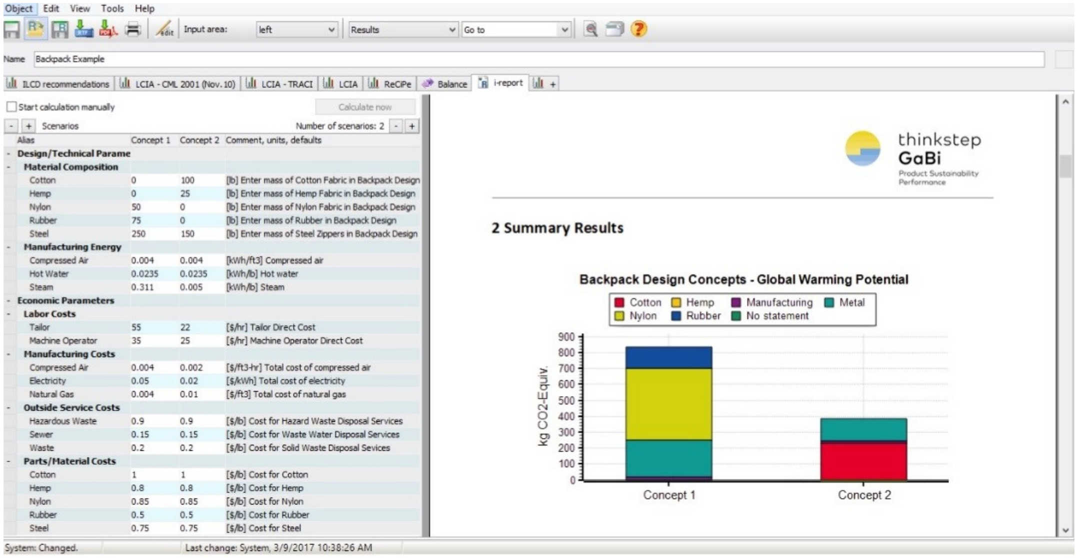
[16] The first studies of LCA date from the late 1960s and early 1970s. A rapidly growing interest rose in the early 1980s, when the first impact assessment method was introduced. Prior to the 1990s, there was a clear lack of

impact assessment methods, and inputs, and offers the most instinctive graphic interface. Like SimaPro (detailed in a following section), GaBi is not focused on U.S. data. In addition, it is highly focused on the automotive and electronics industries. Since GaBi was one of the earliest LCI databases developed globally and did contain some data for building and construction materials, LCA researchers used it as a primary database and tool for buildings until the databases that were more building-sector focused were developed.



Alias	Concept 1	Concept 2	Comment, units, defaults
Design/Technical Parame			
Material Composition			
Cotton	0	100	[lb] Enter mass of Cotton Fabric in Backpack Design
Hemp	0	25	[lb] Enter mass of Hemp Fabric in Backpack Design
Nylon	50	0	[lb] Enter mass of Nylon Fabric in Backpack Design
Rubber	75	0	[lb] Enter mass of Rubber in Backpack Design
Steel	250	150	[lb] Enter mass of Steel Zippers in Backpack Design
Manufacturing Energy			
Compressed Air	0.004	0.004	[kWh/ft3] Compressed air
Hot Water	0.0235	0.0235	[kWh/lb] Hot water
Steam	0.311	0.005	[kWh/lb] Steam
Economic Parameters			
Labor Costs			
Tailor	55	22	[$/hr] Tailor Direct Cost
Machine Operator	35	25	[$/hr] Machine Operator Direct Cost
Manufacturing Costs			
Compressed Air	0.004	0.002	[$/ft3-hr] Total cost of compressed air
Electricity	0.05	0.02	[$/kWh] Total cost of electricity
Natural Gas	0.004	0.01	[$/ft3] Total cost of natural gas
Outside Service Costs			
Hazardous Waste	0.9	0.9	[$/lb] Cost for Hazard Waste Disposal Services
Sewer	0.15	0.15	[$/lb] Cost for Waste Water Disposal Services
Waste	0.2	0.2	[$/lb] Cost for Solid Waste Disposal Sevices
Parts/Material Costs			
Cotton	1	1	[$/lb] Cost for Cotton
Hemp	0.8	0.8	[$/lb] Cost for Hemp
Nylon	0.85	0.85	[$/lb] Cost for Nylon
Rubber	0.5	0.5	[$/lb] Cost for Rubber
Steel	0.75	0.75	[$/lb] Cost for Steel

Figure 10. GaBi Interface. Source: Doyle 2017.

TALLY

Kieran Timberlake, an architectural firm, and Sphera (formerly thinkstep), began to develop a plug-in tool called Tally in 2008, which can extract data from Autodesk Revit models to calculate the embodied emissions of a whole building (Schultz et al. 2017; Bueno and Fabricio 2018). It aims to leverage Revit (the most popular tool for developing building design and construction documents) to provide users with life-cycle impact information for building materials and building assemblies throughout the design process (Tally 2021). Because Tally is a plug-in tool, it provides a familiar interface for designers to use in their early design stage. Tally also uses the GaBi database. So far it is the only application to be fully integrated into Revit as a plug-in tool that is used in the United States. One Click LCA,

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international consensus on approaches, frameworks, and terminologies, which resulted in great discrepancies in results and limited LCA adoption. The 1990s saw a remarkable growth of coordinated activities, including the involvement of the ISO in 1994 (Guinee et al. 2011).

developed in Finland, is another software tool that has a plug-in function in Autodesk; however, its database is focused on Europe (One Click LCA 2021b).

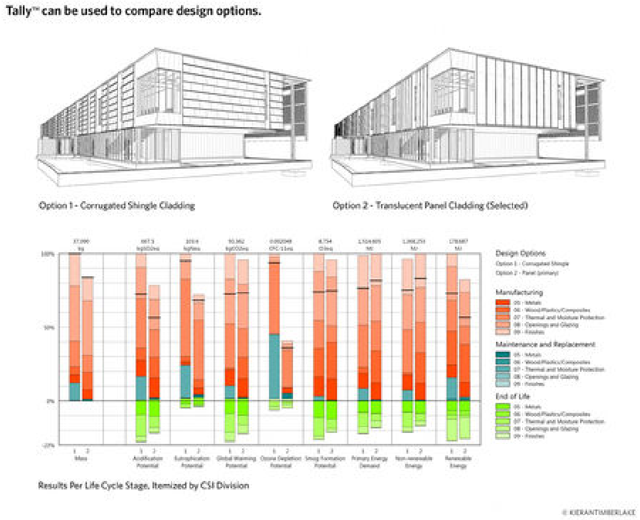


Figure 11. Tally sample screenshot

SIMAPRO

SimaPro is produced by Pre Sustainability consultants in the Netherlands and was created in the mid 1990s. Like GaBi, it is one of the most well-known LCA tools, now used in over 80 countries. Unlike GaBi, Simapro is used primarily for research in academia and by experienced LCA consultants. Compared to GaBi, it is more sophisticated, with many optional add-ons that make it very versatile (Ecochain 2020). SimaPro allows users to customize the database and impact assessment methods and inputs. Simapro data include the ecoinvent database and the Japan database. For the U.S. data, it uses NREL's LCI database.

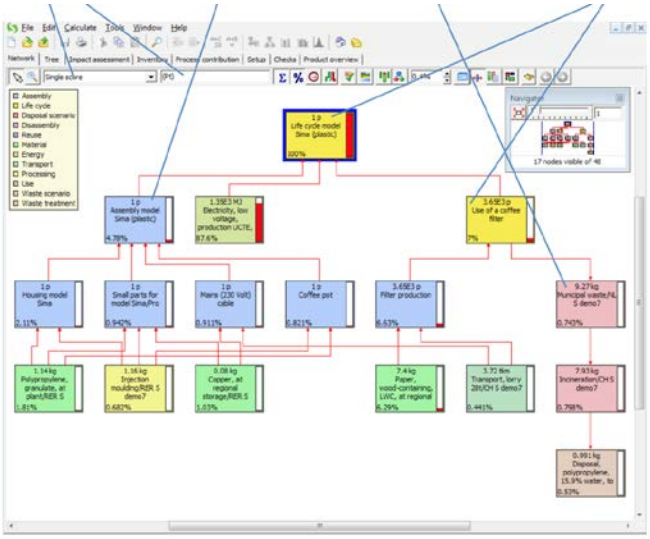
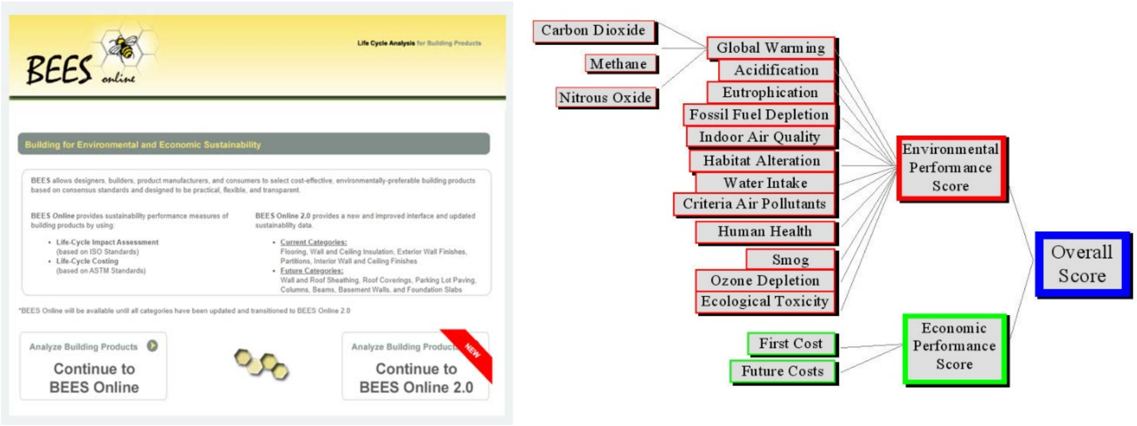


Figure 12. SimaPro Interface. Source: Goedkoop et al. 2016b.

BEES (NIST)

The Building for Environmental and Economic Sustainability (BEES) tool was developed by the National Institute of Standards and Technology (NIST) in the United States. Its building products' environmental performance measures follow ISO 14040 standards, and its economic performance measure uses ASTM E917 – 17e1 or "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems," which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal (Lippiatt 2007). Environmental and economic performance are combined into an overall performance measure using the ASTM standard for multi-attribute decision analysis. For the entire BEES analysis, building products are defined and classified according to the ASTM standard classification for building elements known as UNIFORMAT II (NIST 2020).

The advantage of BEES is that it integrates LCA and LCCA and provides environmental impact assessment and life-cycle cost simultaneously for building products and assemblies. However, unlike Athena and Tally, BEES does not allow the same flexibility to customize building products, and it also does not provide whole-building assessment.



Building for Environmental and Economic Sustainability

BEES allows designers, builders, product manufacturers, and consumers to select cost-effective, environmentally-preferable building products based on consensus standards and designed to be practical, flexible, and transparent.

BEES *Online* provides sustainability performance measures of building products by using:

- Life-Cycle Impact Assessment (based on ISO Standards)
- Life-Cycle Costing (based on ASTM Standards)

BEES Online 2.0 provides a new and improved interface and updated sustainability data.

- Current Categories: Flooring, Wall and Ceiling Insulation, Exterior Wall Finishes, Partitions, Interior Wall and Ceiling Finishes
- Future Categories: Wall and Roof Sheathing, Roof Coverings, Parking Lot Paving, Columns, Beams, Basement Walls, and Foundation Slabs

*BEES Online will be available until all categories have been updated and transitioned to BEES Online 2.0

Figure 13. BEES Example Screenshot. Source: NIST.

EMBODIED CARBON CALCULATOR FOR CONSTRUCTION (EC3)

EC3 is both a tool and database developed by the Carbon Leadership Forum along with Skanska and C-Change Lab (BuildingTransparency.org 2021). The nonprofit Building Transparency was established in 2020 to manage the development of EC3 and other open-access LCA tools and resources. EC3 is an open-access tool that allows benchmarking, assessment, and reductions in embodied carbon and is focused on the upfront supply chain emissions of construction materials. The EC3 tool utilizes building material quantities from construction estimates and/or BIM models and a database of digital, third-party verified Environmental Product Declarations (EPDs) (BuildingTransparency.org 2021). The EC3 database is created with digitized versions of EPDs. Compared to other tools, EC3 has a limited temporal boundary (A1–A3), but greater precision and accuracy in the level of estimation (non-generic data). EC3 is particularly focused on the range of impacts that exist within a given product type (e.g., rebar or mineral wool) due to differences in manufacturing practices, supply chains, fuel mixes, and so on. By having EPDs grouped and sorted and with equivalent units, it facilitates appropriate comparison of like products.

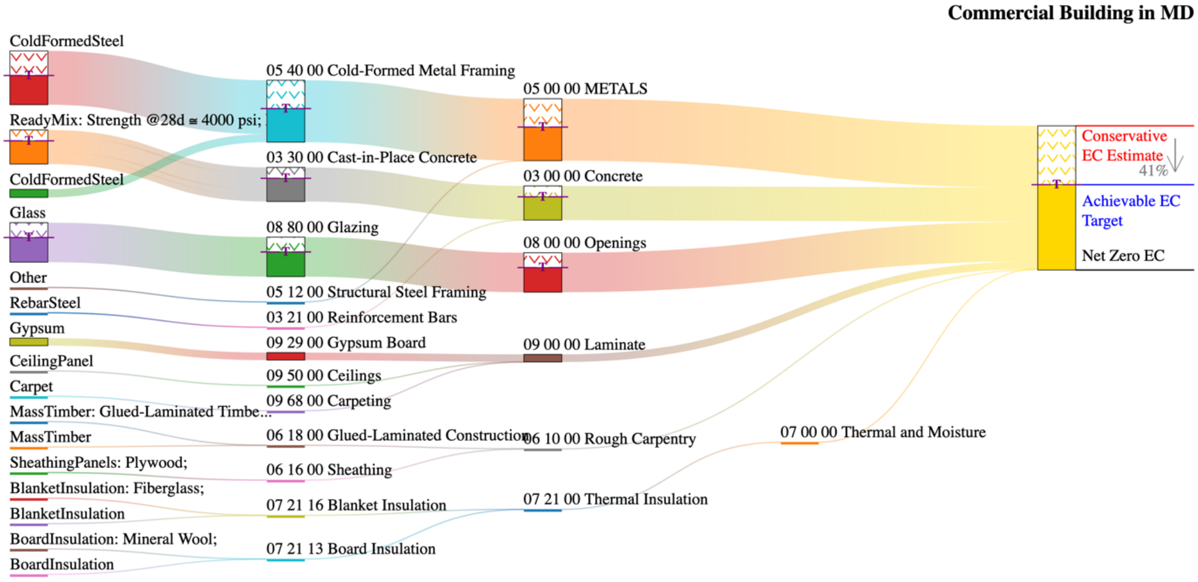


Figure 14. EC3 report interface. Source: Carbon Leadership Forum.

ONE CLICK LCA

One Click LCA was developed specifically for the building and construction sector, by Bionova, Ltd. (now One Click LCA, Ltd.) in Finland. It focuses on whole-building LCA, and its database includes both generic data and manufacturer-specific, third-party verified EPD data from around the world. The North American data are mainly derived from EPDs that comply with the ISO 14040/44 standard (based on their website description) (One Click LCA 2021a). One Click LCA analysis complies with EN/ISO standards and more than 40 green building certifications requirements, such as LEED and BREEAM.

The advantage of One Click LCA is that it can be fully integrated with other software. Based on the description on its website, One Click LCA can be integrated with widely used BIM software and building performance analysis software, such as Autodesk Revit, Solibri, DesignBuilder, IES-VE, and Taqkla. The full integration of multiple software can improve the efficiency and accuracy of the assessment. At the same time, One Click LCA is not an open-access tool, and the price is not transparent.

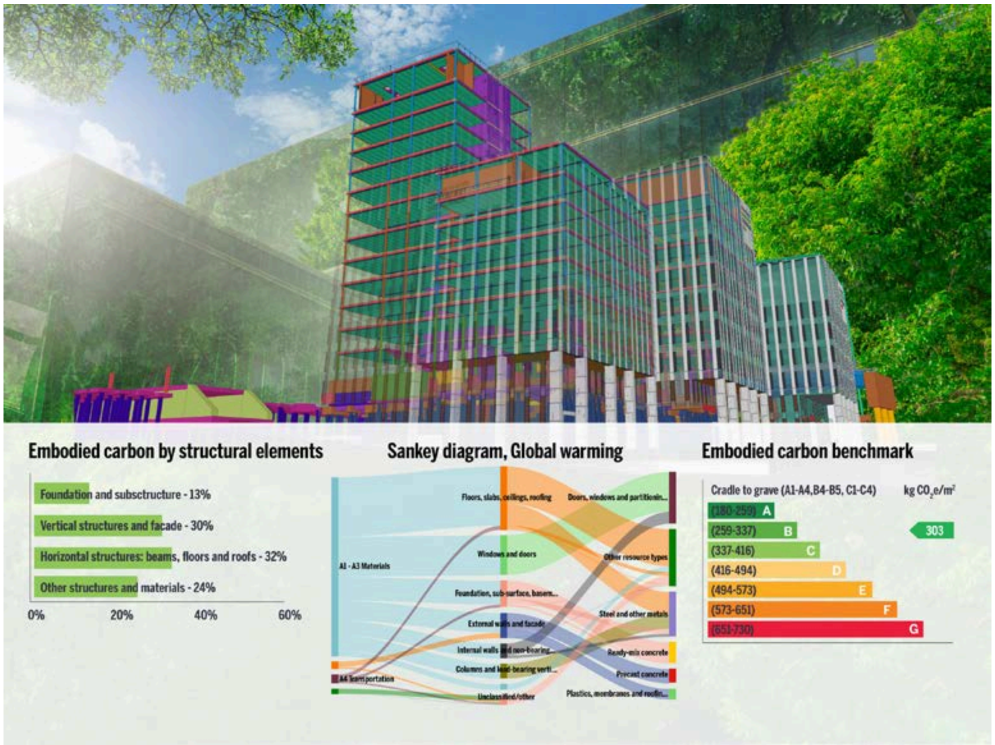


Figure 15. One Click LCA. Source: One Click LCA.

Discussion: Identified Knowledge Gaps and Needed Improvements

KNOWLEDGE MATRIX

To gain a holistic view of the current knowledge infrastructure for embodied carbon research and practice, we examine the three EC assessment components (method, data, and tool) at three different levels (material, product, and building). The product level includes the building components (e.g., windows, doors) and building assemblies (e.g., exterior walls, floors). The amount of available knowledge on a particular topic area is calculated as a percentage of the total research content that we found on the three topics (data, methodology, and tools) at each of the four different levels. The total amount of knowledge (denominator) is represented by the total number of articles and documents that are included in this analysis (refer to the Review of Existing Standards, Methods, Data, and Tools section). Some articles covered more than one topic (or component); others included studies across multiple levels. We counted these articles multiple times in our knowledge matrix, and therefore, the sum of the percentages exceeds 100%. For example, an article that discussed both the embodied carbon data collection and tool development at the building level is counted twice in the knowledge matrix. Among the 44 reviewed papers, there are 8 that focus on case studies; they are excluded from the table. A summary of the topic counts is shown in table 4.

Table 4. Counts of subject topics in the 36 reviewed articles

Topics	Method	Percentage	Data		Tool	
Buildings	2	5%	1	2.7%	1	2.7%
Product	23	64%	1	2.7%	27	75%
Materials	22	61%	4	11%	27	75%
Total (at all levels)	25		4		28	
Percentage = *n* / 36						

Figure 16 visualizes the existing body of knowledge. The *x*-axis represents the EC assessment components, and the *y*-axis represents the level of assessment. Shown as a hierarchy, the size of the circles represents the relevant 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 existing knowledge that has been and is being developed. For example, 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). Of the research activities that we reviewed, 65% focus on the development of methods and 75% on the development of tools. In contrast, the building level has the least knowledge developed: Only about 5% of the information we discovered in our literature review was related to embodied carbon data, 10% to methodology, and 10% to tools at the whole-building level. Hence, embodied carbon at the whole-building level needs the most development and investment.

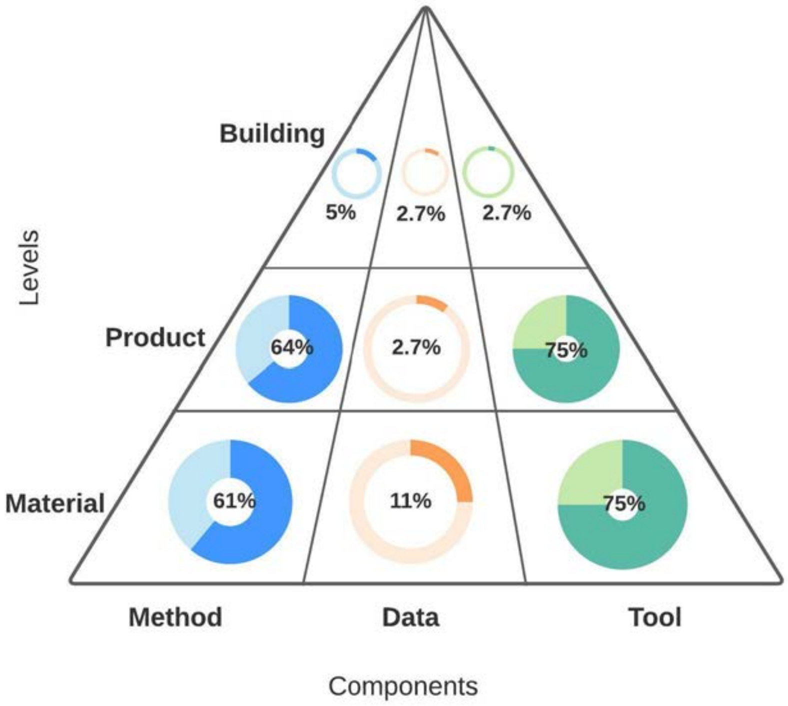


Figure 16. Embodied carbon assessment knowledge matrix

The figure and the percentages serve to illustrate rather than provide an exact quantification. Our literature review, while comprehensive, 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. Furthermore, it should be noted that new knowledge is constantly being added to the literature. In the following sections, we further discuss the major gap areas deduced from this knowledge matrix.

We acknowledge that our review is mainly focused on peer-reviewed publications. More reports, case studies, and best practice guides on the whole-building level exist in the building design community. Some are discussed in this report, but many are not included in our review due to the challenge of evaluating and verifying their contents. Nonetheless, we believe that a review of the peer-reviewed publications does provide a good overview of the knowledge landscape in the space of embodied carbon in the built environment, and it has allowed us to identify the critical gaps to guide our next steps.

GAPS IN DATABASE DEVELOPMENT ACROSS ALL LEVELS

We identified four primary issues pertaining to database quality and the data collection process. The first issue relates to data availability for the use stages (B) and the end-of-life stages (C), since they are both highly dependent on the assessor’s assumptions of how a building may be used and maintained (De Wolf, Pomponi, and Moncaster 2017). Predictions of repair and replacement are particularly challenging and can be very subjective. Within a single building, different building components have varying individual life spans. For example, roofing materials and window units have different life spans and repair cycles, where each time span not only depends on the product quality, but also depends on the use conditions. Such information can only be obtained at the local level, which becomes a bottleneck for data collection partially due to the lack of awareness, knowledge, skills, and tools to include the total cost of ownership and the associated embodied carbons in building design and development. Building energy standards provide operational assumptions when calculating the whole-building operational energy use, but similar assumptions do not exist for product life cycles. This may introduce potential bias by favoring products that have lower upfront embodied carbon (in A stages) but a short life span (in B stages). The lack of information on product durability may also introduce conflicts between resilience and embodied carbon. Both are critical components that must be addressed to combat climate change.

The second issue lies within the pre-use stages (A). There are limited published data for A4 (transport to site) and A5 (construction and installation) in comparison to that of A1–A3. More standards have been developed and knowledge gathered for products from A1 to A3, which are associated with raw material extraction, transport, and manufacturing. Research into reducing the A1–A3 substage-related carbon emissions has stimulated practice and policy changes in the building industry. One example is the EPDs and product category rules (PCRs). A growing number of local, state, and federal procurement policies require EPDs for reporting the embodied carbon of eligible products (Lewis et al. 2021). However, the A4 and A5 substages are critical components of building construction and should not be neglected. Otherwise, another potential bias would favor low-carbon materials or products that are heavy, shipped over a long distance, or require energy-intensive equipment or processes to assemble onsite. For example, wood is a low-carbon construction material, but its embodied carbon (in A4) may significantly increase as logs are shipped from their origin to a second location for primary processing (e.g., producing timbers of specific size and dimensions), to a third location for secondary processing (e.g., making more-specific building products), and to a distributor' warehouse before reaching the construction site.

One potential cause of the lack of data for the A4 and A5 substages may be that those data are highly context and project dependent (De Wolf, Pomponi, and Moncaster 2017). After products are shipped following manufacture, it is difficult or sometimes impractical for the manufacturer to track how and where the product is shipped and used at the final destination. For instance, a stone product wholesale distributor may import products from different countries and store them in warehouses across the United States. Those products would then be shipped to different project sites within or outside of the country. Therefore, the embodied carbon in the A4 and A5 substages is out of reach of the manufacturer and is often neglected in tracking. Such tracking and reporting responsibilities should be shared by manufacturers and project developers. Guidelines or standards should be developed to guide data collection and tracking in these stages.

The third issue concerns missing guidelines for supply-chain-specific and facility-specific data collection and reporting. In existing and proposed legislation on embodied carbon, all

EPDs are required to be third-party verified. Half of these pieces of legislation require product-specific EPDs (a specific product and manufacturer across multiple facilities), and the other half require either supply-chain-specific EPDs (using supply-chain-specific data for key processes) or facility-specific EPDs (attributing to a single manufacturer and manufacturing facility) (Lewis et al. 2021). Supply-chain- and facility-specific EPDs aim to incentivize individual manufacturers to better distinguish their low-carbon products. However, PCRs only provide guidelines for calculating industry-average and product-specific EPDs. To improve data accuracy for comparison, the Carbon Leadership Forum (CLF) suggested that EPDs and PCRs should be improved by including supply-chain-specific upstream data for processes with large impacts (e.g., production of cement for concrete (A1), manufacturing of mineral wool board (A3) and developing corresponding guidelines (Lewis et al. 2021).

The fourth issue revolves around the lack of consensus on how to integrate the benefits and loads of reuse, recycling, and recovery potentials (Stage D) into the whole life-cycle assessments. So far, most EC assessment tools and databases focus on life-cycle stages A through C. Phase D is a particularly important stage that could provide incentives to promote recycled and reused products and materials. As such it is a huge, missed opportunity to further reduce the embodied carbon in the built environment. A new building that is 30% more efficient than average may take at least 10 years and up to 80 years to offset the emissions generated from the construction process (Preservation Green Lab 2012). Although buildings codes and standards traditionally do not address end-of-life building activities, guidelines are needed to calculate the avoided carbon emission from reused building components, structure, or even the whole building (e.g., adaptive reuse).

THE LACK OF QUANTITATIVE RESEARCH AT THE BUILDING LEVEL

Currently, very few activities are focused 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 by Btu/sf^2) by property type. This helps a design team compare its building energy use with similar properties across the nation (ENERGY STAR 2021). Still, currently there is no consensus on how to baseline or benchmark the embodied carbon of a building.

The most comprehensive assessment of embodied energy in buildings was published in 1979, in a publication entitled "Energy Use for Building Construction" (Hannon et al. 1976), commissioned by The Advisory Council on Historic Preservation. It aimed to assess the benefits of restoring and rehabilitating existing buildings; hence, 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, although embodied carbon includes carbon emissions from non-energy sources. Figure 16 shows a sample table from this report. The Advisory Council assessment included three separate embodied energy categories corresponding to different life-cycle stages: embodied energy (A1–B5), demolition energy (C1–C4), and operational energy (B6). Figure 17 illustrates a sample of the average embodied energy value assessed in their study.

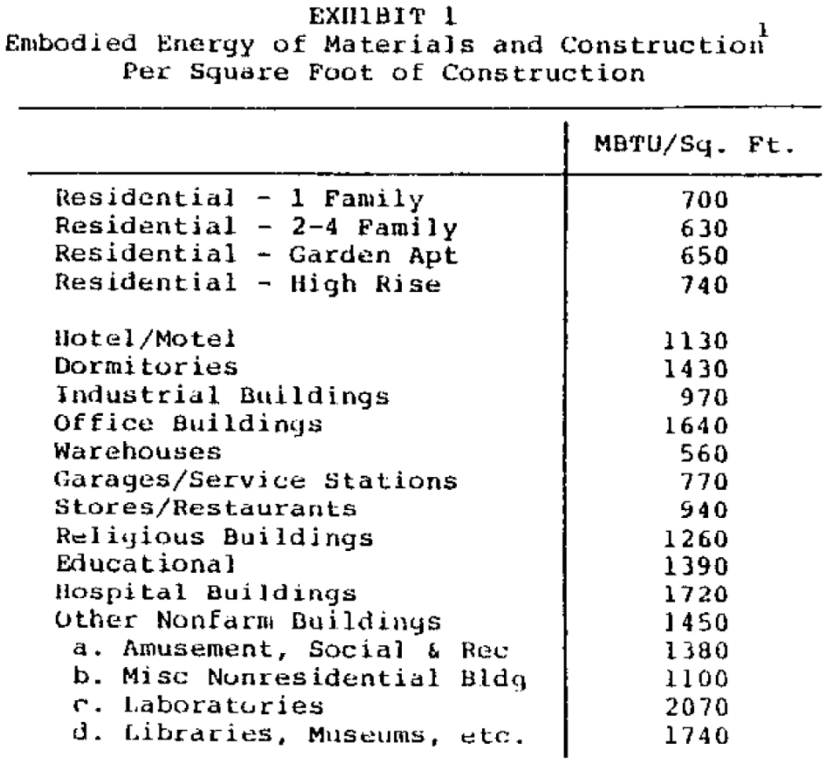


EXHIBIT 1
Embodied Energy of Materials and Construction[1]
Per Square Foot of Construction

	MBTU/Sq. Ft.
Residential - 1 Family	700
Residential - 2-4 Family	630
Residential - Garden Apt	650
Residential - High Rise	740
Hotel/Motel	1130
Dormitories	1430
Industrial Buildings	970
Office Buildings	1640
Warehouses	560
Garages/Service Stations	770
Stores/Restaurants	940
Religious Buildings	1260
Educational	1390
Hospital Buildings	1720
Other Nonfarm Buildings	1450
a. Amusement, Social & Rec	1380
b. Misc Nonresidential Bldg	1100
c. Laboratories	2070
d. Libraries, Museums, etc.	1740

Figure 17. Sample embodied energy per building type table

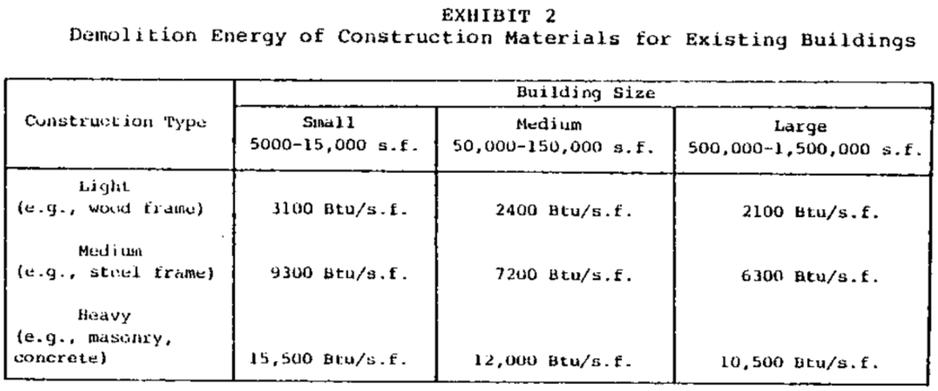
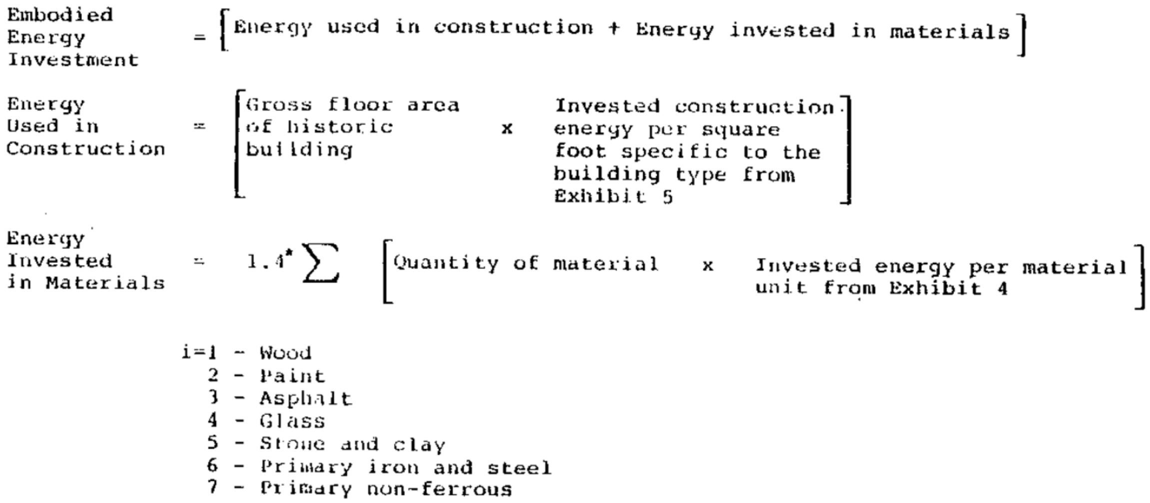


EXHIBIT 2
Demolition Energy of Construction Materials for Existing Buildings

Construction Type	Building Size		
	Small 5000-15,000 s.f.	Medium 50,000-150,000 s.f.	Large 500,000-1,500,000 s.f.
Light (e.g., wood frame)	3100 Btu/s.f.	2400 Btu/s.f.	2100 Btu/s.f.
Medium (e.g., steel frame)	9300 Btu/s.f.	7200 Btu/s.f.	6300 Btu/s.f.
Heavy (e.g., masonry, concrete)	15,500 Btu/s.f.	12,000 Btu/s.f.	10,500 Btu/s.f.



$$\text{Embodied Energy Investment} = \left[\text{Energy used in construction} + \text{Energy invested in materials}\right]$$

$$\text{Energy Used in Construction} = \left[\text{Gross floor area of historic building} \quad x \quad \text{Invested construction energy per square foot specific to the building type from Exhibit 5}\right]$$

$$\text{Energy Invested in Materials} = 1.4^{*} \sum \left[\text{Quantity of material} \quad x \quad \text{Invested energy per material unit from Exhibit 4}\right]$$

i=1 - Wood
2 - Paint
3 - Asphalt
4 - Glass
5 - Stone and clay
6 - Primary iron and steel
7 - Primary non-ferrous

Figure 18. Sample calculations for assessing embodied energy

The Advisory Council research project was a collaboration between the University of Illinois at Urbana-Champaign and Richard Stein Associates, Architects, of New York City. 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 ever been produced in the United States. The building materials in the report were based on construction industry data from 1967. Obviously, since then, there have been significant changes in building products, technologies, and manufacturing processes. 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 and revision and updates are required.

The Carbon Leadership Forum conducted an embodied carbon benchmarking study in 2017 by compiling the embodied carbon results from 1,191 building LCA studies, including office, education, multi- and single-family residential buildings, and so on. (Simonen et al. 2017). Half of the entries are from buildings in Northern America. The study found that the upfront carbon emission is typically less than 1,000 kgCO_2e/m^2; 50% of the office buildings in the database have upfront carbon emissions between 200 and 500 kg CO_2e/m^2. (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-CO_2e/m^2.) The study provides a good reference for benchmarking embodied carbon in buildings; however, the sample size is insufficient to provide statistically significant results.

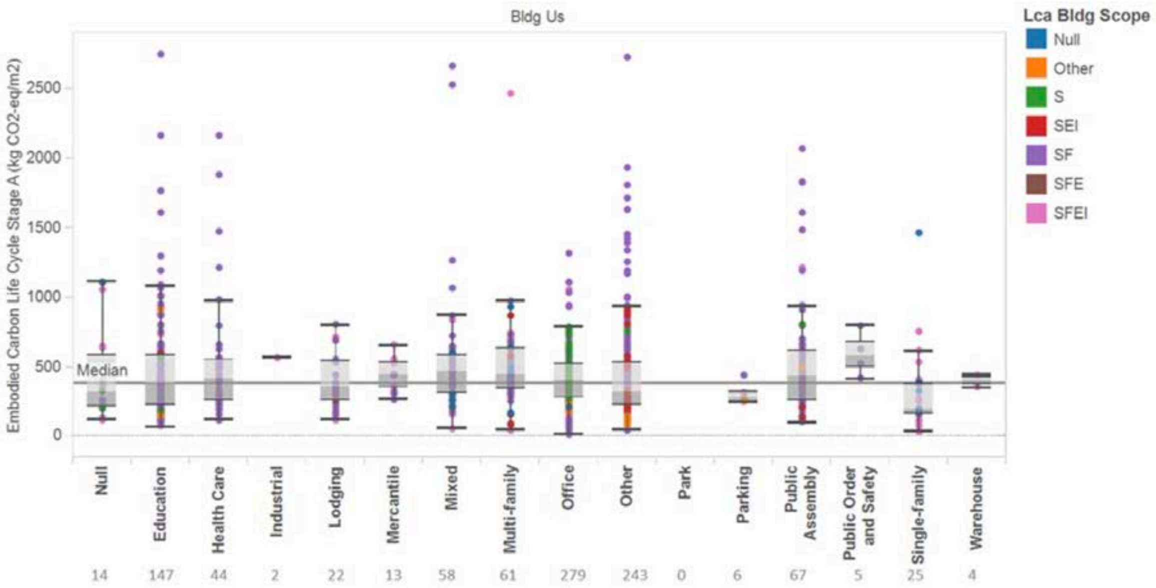


Figure 19. Range of embodied carbon emissions in the benchmarking study. Source: Carbon Leadership Forum.

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. Since ASHRAE 90-75: Energy Conservation in New Building Design was published as the first national energy code in 1975, the ASHRAE standard has been updated every three years since the 1999 version, gradually increasing building energy use standards. A similar path is needed for embodied carbon building codes.

The whole-building approach encourages innovative strategies that utilize alternative structural systems, building technologies, and construction techniques and processes. To enable a whole-building approach, standards are needed 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 up-front embodied carbon (A1–A5) can be reduced by 24–46% with less than a 1% cost premium (Esau et al. 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 carbons of buildings will decrease. The question is whether reduction of operational carbons 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 located 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 were able to find optimal solutions that resulted in the lowest life-cycle carbon footprint. One of the solutions has a higher operational carbon impact compared to 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, and 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 and 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 life cycle of a building.

Conclusions and Recommendations

In sum, there are well-established international standards to guide LCA methodology development for assessing embodied carbon in the built environment. 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 life-cycle 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 2016). 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 life-cycle assessment (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, life-cycle 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 utilize multiple methods to overcome the challenge of upstream data complexity.

Comprehensive embodied carbon data exist to evaluate all life-cycle 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 to end users. Data collection and reporting guidelines are also needed for supply-chain-specific and facility-specific data and for transport and construction data, which are currently missing in many databases. A robust database is the backbone of reliable LCA analyses, and we need guidelines for data standardization and transparency.

A significant effort has been focused on tool development. Most LCA tools are focused on product or material levels and 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 software. This is critical to increase confidence in the use of embodied carbon tools.

The largest knowledge gap exists at the whole-building level. No consensus exists on how to baseline or benchmark the embodied carbon of a building due to the lack of building-level data. 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 life-cycle stage beyond initial building construction. Trade-offs between operational carbon, material/product durability, and embodied carbon should be addressed. Material and product durability are not only relevant to embodied carbon, but also important to resilience planning, which is another critical approach to combat climate change.

LCAs have been mostly conducted in the absence of LCCA. Economic impact and technology maturity are critical considerations during the building codes development process. Guidelines and standards on embodied carbon data collection and reporting require manufacturers' participation. Embodied carbon standards cannot be driven solely by the building communities. Architects and engineers can specify or select low-carbon materials and products only when they are economically viable and their performance (energy, structural, durability, etc.) is comparable to other alternatives. Developing business cases for manufacturers and integrating building decarbonization with industrial decarbonization are essential steps to building the knowledge infrastructure to reduce embodied carbon in buildings.

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 (manufacturers, building owners and developers, builders, occupants, etc.). All of these need the support of a solid knowledge infrastructure. Current efforts have been creating important momentum and providing important pieces of the puzzle, but the multilayered solutions needed for successful implementation across complicated supply chains still need additional rigor, testing, and response to a dizzying array of products. An agreed-upon pathway still eludes us but is necessary to guide the long-term trajectory of building code development and adoption.

We recommend that the federal agencies (e.g., Department of Energy, Environmental Protection Agency, National Institute of Standards and Technology), model code-writing organizations (e.g., ASHRAE and the International Code Council), local code officials, and other research institutes and advocacy groups should collaboratively fill in the identified gaps. A national roadmap could be the starting point. The roadmap should include what we know now to start the development of embodied carbon codes at the building level, what we need to develop immediately, which can be mandatory and which should start as voluntary, and what knowledge we can build over time to strengthen the embodied carbon building codes.

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 standard features of commercial as well as 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 life-cycle assessment at 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. U.S. federal agencies can immediately take two actions: (a) develop U.S. applicable standards based on ISO standards referencing EN standards; and (b) fund the collection and organizing of LCI data. The federal agencies and the federally funded research and development centers should take the lead to develop whole-building LCA baselining methods and establish the embodied carbon reduction targets considering its impact on operational carbon.

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