U.S. DEPARTMENT OF
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RENEWABLE ENERGY

Embodied Carbon Reduction in New Construction

Reference Guide

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Key Definitions & Acronyms

- **Circular Economy:** An economy that uses a systems-focused approach and involves industrial processes and economic activities that are restorative or regenerative by design, enable resources used in such processes and activities to maintain their highest value for as long as possible, and aim for the elimination of waste through the superior design of materials, products, and systems (including business models) [1].
- **Embodied Carbon:** Embodied carbon is the estimate of the greenhouse gas (GHG) emissions associated with stages of a building's life cycle not including operating the building [2].
- **Environmental Product Declaration (EPD):** Independently verified and registered document that communicates transparent and comparable information about the life cycle environmental impact of products [3].
- **Life Cycle Assessment/Analysis (LCA):** Comprehensive method for assessing a range of environmental impacts across the full life cycle of a product system, from materials acquisition to manufacturing, use, and final disposition [4].
- **Life Cycle Carbon:** The GHG emissions associated with all stages of a building's life [5].
- **Product Category Rules (PCR):** A set of specific rules, requirements, and guidelines for developing environmental product declarations for one or more product categories [6].

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1 Introduction

The U.S. Department of Energy launched the **Advanced Building Construction (ABC)** Initiative in 2019 to modernize and streamline building renovation and construction processes that facilitate the integration of high-performance and low-carbon solutions in the U.S. building stock. There are four attributes of ABC that are the focus of the Initiative: **affordable, fast, appealing, and low carbon.**

Substantial improvements have been made to reduce operational carbon emissions of buildings through efficiency and electrification. However, to achieve low-carbon new construction buildings, increased efforts to reduce the embodied carbon of buildings are needed. Embodied carbon emissions in buildings come primarily from the manufacturing of building envelope materials such as concrete, steel, lumber, and glass, among others. Recent studies show that construction and renovation of buildings account for 5% of energy use and 10% of carbon emissions globally [7].

Architects, designers, and construction companies have a significant opportunity to reduce embodied carbon in new buildings through strategies including improved designs and construction practices, utilizing low embodied carbon materials and products, and using recycled materials/reusing waste materials. This document is intended to serve as a brief reference document for builders, architects, and companies that are interested in reducing the embodied carbon in their new construction building projects. The reference guide provides an overview of key terms, strategies, tools and databases, standards, and available resources to help achieve low-carbon new buildings. For more information on how to measure, reduce, and report embodied carbon emissions in building products, refer to RMI's Introduction to Embodied Carbon for Advanced Building Construction: The Basics of Embodied Carbon Measurement, Reduction, and Reporting.[1]

2 What is Embodied Carbon?

Embodied carbon in buildings refers to the greenhouse gas (GHG) emissions associated with the manufacturing, transportation, installation, maintenance, and disposal of building materials and products over the entire life cycle of a building, not including the operations or use phase [8]. The sources of embodied carbon emissions in building construction, materials, and equipment include, but are not limited to:

- Fossil fuel combustion in transport and extraction of raw materials
- Fossil fuel (e.g., coal, natural gas) combustion in materials manufacturing
- Fossil fuels used in the energy supply for materials manufacturing
- Chemical reactions in manufacturing of materials (e.g., cement, iron)
- Fossil fuel combustion in transport and site machinery for construction
- Carbon emissions released at the end-of-life handling of materials (e.g., incineration of products or lumber biodegradations in landfills)
- Carbon emissions released from degradation of forestry and release of soil carbon (e.g., land use for development, harvesting of lumber)
- Hydrofluorocarbons (HFC) emissions released from leakages of refrigerants and released at the end of life [9]

Building life cycle emissions are typically categorized in four stages: the product stage, the construction stage, the use stage, and the end-of-life stage (as shown in Figure 1) [10]. The product stage (A1-A3) is also known as the cradle-to-gate stage of emissions. Data beyond stages A1-A3 varies greatly and is more difficult and expensive to evaluate, thus, most data and researcher and industry efforts to reduce the embodied carbon of buildings and materials have been focused on the cradle-to-gate life cycle phase. However, to assess the true life cycle carbon emissions attributed to a building, all stages (cradle-to-cradle impacts) should be evaluated including: the product stage (A1-A3), the

[1] Available online here: https://advancedbuildingconstruction.org/embodied-carbon-for-advanced-building-construction/

construction stage (A4-A5), the use stage (B1-B7), the end-of-life stage (C1-C4), and the beyond life stage (D); embodied carbon calculations exclude B6 and B7 (operational impacts) specifically.

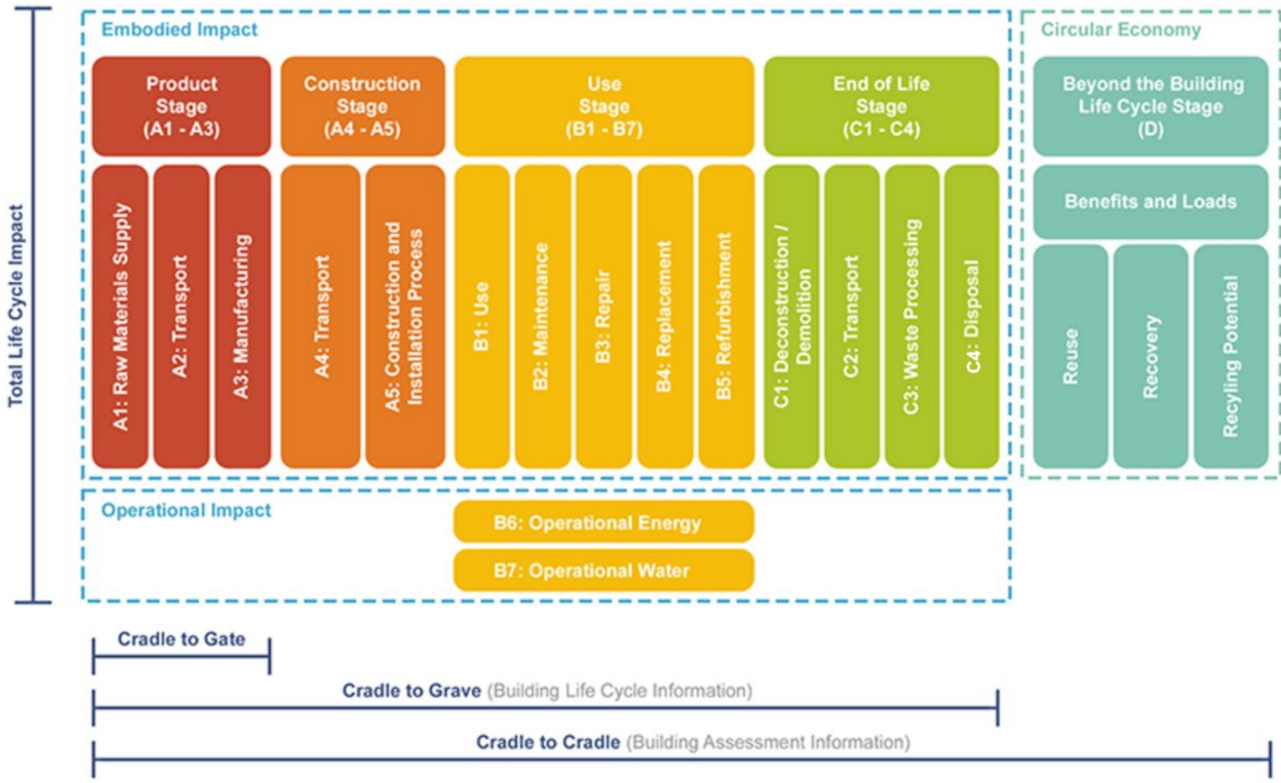

Figure 1: Building Life Cycle, Adapted from EN 15978:2011

Image Source: Building Enclosure [11]

3 What is a Life Cycle Assessment?

Embodied carbon is typically measured through a **life cycle assessment (LCA)**. An LCA is "a methodology that is used to measure the environmental impacts of a building, product, or process over its full life cycle, from raw material extraction through end-of-life and disposal" [12]. LCAs can be used to estimate a variety of environmental impacts. Embodied carbon in LCAs is quantified in terms of kg or metric tons of carbon dioxide equivalents (CO_2e), in which all greenhouse gases are converted to the equivalent amount of CO_2 based on their global warming potentials (GWP), typically on a 100-year time horizon. LCAs can be performed at the entire building level (whole building LCA or WBLCA), the product level, or the material level.

A WBLCA measures the embodied carbon of an entire building and is often performed by architects and consultants during the design phase of the building to help lower the embodied carbon of the new building. A WBLCA can also be used to meet green building certifications requirements or to benchmark the embodied carbon of the building relative to established baseline buildings [13]. There are many tools available that allow users to complete a WBLCA, both standalone and design integrated such as Tally, Athena, OneClick LCA, and Beacon. However, the largest gap in the knowledge infrastructure of embodied carbon is at the whole building level because of the lack of projects completing WBLCAs in the United States [14]. Most available data are for single building case studies which makes it challenging to establish benchmarks for whole building embodied carbon. The steps involved in creating a WBLCA are outlined in the Embodied Carbon Toolkit for Architects: Part II.[2]

Product and material level LCAs are most often performed by manufacturers or LCA practitioners for publication in environmental product declarations (EPDs). EPDs are standardized documents which are 3rd party verified and

[2] Available online here: https://content.aia.org/sites/default/files/2021-10/21_10_STN_DesignHealth_474805_Embodied_Carbon_Guide_Part2.pdf

governed by product category rules (PCRs). PCRs establish EPD rules for a specific product through committees, and they provide guidance on how to perform an LCA for each product type. Due to limitations in available data, EPDs generally use LCAs that cover product extraction, transportation to manufacturing site, and manufacturing (stages A1-A3) [15]. There are four major categories of EPDs, from least to most specific; they are:

- **Industry-wide EPDs**, which calculate average embodied carbon impacts from a range of products and manufacturers within a single industry
- **Product-specific EPDs**, which calculate the embodied carbon of a specific product and manufacturer
- **Facility-specific EPDs**, which calculate embodied carbon of a specific product from a single manufacturer and manufacturing facility
- **Supply-chain-specific EPDs**, which calculate embodied carbon of a specific product using primary data from key upstream inputs and materials [16]

Currently, thousands of product-specific and industry-wide EPDs are available, but some major data gaps remain for certain building materials and technologies including fenestration, adhesives, and mechanical, electrical, and plumbing systems. In addition, another main challenge with EPDs is that they are not designed to be comparable between products for the purpose of procurement and specification. The comparability of EPDs is affected by the inconsistency in LCA methodologies and background data, differences in the analysis tools used to develop EPDs, and the need for more rigorous PCRs.

There are currently three accepted and recognized methodologies for conducting LCAs: the input-output method, the process method, and the hybrid method, which are described in Figure 2 below. However, the accuracy and consistency of LCA results from these methods are highly dependent on the data quality and definitions of the system boundary, which need more improvements and standardization [17]. For more information on how to conduct an LCA and how to create an EPD, refer to RMI's Introduction to Embodied Carbon for Advanced Building Construction: The Basics of Embodied Carbon Measurement, Reduction, and Reporting.[3]

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

Figure 2. Primary LCA Methodologies

Image source: ACEEE [18]

[3] Available online here: https://advancedbuildingconstruction.org/embodied-carbon-for-advanced-building-construction/

4 Tools and Databases for Architects and Builders

There are various types of tools and databases for calculating embodied carbon with different functions, qualities, and price points (including free tools). Some tools and databases can also be embedded or integrated with commonly used building design software (e.g., Revit and Building Information Modeling (BIM)). The different types of tools related to embodied carbon and LCA for buildings include:

- **Design Integrated Whole Building LCA (WBLCA) Tools.** These tools are embedded in existing design tools and allow you to perform a WBLCA of a modeled building. These tools need to be upgraded to include the supply chains of the energy systems such as electricity and natural gas.
- **Standalone Building Materials and Whole Building LCA Tools.** These tools allow you to complete LCAs of materials, products, assemblies, and/or whole buildings to compare building materials, assemblies, and/or whole buildings. These tools are designed to produce embodied GHG results.
- **Embodied Carbon Calculators.** These tools perform embodied carbon emissions calculations and estimates for whole buildings, building assemblies, products, and/or materials used in buildings.
- **Product and Material Selection Tools.** These tools allow you to perform LCA of products or materials for comparison or to generate EPDs.

Many databases are also used or embedded in tools, while others are used as standalone resources for analysis and comparison of materials and products. Data in databases can come from EPDs, manufacturer data, academia research, industry statistics, government publications or other databases, which can affect the accuracy and comparability of the data. Some databases incorporate regional variations in life cycle inventory (LCI), baseline LCA, and EPD data; some are only able to produce analysis for certain countries, and some are geared toward specific regions like Europe.

Depending on the type of tool or carbon calculator, it may require anywhere from no expertise/training to substantial training/expertise or a professional LCA practitioner to use the specific tool to produce accurate results. Like EPDs and LCAs, different embodied carbon tools and calculators include different life cycle stages in their calculations, with some being cradle-to-gate and some being cradle-to-grave. This affects the accuracy and comparability of data produced by embodied carbon tools and calculators. Most tools and calculators are also geared toward either materials/product analysis or whole-building analysis.

The following lists provide an overview of the different types of embodied carbon and LCA tools available that could assist architects, builders, and construction companies in developing low-carbon buildings.

4.1 Design Integrated Whole Building LCA (WBLCA) Tools

These tools are embedded in existing design tools and allow you to perform a WBLCA of a modeled building.

- **Tally** *(Annual fee)*: Plug-in for Revit that allows design teams to perform WBLCA within their design model and uses the GaBi database; covers A1-C4 life cycle stages.
- **Beacon** *(free)*: Plug-in for Revit that allows design teams to perform WBLCA within their design model and uses various databases; covers A1-A3 life cycle stages.
- **Buildings and Habitat Object Model** *(free)*: Open computational toolkit for integrated building performance analysis via Grasshopper/Rhino, Excel, and other formats; uses EC3 and Quartz databases, among others, and covers A1-C4 life cycle stages.
- **Hawkins Brown Emissions Reduction Tool** *(free)*: Plug-in for Revit that allows design teams to perform WBLCA within their design model; uses ICE database and covers A1-A3 life cycle stages.

4.2 Standalone Whole Building LCA Tools

These tools allow you to complete LCAs of materials, products, assemblies, or whole-buildings or to compare building assemblies and materials.

- **Athena** *(free)*: Freestanding software package that can be used to complete WBLCA or to compare building assemblies and materials; uses Athena database and covers A1-C4 life cycle stages.
- **OneClick LCA** *(License needed)*: Web-based tool that can be used to complete WBLCA or to compare building assemblies and materials; can be standalone but also supports BIM integration; covers A1-C4 life cycle stages.
- **GREET Building LCA model** *(free)*: Excel-based tool that can be used to complete WBLCA or to compare building assemblies and materials; covers A1-C4 life cycle stages.

4.3 Embodied Carbon Calculators

These tools perform carbon emissions calculations and estimates for whole buildings, building assemblies, products, and/or materials used in buildings.

- **Building Carbon Neutral** *(free)*: Web-based carbon calculator for high-level estimates of whole-building carbon impacts; covers A1-A5 life cycle stages.
- **EPIC** *(free)*: Web-based calculator for early design-stage analysis of whole-life carbon (embodied, operational, and landscape carbon footprints).
- **Kaleidoscope** *(free)*: Web-based calculator used for comparing embodied carbon impacts of building assemblies; uses GaBi database and covers A1-C4 life cycle stages.
- **Pathfinder** *(free)*: Web-based calculator for quantifying GHG emissions and sequestration potential of landscape and site design projects.
- **Upstream** *(free)*: Excel-based tool for evaluating wood products. The tool explores carbon emissions and biogenic carbon accounting; uses GaBi database and covers A1-C4 life cycle stages.
- **ZFG Concrete Tool** *(free)*: Excel-based calculator for generating and comparing the LCA results of specific concrete mix designs; covers A1-C4 life cycle stages.
- **Building Emissions Accounting for Materials** (BEAM) *(free)*: Google Sheets-based estimator that allows for easy comparison between different building materials and assemblies; covers A1-A3 life cycle stages.
- **OneClick Planetary** *(free)*: Web-based calculator for exploring the impacts of 10 common carbon-intensive building materials; covers A1-A3 life cycle stages.

4.4 Product and Material Selection Tools

These tools help users compare the embodied carbon of different products and materials for selection in building designs.

- **Embodied Carbon in Construction Calculator** (EC3) *(free)*: Web-based tool allows users to access published EPDs, compare products and materials, and calculate realized or potential reductions based on material quantities; uses EC3 database and covers A1-A3 life cycle stages.
- **Building for Environmental and Economic Sustainability** (BEES) *(free)*: Web-based tool allows users to select cost-effective, environmentally preferable building products; uses NIST database and covers A1-C4 life cycle stages.

4.5 Material/Product LCA Tools

These tools allow you to perform LCA of products or materials for comparison or to generate EPDs.

- **SimaPro** *(Paid subscription)*: Professional LCA software used to conduct fully customizable LCA models of materials, products, assemblies, or systems; uses Ecoinvent and NREL LCI data and covers A1-A3 life cycle stages.

- **GaBi** *(Need paid license)*: Professional LCA software used to conduct fully customizable LCA models of materials, products, assemblies, or systems; uses GaBi database and covers A1-C4 life cycle stages.
- **OpenLCA** *(free)*: Professional LCA software used to conduct fully customizable LCA models of materials, products, assemblies, or systems; uses OpenLCA and Nexus databases and covers A1-C4 life cycle stages.
- **GREET Building LCA model** *(free)*: Excel based tool used to facilitate detailed, transparent, and consistent LCA of new building materials; uses GREET database and covers A1-C4 life cycle stages.
- **Circular Economy Life Cycle Assessment and Visualization Framework** (CELAVI) *(free)*: a dynamic and flexible tool that models the impacts of clean energy supply chains during the transition from a linear to a circular economy; covers A1-C4 life cycle stages.

4.6 Databases

These databases are both standalone resources and embedded in tools for analysis and comparison of materials and products.

- **Ecoinvent** *(Pay to use)*: Database of life cycle inventory data, covering a range of sectors; uses secondary data and the regional focus is Europe and global.
- **NREL LCI** *(Need paid license)*: Provides individual gate-to-gate, cradle-to-gate, and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the United States; uses primary data and the regional focus is the United States.
- **LCA Digital Commons** *(free)*: Opensource repository and publication workflow for federally funded and federally produced LCA data; uses primary data and the regional focus is the United States.
- **NIST BEES** *(free)*: Hybrid database with economic and environmental item level data; uses secondary data and the regional focus is the United States.
- **Quartz** *(free)*: Database for users to quantify the human health and environmental implications of common commercially available building products; uses secondary data and the focus is the United States.
- **GaBi** *(Pay to use)*: Database of life cycle inventory data spanning multiple industries including regionalized water and land; uses primary and secondary data and the regional focus is Europe and global.
- **Athena** *(free)*: Regionally sensitive database using mill or engineered process models and is not reliant on trade or government data sources.
- **Carnegie Mellon database** *(free)*: Database traces economic transactions and environmental emissions data associated with the production of a particular product or service, enabling economic input-output LCA.
- **EPD library** *(free)*: Run by the International EPD system, the EPD library has third party verified EPDs and Carbon Footprint Declarations for markets globally.
- **EC3** *(free)*: Database of building material EPDs, used for product selection and procurement.
- **ICE** *(free):* Database made up of GWP data published from academic research, industry statistics, government publications, and references from other primary LCI databases.
- **OpenLCA Nexus** *(free)*: Database where users can search for individual datasets, based on customized search criteria such as country, price, sector, etc.

4.7 Standards

There are currently several well-established international standards that can be used to guide LCA methodology for embodied carbon in buildings. The International Organization for Standardization (ISO) has established standards including methods for conducting LCAs, developing and using EPDs, and sustainability performance indicators. ISO

14040 and 14044 are key in developing LCA principles, frameworks, requirements, and procedures. ISO also established the International Green Construction Code which includes environmental performance as code minimum and includes LCA and EPD requirements. The primary international standards for LCAs are outlined in Table 1 below.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and International Code Council (ICC) established a draft standard in 2023 to assess whole building life cycle emissions which is currently being reviewed and edited. The draft standard–ASHRAE/ICC Standard 240P: Evaluating Greenhouse Gas and Carbon Emissions in Building Design, Construction and Operation–establishes methods to measure and verify carbon emissions of a building or group of buildings over the entire life cycle [19]. This standard could help provide consistent procedures and data to be referenced by policies and building codes. In addition, the Northeast Home Energy Rating System Alliance has proposed to add embodied carbon into the Residential Energy Services Network (RESNET) carbon index and has created a committee to work on this.[4]

Table 1. Key International Embodied Carbon Standards and Codes

Location	Type	Policy	Overview
International	Standard, LCA, Carbon Reporting	ISO14040 ISO14044	Describes the framework for LCA, including goal, scope, and different elements within an LCA such as life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation, as well as the limitations of the LCA.
International	Standard, Sustainability indicators	ISO FDIS 21929-1 ISO FDIS 21931-1	Establishes core set of indicators that can assess the sustainability performance of new or existing buildings. Includes design, construction, operation, maintenance, refurbishment, and end of life.
International	Standard, EPD	ISO 21930	Provides principles, specifications, and requirements to develop an EPD.
International	Standard, EPD	ISO 14020 ISO 14021 ISO 14024 ISO 14025 ISO 14027	These standards establish the principles for developing and using EPDs. Includes development procedures for Type I, Type II (self-declared), and Type III (product specific, third-party verified) environmental labeling programs.
International	Code, Building Construction	International Green Construction Code (IgCC®)	An ICC building code that includes environmental performance as code minimums, focused on whole systems approach to design, construction, and operation of buildings. Chapter 9 specifically focuses on construction materials, including LCA and EPD requirements.

In addition to these international standards, the United States, Canada, and some states have established standards and codes addressing embodied carbon in buildings. The American Society for Testing and Materials established ASTM

[4] More information online: https://nehers.org/embodied-carbon/the-details

E2921-16a[5] which establishes criteria that can be used when comparing whole building LCAs. California and Minnesota have also established building codes which address embodied carbon through LCAs. The CAL Green Standards Code,[6] the first mandatory green building code in the United States, details a pathway to compliance through Life Cycle Analysis. The Minnesota B3 Guidelines[7] apply to all new construction and renovation projects that receive state funding and requires whole-building LCA and product EPDs for large buildings.

5 Key Resources

Though not comprehensive, this section provides a list of some additional resources and guides which architects, builders, and construction companies can use to obtain more information on topics related to reducing embodied carbon in new buildings. The Carbon Leadership Forum compiled a database of over 200 embodied carbon resources which can be found here.

5.1 New Buildings Institute (NBI)

- **Getting to Zero Embodied Carbon Resources**

  This site includes "embodied carbon and life cycle analysis resources, including methodology and tools, policies and codes, and project case studies, to support low-carbon construction materials. Introductory guides explain the basics of calculating carbon throughout the life cycle of a building; calculators and web-tools will highlight material carbon intensities, and other references will suggest how materials should be specified."

5.2 Carbon Leadership Forum (CLF)

- **Embodied Carbon Toolkit for Architects: Part 1 through 3**

  The American Institute of Architects (AIA)-CLF Embodied Carbon Toolkit for Architects serves to provide architects an overview and the necessary steps to be taken to reduce embodied carbon in their projects. This resource is divided into three parts, introducing the necessary steps and resources for reducing embodied carbon.

- **Life Cycle Assessment of Buildings: A Practice Guide**

  This guide introduces the concept of life cycle assessment to building professionals and explains how to determine the environmental impacts of a building, step by step.

- **An Analysis of Environmental Product Declaration (EPD) Definitions in Buy Clean and Other North American Procurement Policies**

  The EPD Requirements in Procurement Policy Report provides an overview of current EPD requirements in existing and proposed policies and an analysis of the supply-chain–specific EPD definition introduced by the Buy Clean Buy Fair Washington Act in 2021.

- **Life Cycle Assessment of Buildings: Technical Guidance**

  The LCA of Buildings Technical Guidance Report is directed at LCA experts who are looking for technical recommendations to support the development of LCAs of buildings in North America.

- **Embodied Carbon Benchmark Study**

  CLF produced this report with collaborators in order to assist with LCA for low-carbon construction. The report is aimed at building industry professionals integrating embodied carbon into their decision-making process(es).

- **Life Cycle Assessment of Mechanical, Electrical, and Plumbing in Commercial Office Buildings**

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[5] Available online here: https://www.astm.org/e2921-16a.html
[6] Available online here: https://codes.iccsafe.org/content/CAGBSC2019/cover
[7] Available online here: https://www.b3mn.org/guidelines/

This project provides estimates of ranges of material quantities consumed and LCA impacts due to mechanical, electrical, and plumbing (MEP) systems and interior tenant improvement (TI) fit out (walls, ceilings, lights, finishes, and furnishings) for typical commercial office buildings in the Pacific Northwest.

5.3 American Institute of Architects (AIA)

- **AIA Guide to Building Life Cycle Assessment in Practice**

AIA provides guidelines to help architects understand and use LCA methodology as part of the design process by identifying scenarios for the use of whole building LCA.

5.4 American Council for an Energy Efficient Economy (ACEEE)

- **Knowledge Infrastructure: The Critical Path to Advance Embodied Carbon Building Codes**

Provides a comprehensive review of the current state of knowledge of embodied carbon in buildings including data, tools, and standards, and identifies knowledge gaps.

- **Framework for Design Excellence**

The Framework seeks to inform progress toward a zero carbon, equitable, resilient, and healthy built environment. The Design for Resources section is focused on material selection, health, embodied carbon, and waste diversion.

5.5 RMI

- **Reducing Embodied Carbon in Buildings**

Highlights low-cost and no-cost solutions for reducing embodied carbon in buildings during a project's design and construction.

- **Concrete Solutions Guide**

Overview of proven and scalable solutions to reduce concrete's contribution to climate change.

5.6 Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub

- **LCA for Residential Buildings: Literature Review & Gap Analysis**

Summarizes research on LCA of residential buildings to identify gaps in understanding as well as best practices for LCA methodology.

- **Critical Issues When Comparing Whole Building & Building Product Environmental Performance**

Addresses critical issues and makes recommendations to practitioners and those developing guidance to enable more robust comparisons of building products and whole buildings.

5.7 Zero Emissions Building Exchange

- **Life Cycle Assessment Practice to Estimate Embodied Carbon in Buildings**

Guide to creating a whole building life cycle assessment to estimate embodied carbon.

5.8 Royal Institute of British Architects

- **Embodied and whole life carbon assessment for architects**

Document for providing architects a better understanding of an in-depth methodology for embodied and whole life carbon assessment.

5.9 Carbon Smart Materials Palette

- **High Impact Materials**

Provides an overview of carbon emissions from key building materials (concrete, steel, wood, insulation, carpet, and gypsum board) and current available options for reducing the embodied carbon from these materials.

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[13] Ibid

[14] Wang et al., *Knowledge Infrastructure* (see 7)

[15] Lewis et al., AIA-CLF Embodied Carbon Toolkit (see 12)

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